ENDLESS STAIR

A towering Escher-like structure made from American tulipwood CLT for the London Design Festival 2013.


PHOTO: JOHN SWANNELL

Projects like this can inspire not only the designers of today but also those of tomorrow.

I am delighted to be introducing this publication on Endless Stair, one of the stars of the 2013 London Design Festival. Since we founded the London Design Festival in 2003, the aim has been to challenge, educate, inspire and entertain Londoners and visitors about design.

Endless Stair is exciting because it is not only in the city, but of the city. It allows visitors new views of London by offering them a unique vantage point of the Thames, Tate Modern and the Millennium Bridge. It is a magnificent and daring piece of architecture and engineering, but one that can only be appreciated fully when it is animated by visitors. This makes it an excellent ambassador for the London Design Festival, since design, after all, is all about people.

As the London Design Festival has grown, it has occupied increasingly large areas of the city. To have a project like Endless Stair in such a prominent position at Tate Modern means that it is an ambassador not only for itself but also for the whole of the Festival, helping to attract attention to the range of activities that make up the Festival.

The fact that Endless Stair is not only a beautiful sculpture but also an investigation of a new technology is most welcome. Design needs to evolve and projects like this can inspire not only the designers of today but also those of tomorrow, who may, by walking up Endless Stair, be taking the first steps toward creating the even more exciting objects that will grace future London Design Festivals.

This is the sixth collaboration between the London Design Festival and the American Hardwood Export Council. All have been different, challenging and surprising, and Endless Stair is no exception.

John Sorrell
Co-founder, London Design Festival

CONTENTS

INTRODUCTION	**06**
First Thoughts	08
CLT and Tulipwood	10
Sustainable Forestry	14
DESIGN	**18**
Design Concept	19
Designing in Detail	24
MANUFACTURE	**32**
CLT Manufacture	33
Fabrication	36
Assembly	38
Lighting	40
LIFE-CYCLE	**42**

01 | INTRODUCTION

ESCHER COMES TO THE THAMES

The immediate fascination of a structure that visitors could inhabit was backed up by rigorous research that offers new potential for construction.

Endless Stair, a timber installation that seems to challenge the rules of perspective and which was installed outside Tate Modern in London in the autumn of 2013, takes its inspiration from the drawings of Escher. But unlike the works of the Dutch graphic artist, whose designs were famously mathematically impossible, Endless Stair was not only realisable but actually achieved.

Endless Stair was made up of a series of timber flights, some veering to the right some to the left, offering a number of routes to a top flight that culminated in a dramatic viewing platform.

It was a great contribution to the London Design Festival. Equivalent to three storeys in height, the network of stairs allowed visitors to enjoy the capital from different viewpoints.

But it was much more than just a piece of art. The latest in a series of collaborations between the London Design Festival and the American Hardwood Export Council (AHEC), it pioneered the use of hardwood in cross-laminated timber. A fast-establishing technology, cross-laminated timber is usually made from softwood, but AHEC believes that there is real potential for using tulipwood - an abundant, relatively inexpensive and structurally impressive American hardwood.

To explore the use of tulipwood CLT, AHEC commissioned dRMM Architects and Arup Engineers, to create a design that is not only visually exciting but that also tests the potential of this new form of timber construction. Manufacturers in Italy and Switzerland made the elements, which were assembled quickly and efficiently on site.

Part of the thinking behind the project was a desire to make the structure as environmentally friendly as possible, with each flight of stairs built up from standard elements, as little waste as possible in construction, and the ability to re-use and relocate the design either in part or as a whole. These laudable aspirations have been backed up by hard figures, using AHEC's ISO-conformant life-cycle assessment (LCA) prepared by PE International, leaders in the field of LCA. This is the latest piece of work in AHEC's ongoing mission to demonstrate scientifically the real sustainable credentials of American hardwoods.

Endless Stair combined the visual excitement of an art installation with the seriousness of a research project – a winning combination.

THE TEAM COMES TOGETHER

Architectural imagination, engineering expertise, and a shared love for and curiosity about timber were the vital ingredients in the success of Endless Stair.

> Team work may be an over-used term, but it has been essential in this project.

Alex de Rijke of de Rijke Marsh Morgan (dRMM) has long been a fan of using timber in architecture and pioneered the use of cross-laminated timber (CLT) in the UK at Kingsdale School in 2004. In an article entitled '*Timber is the new concrete*', he predicted that timber would be the dominant construction material of the 21st Century. The challenge of using timber in a new way was, therefore, a perfect fit. On embarking on the project, de Rijke commented, 'Swiss, Austrian and German development of laminated mass-timber construction techniques (with increasingly fine consequences) are now challenging the preconception that timber is modern architecture's poor relation.'

When David Venables, European director of the American Hardwood Export Council, approached de Rijke to discuss a possible collaboration, it was of great interest to him. 'We thought it was an opportunity to do some research with a hardwood,' de Rijke said. He is committed to designing structures that do not waste materials. 'We have tried to dimension the panels according to the size that can be laminated,' he said. 'They can be simply cut with no waste.'

For Venables, it was an exciting way to further explore the potential of a hardwood that he describes as 'one of the most intriguing timbers that we have.' He was aware of dRMM's work, and keen to establish a new collaboration that could bring creative architectural thinking to the use of timber, in the same way that earlier projects for the London Design Festival had done. These included 'Sclera', a pavilion designed by David Adjaye in 2008 and the 'Timber Wave', a complex arched structure by AL_A Architects that stood outside the Victoria & Albert Museum in 2011. Venables said 'the Timber Wave brought us very close to Arup,' the engineer that worked on the design, and this latest project is a further collaboration with the same engineer.

Arup has built up great expertise in the use of timber, but this project has allowed its team to explore its use further. 'What is really exciting,' said Andrew Lawrence of Arup, 'is that every element of design, manufacture and installation has to be investigated. How does it perform? How is it glued? How long do you press it for?' The practice has carried out sophisticated analyses of the material, in particular in the way it behaves under a movement known as rolling shear. At the same time, Arup has applied its judgment and its understanding of the material. 'We have loved the learning journey,' said Arup's Adrian Campbell, 'and helping Alex to realise his visual criteria is incredibly important'.

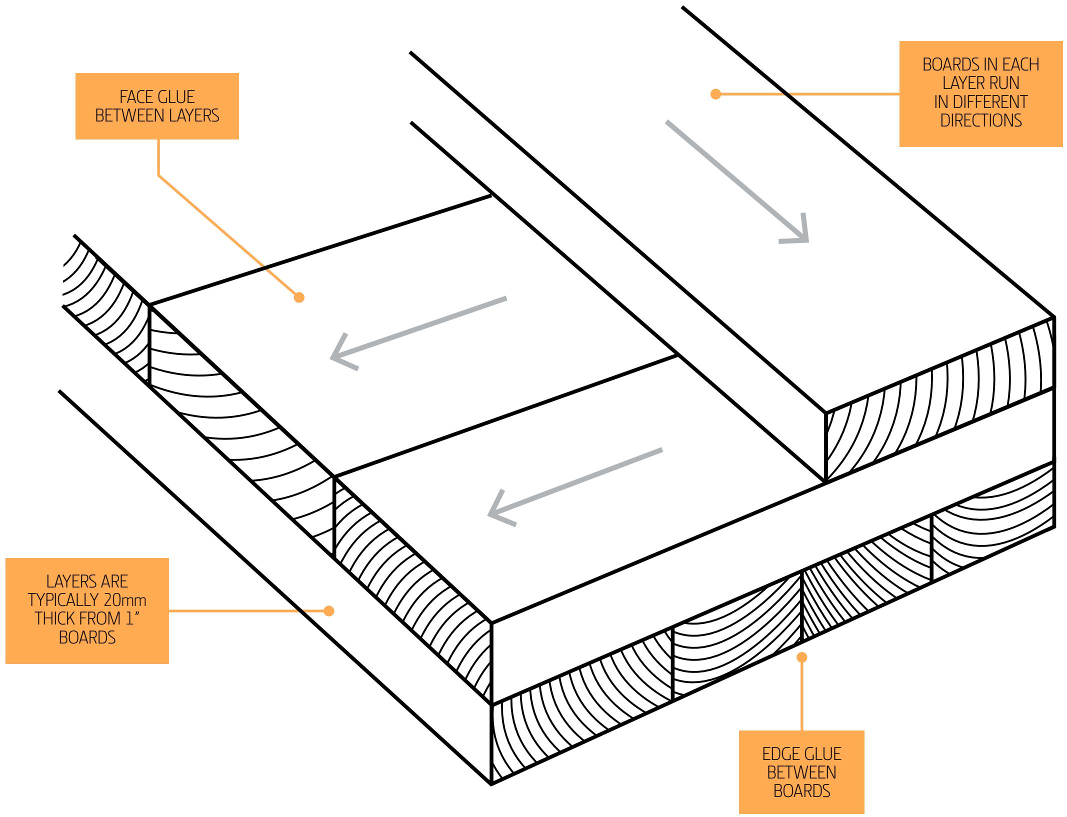
Teamwork may be an over-used term, but it has been essential in this project, with the architect and engineer exchanging ideas with each other and with the manufacturers who understand what the best approach can be. The last members of the team were the public who, by populating the stair, gave it a meaning that it would never have had while standing empty.

Alex de Rijke (standing) and Jonas Lencer of dRMM explore the geometric complexity of the test flight in manufacturer Nüssli's plant.

Building up tulipwood CLT is a way of making large panels from small trees.

STRENGTH IN SANDWICHES

CLT is an impressive technology and tulipwood offers great potential for its further improvement.



Cross-laminated timber (CLT) is an engineered timber product that is used increasingly to create the walls and floors of buildings. It is of a 'sandwich' construction, normally with an odd number of layers in the sandwich. On each successive layer the fibres of the timbers run in opposing perpendicular directions, so that if you could look through the CLT from above you would see a kind of grid of fibres. It is orthotropic – that is, it has different properties in three directions. This is important because timber is strong along the directions of the fibres, but less so in the cross direction. Building up tulipwood CLT is a way of making large panels from small trees. It also gives it dimensional stability. Modern off-site manufacturing methods mean that CLT panels can be made in a factory and then delivered on site for assembly in a fast and accurate manner, cutting down on the time needed for construction and the risks involved.

Another advantage of CLT is that, because each sheet is built up from a number of planks, any local weak areas, such as knots, have relatively little effect on the overall strength. This makes it possible to use lower grades of timber than are traditionally considered for construction, without any loss of quality in the finished product.

Solid CLT panels also have inherent fire resistance and therefore can be left exposed in finished structures without applied fire protection.

European manufacturers of CLT panels use softwood – most commonly spruce. The question that AHEC posed was, would it be feasible to use a stronger hardwood to make the panels, to combine the advantages of CLT with the visual appearance and inherent strength of a hardwood?

David Venables of AHEC saw tulipwood as particularly suitable for this purpose. One of the most abundant hardwoods in American forests it is, like all American hardwoods, grown sustainably. Its botanic name is *Liriodendron tulipifera* and one common name in the U.S. is yellow poplar – confusing, as it is biologically entirely different to poplar, and has much better mechanical properties. Tulipwood is often referred to as 'Queen of the Forest', derived from the fact that it grows tall and straight, often towering over other trees in the canopy. As it grows upwards, it tends to drop its branches resulting in timber with fewer knots than other U.S. hardwoods.

Tulipwood's structural strength is well understood, since it is one of a number of species on which Arup and the Building Research Establishment carried out tests several years ago (the others were American red oak, American white oak and American ash). Tulipwood is an anomalous material in that although it has the same bending strength as oak, its density is similar to softwood. The idea of using CLT made from this light, strong, affordable timber was, therefore, an intriguing one. Endless Stair is the first step in this investigation.

Page 13: American tulipwood trees.

Above Right: Tulipwood CLT and glulam panels in Endless Stair.

Right: dRMM's Kingsdale school pioneered the use of softwood CLT in the UK .

PHOTO:AHEC

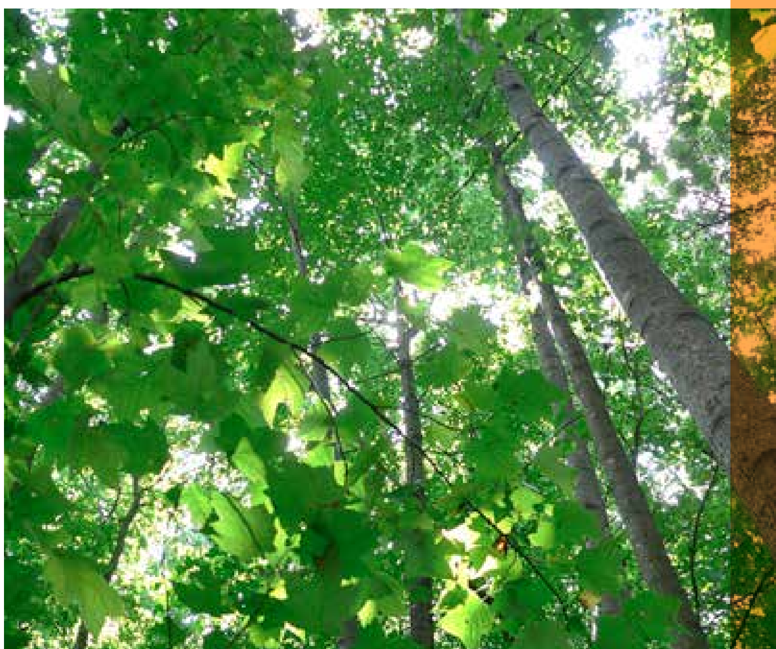


PHOTO: APPALACHIAN HARDWOOD MANUFACTURERS, INC.

> The structural strength of tulipwood is well understood.

Liriodendron tulipifera

TULIPWOOD FACTS

Tulipwood is a creamy white timber with colour variations. The CLT panels include brown, green and purple streaks which are natural character marks.

A tulipwood tree will grow for approximately 40 – 60 years before it is harvested.

American tulipwood, *(Liriodendron tulipifera)*, derives its name from its distinctive tulip-shaped flowers.

Tulipwood makes up 7.5% of the standing hardwood resource in American hardwood forests.


Hardwood forest in Northern Wisconsin.

PHOTO: J. MARTIN, JMAR FOTO-WERKS

THE BEAUTY OF FORESTS

Forests are natural carbon sinks which operate most effectively if they are harvested sustainably.

Timber is the most sustainable of the major renewable construction materials because, as a growing material, it locks up carbon dioxide, storing it during the period it is in use. If at the end of its life it is recycled into another application, that storage continues. When there is no further use for it, it can be burnt to produce heat, electricity or both. By generating heat or electricity we avoid the burden of burning fossil fuels such as natural gas, which emit greenhouse gases.

The forests in which timber grows can be seen as 'carbon sinks', locking up carbon dioxide within the trees. But not all forests are equal – if they are not harvested, the rate of carbon sequestration decreases. In recognition of this, the UN Intergovernmental Panel on Climate Change wrote in its Fourth Assessment Report that, 'In the long term, a sustainable forest management strategy aimed at maintaining or increasing forest carbon stocks, while producing an annual sustained yield of timber, fibre or energy from the forest, will generate the largest sustained mitigation benefit.'

A 'sustainable forest management strategy,' avoids depletion by excessive harvesting and the American hardwood forest demonstrates this. In the case of American hardwoods, this is not an issue. Between 1953 and 2007, the volume of hardwood standing in American forests more than doubled from 5 billion m^3 to 11.4 billion m^3.

The American Hardwood Export Council has invested in detailed life-cycle analysis of its timbers, taking them from the forest through initial processing to the factory gate. Carried out by leaders in the field, PE International, this work was audited by an international critical review panel. The full ISO-conformant report is available at www.americanhardwood.org

It found, for example, that kiln drying of timber is the greatest source of global warming potential, contributing between 8% and 32%

> If forests are not harvested, the rate of carbon sequestration decreases.

of the potential in the production process. It varies according to the species of timber (some take longer to dry) and also depends on the thickness of the timber.

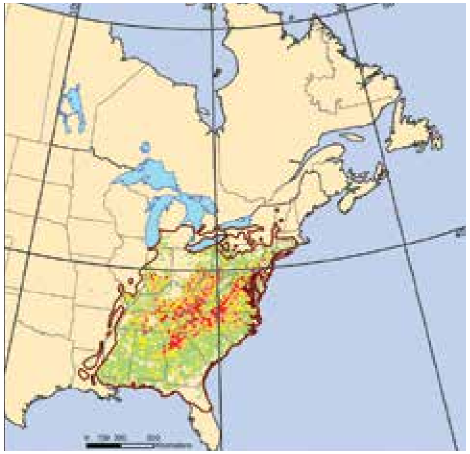
Transport, however, was found to have less of an impact than expected, especially when it is by sea. So for example, road transport from the United States to Canada has a larger impact on global warming potential than transport by ship from the United States to Western Europe. However, other impacts are higher for sea transport, such as the acidification potential, a result of the sulphur contained in the fuel and the ensuing emissions of of sulphur dioxide (SO_2).

Data on material impacts from production has, by definition, to stop at the factory gate – or at the site if there is no further factory processing – since the details of what happens next are unknown. But when it comes to a specific project such as Endless Stair, or a product, such as cross-laminated timber, then it is possible to collect specific data and work out the precise impacts. PE International creates 'i-report' templates which allow you to change certain variables and appraise their impact on a specific product. It has created one for this project (see pages 42-51).

You can see the i-report at www.americanhardwood.org/EndlessStair/

Hardwood forest in Northern Wisconsin.

PHOTO: J. MARTIN, JMAR FOTO-WERKS



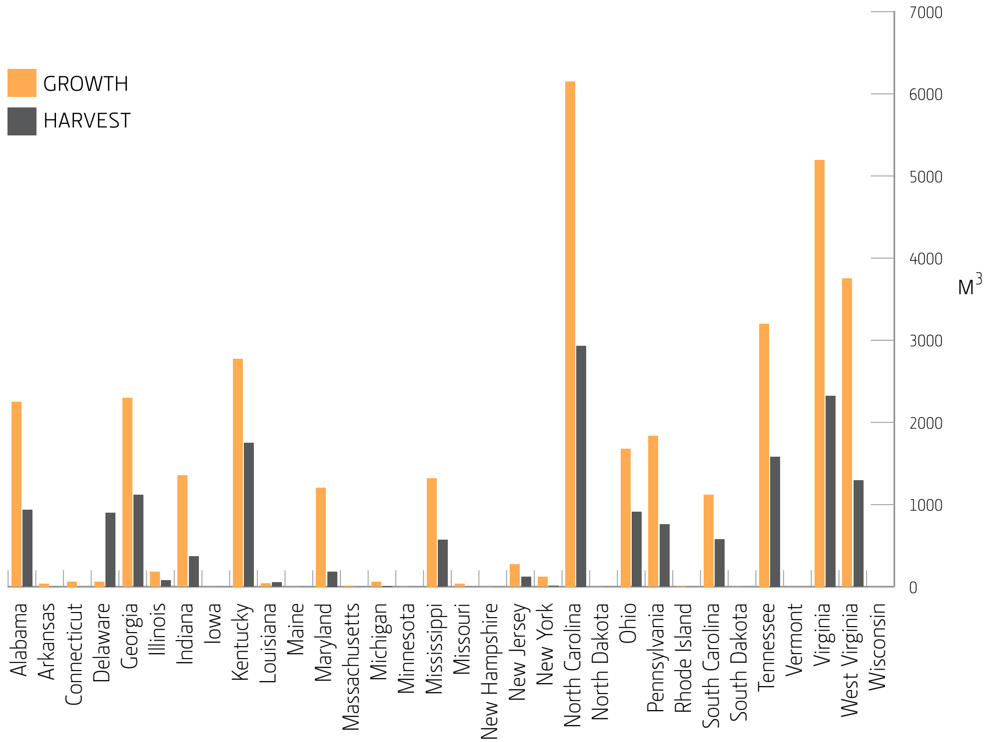
KEY

FIA IMP value*

	0		11 - 20
	1 - 3		21 - 30
	4 - 6		31 - 50
	7 - 10		51 - 100

*FIA IMP Value refers to the species "Importance Value" calculated by the U.S. Forest Service Forest Inventory and Analysis (FIA) programme. It is a measure of the proportion of the forest stand comprised of each species on a scale of 0 - 200.
0 = species not present; 200 = monoculture of the species.

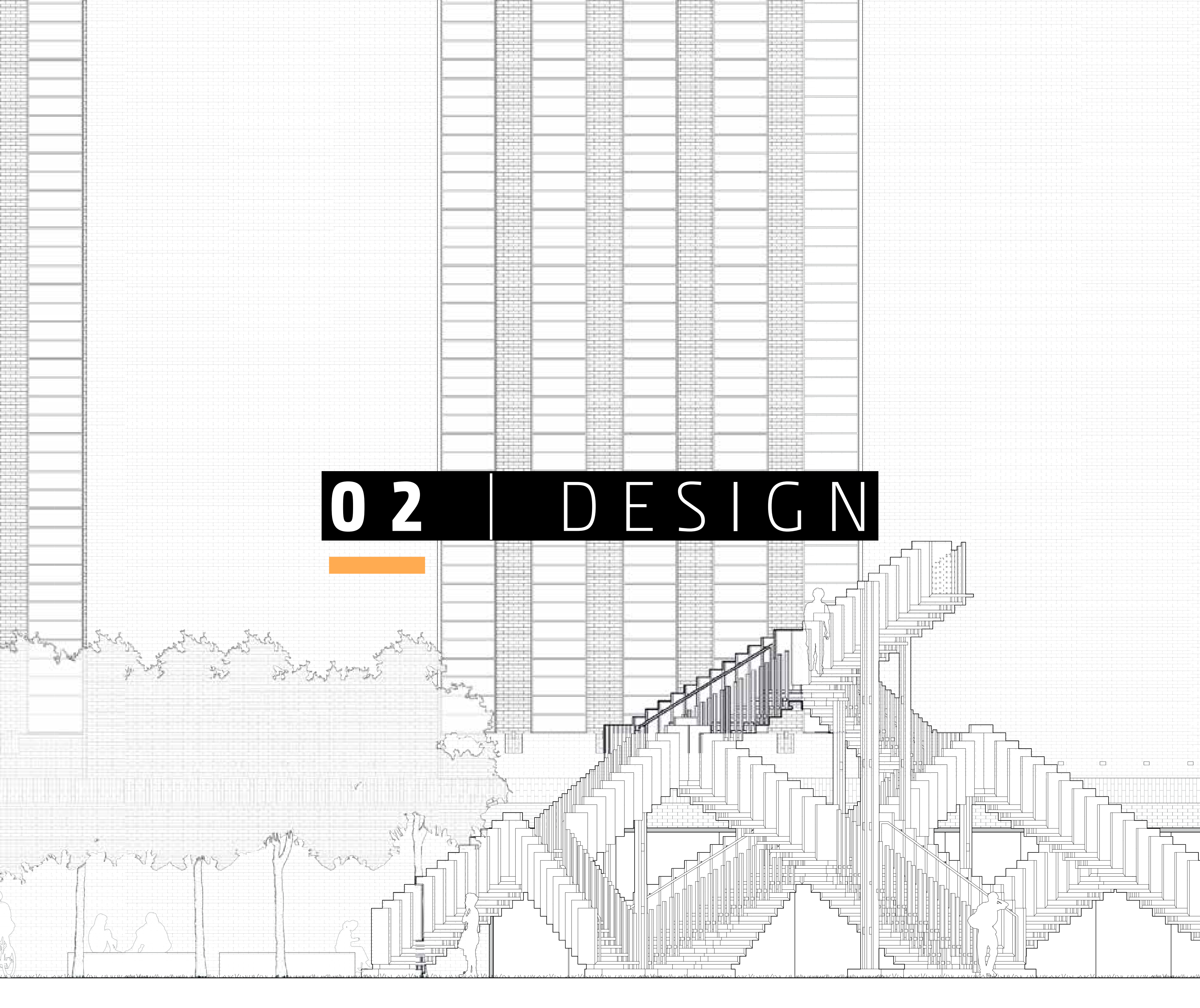
The current range and FIA Importance Value of tulipwood in the United States .
Source: USDA Forest Service

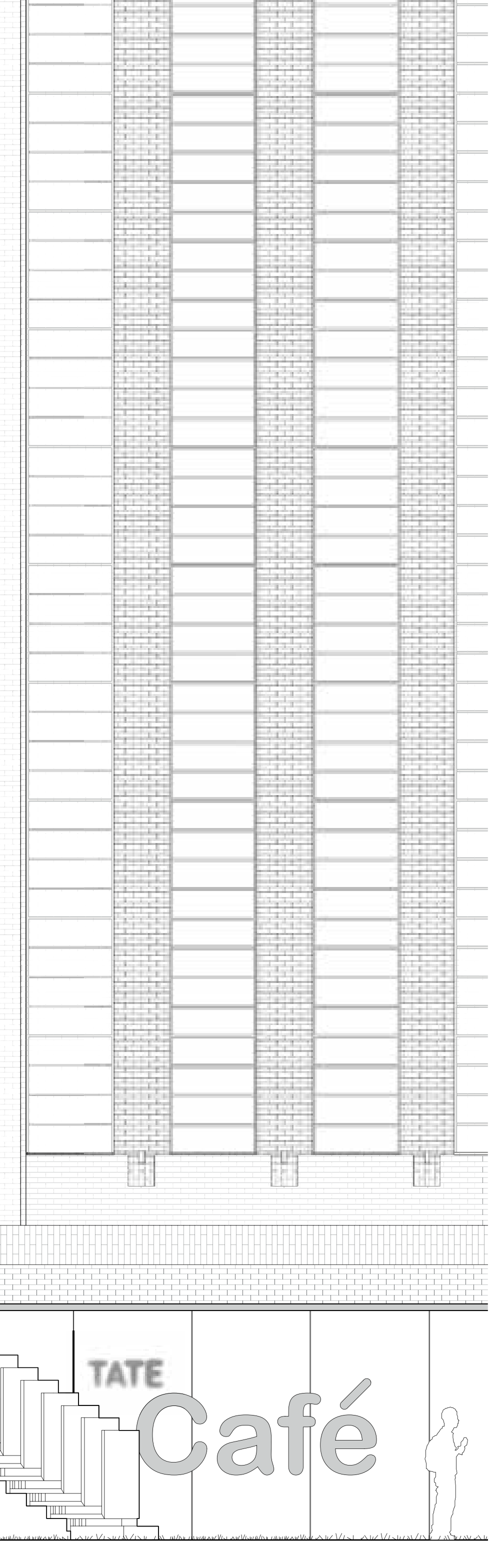


Graph to show annual growth and harvest volume of tulipwood in U.S. hardwood - producing states.

PHOTO: HARDWOOD MANUFACTURERS ASSOCIATION

02 | DESIGN





STEPS TO A SCULPTURE

Endless Stair materialised as a sculptural form, yet posed challenges in terms of public accessibility.

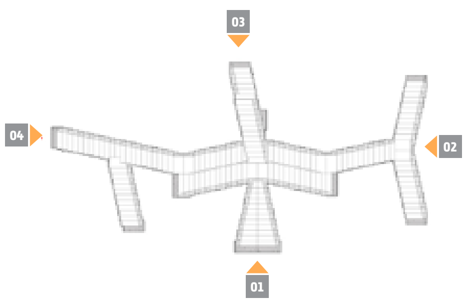
Faced with the challenge from the American Hardwood Export Council to produce a sculptural installation using slender 60mm thick tulipwood CLT panels, Alex de Rijke settled quickly on an idea involving stairs. ‘On stairs people interact, they pass each other, they are always interesting places with spatial and social potential,’ he said. ‘We thought a staircase would be a good vehicle for exploring structure, space and making a sculpture. Stairs are sculpture’s gift to architecture.’

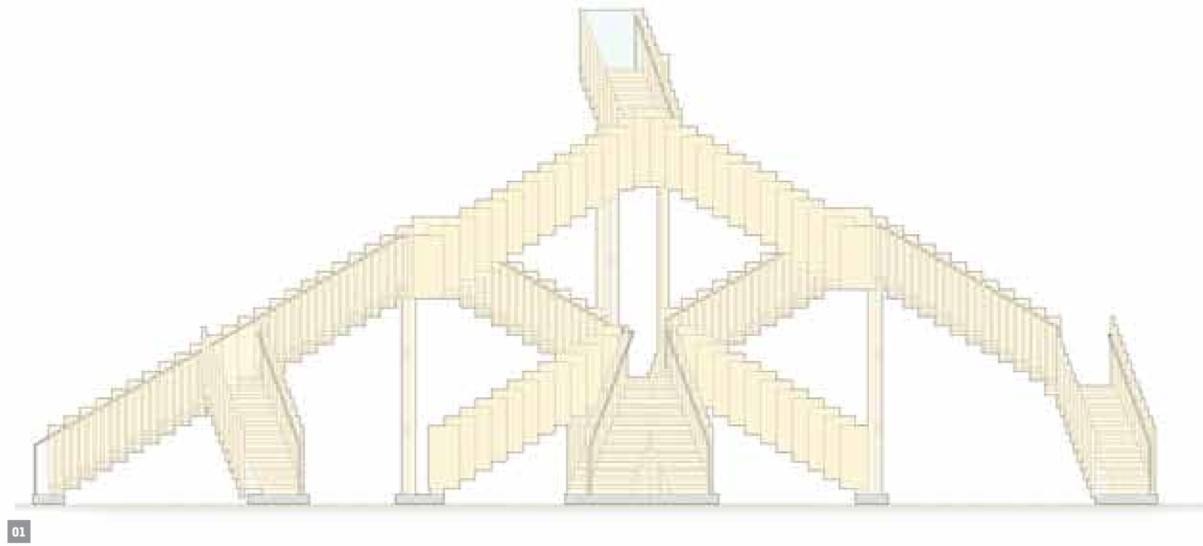
One of the earliest decisions was to make the steps and the balustrades on one side from identical elements of CLT, equivalent in size. These elements are stacked up with a spacer element between them, creating the flights which, as a result of the stacking process, then veer either to the right or to the left, depending on the position of the balustrade.

Although at first glance, the stairs seem to go off in all directions, in fact there is an essential symmetry to the design, with pairs of stairs forming arches for structural stability. The visual tricks that they play are indicated by the fact that the architect had to build physical models because, in computer drawings, the structure was almost impossible to understand. Like the best optical illusions, what came forward at one moment appeared to recede the next.

In order to avoid the possibility of the flights of stairs pushing outwards, they were restrained at the bottom by concrete blocks embedded in the ground. These also served as the bottom tread on every one of the lowest staircases. They have the additional advantage of raising the timber structure off the ground, so that it is not susceptible to rot or swelling from standing groundwater. Five large upright double solid timber columns also stabilise the structure.

One of the biggest challenges came from the fact that this was not simply a sculptural installation, but also one that the public could access.





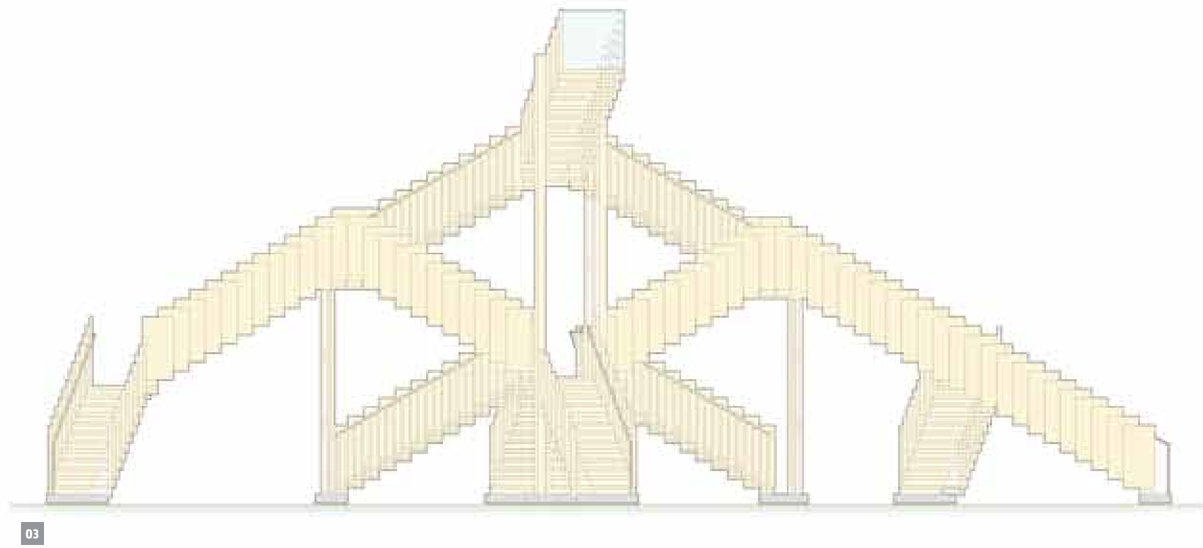
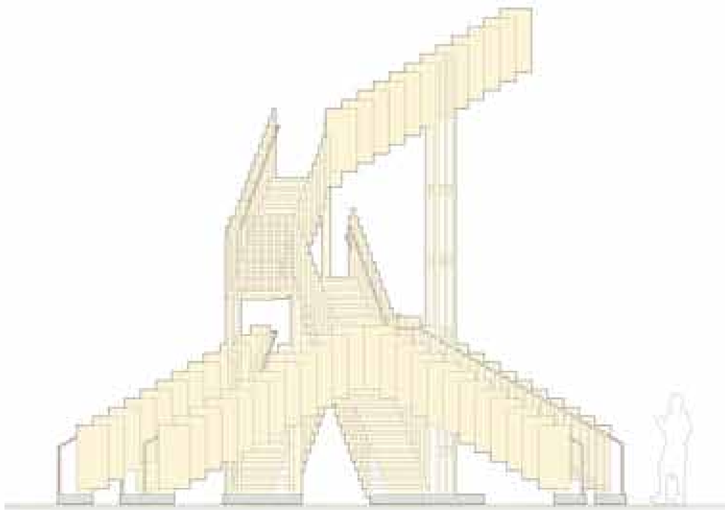
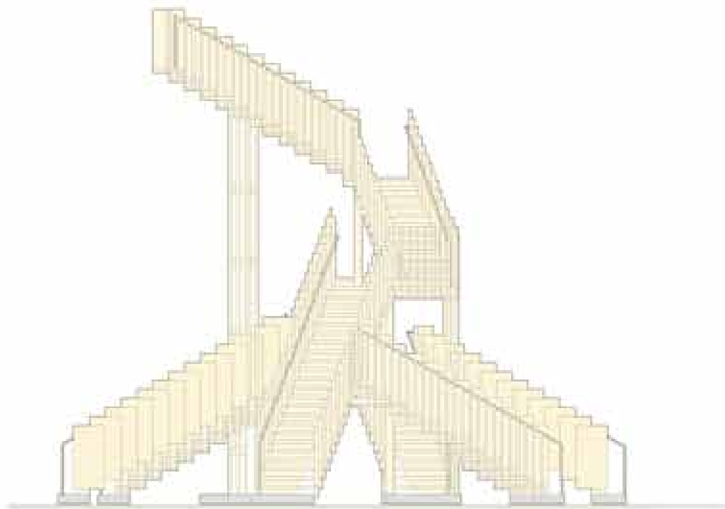


FIG 1 Visualisation by dRRM, showing the model viewed from four different directions.

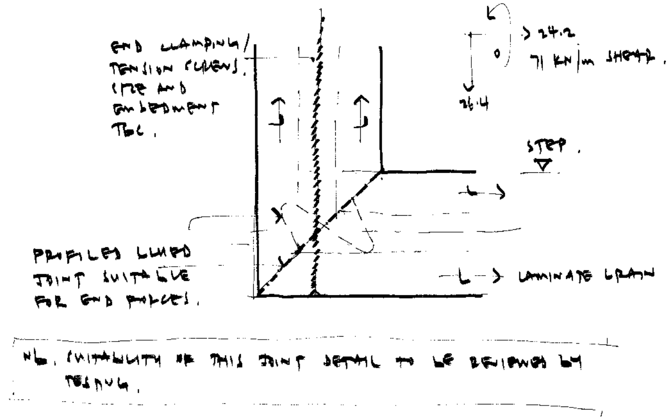


02

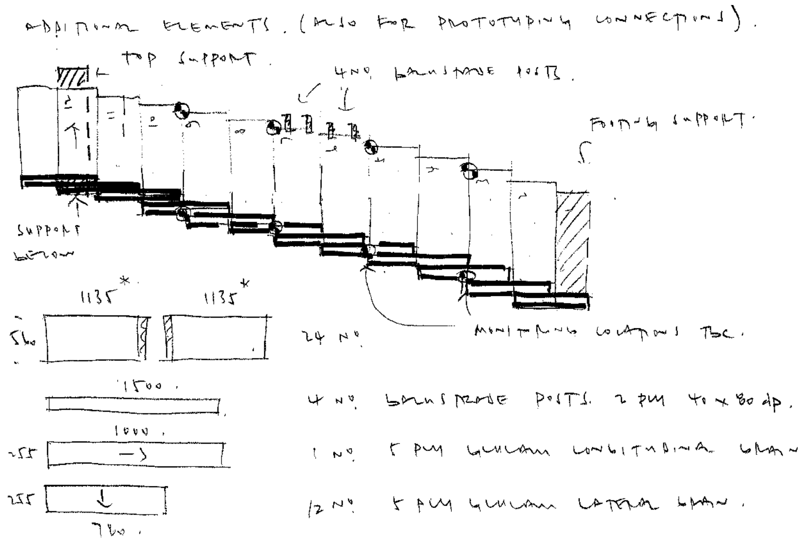


04

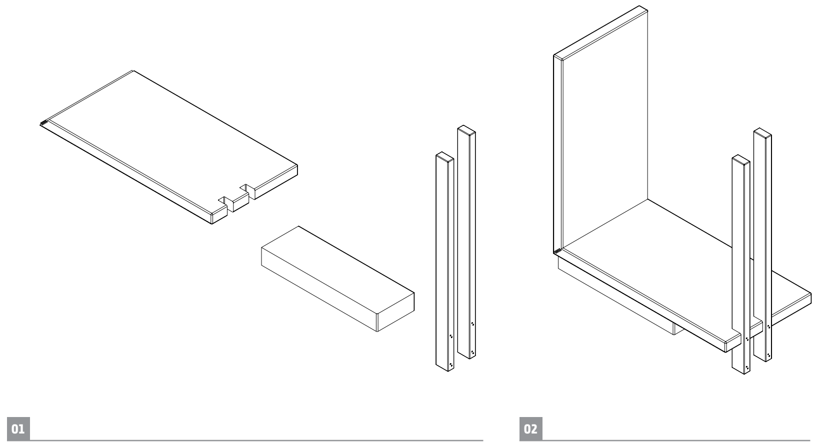
FIG2: EARLY SKETCHES



Sketch by Arup investigating the joint between the tread and the balustrade elements.



Sketch by Arup showing the way that the flights would build up and identifying dimensions.



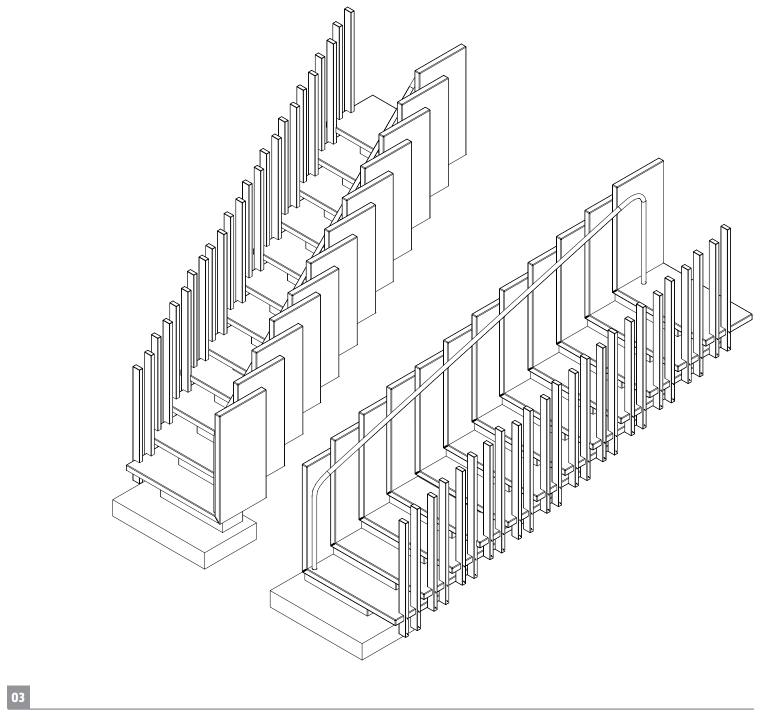
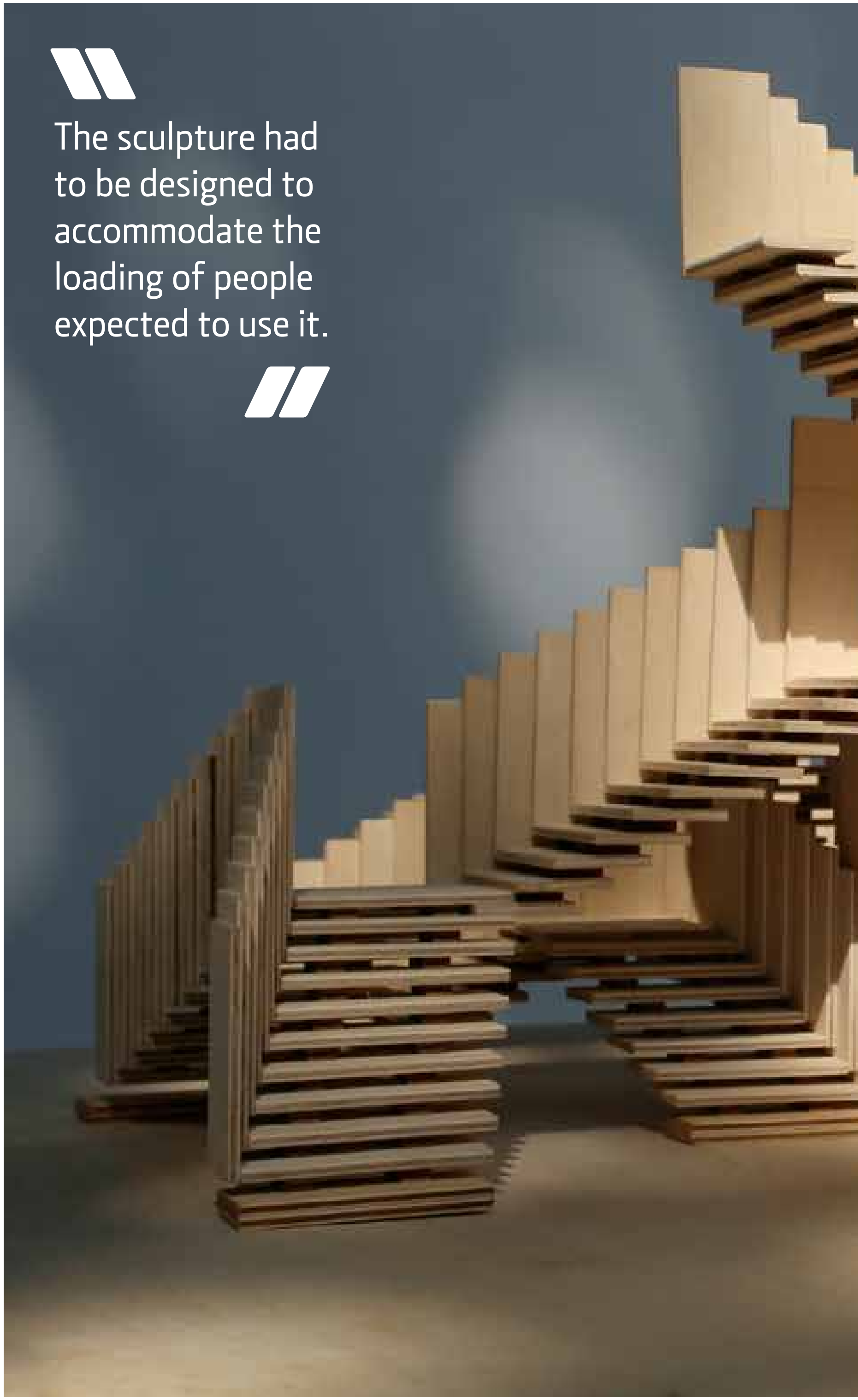


FIG 3: KIT OF PARTS

01 Tread, infill block and balustrade posts.

02 The five elements that come together to make a single step element.

03 Steps joined together into flights, with only a handrail added.



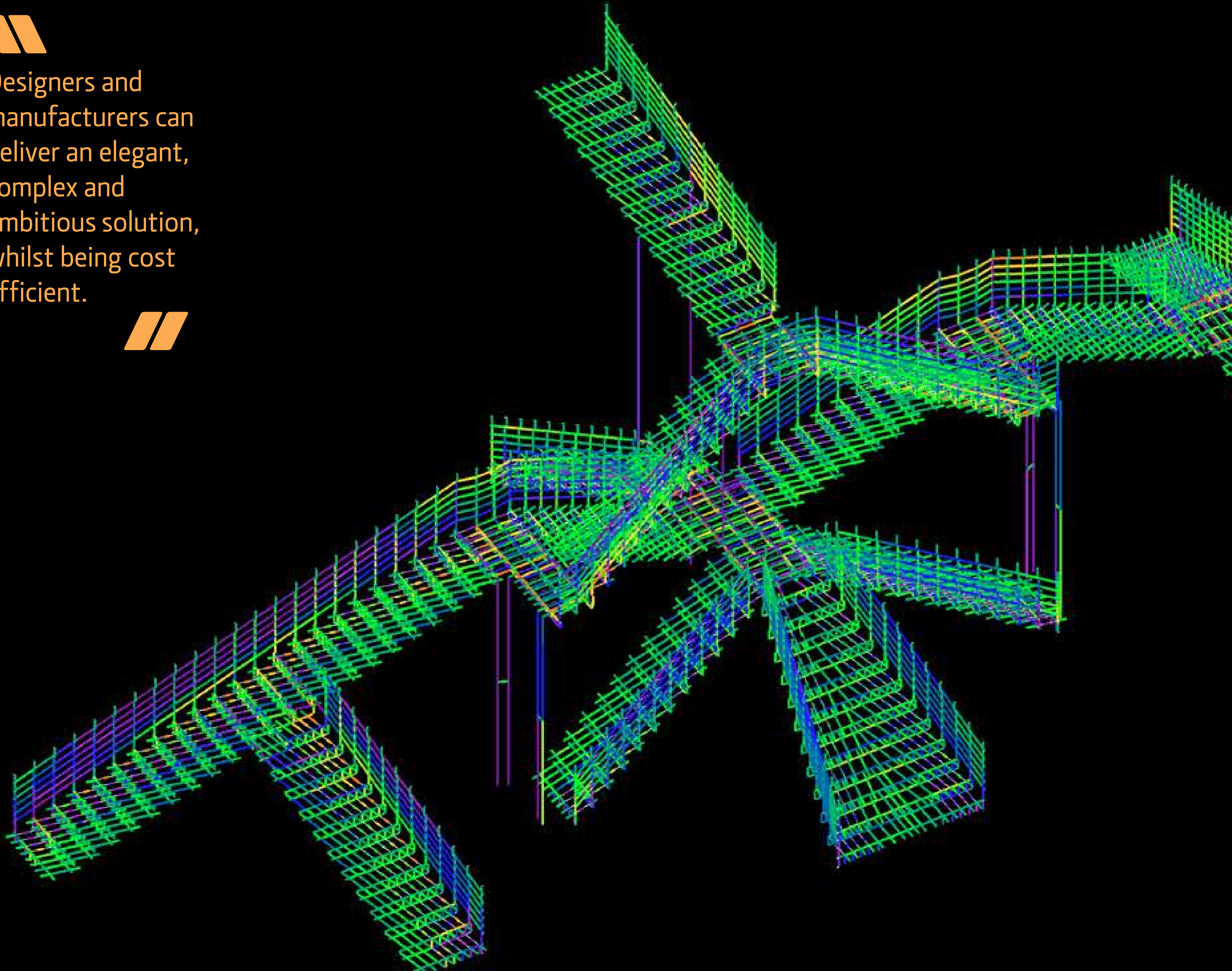
Although it did not need planning permission, because it was only temporary, it still had to be safe to use, with balustrades that would not let people fall through, landings in appropriate positions, and non-slip finishes. And, of course, the sculpture had to be designed to accommodate the loading of people expected to use it.

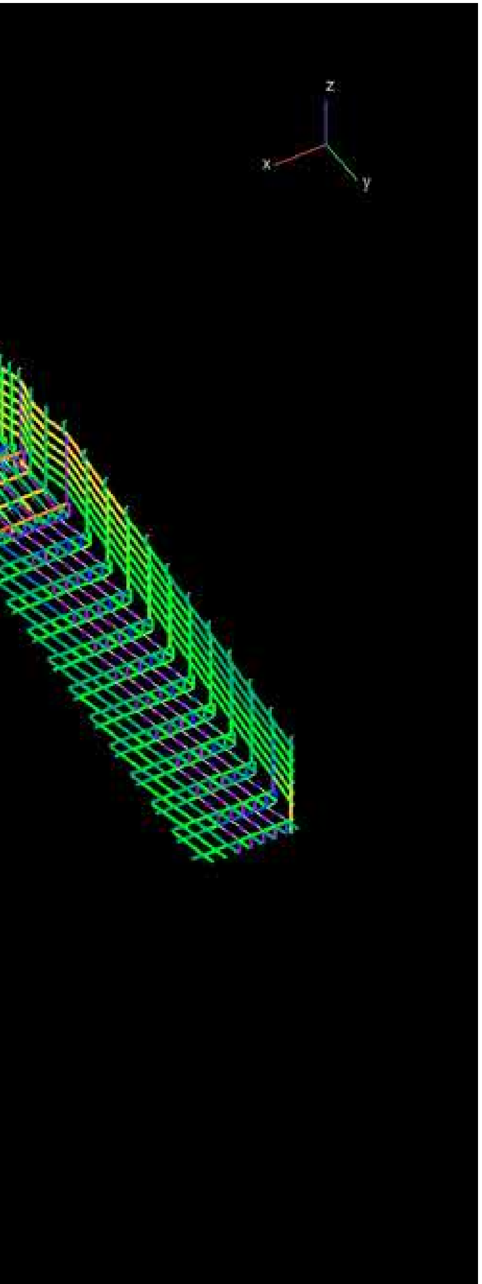
With a total of 187 steps, Arup designed the sculpture so that there could theoretically be about 100 people on the structure at any one time – observations on services such as the London Underground show that, even on crowded escalators, people only occupy every other tread.

While the structural design only required a balustrade on one side of the treads, safety considerations meant that there had to be one on the other side as well. The architect designed a series of uprights. 'I thought at first it would take all the transparency away,' said Alex de Rijke. 'But then I realised that it would add a layer of interest by casting a shadow.'

The entire project required work from first principles, using testing, research and analysis. This will bring endless benefits. The ultimate aspiration is not simply to create a beautiful sculpture, but to bring tulipwood CLT into mainstream building construction.

> Designers and manufacturers can deliver an elegant, complex and ambitious solution, whilst being cost efficient.





Plot showing the axial forces under a wind loading case. Reds and oranges show the largest tension forces, blues and purples show the largest compression forces.

DESIGNING IN DETAIL

How the teams designed an intricate sculpture that pushed the boundaries of conventional thinking.

Arup has undertaken in-depth analysis and research for the engineering design of Endless Stair. Hardwood CLT (cross-laminated timber) had never been manufactured before. ‘Novelty, learning and the pure joy of such an exciting engineering challenge has been a great opportunity,’ said Adrian Campbell, project director at Arup. ‘Working within a fast-paced programme, we demonstrated that designers and manufacturers can deliver an elegant, complex and ambitious solution, whilst being cost efficient.’

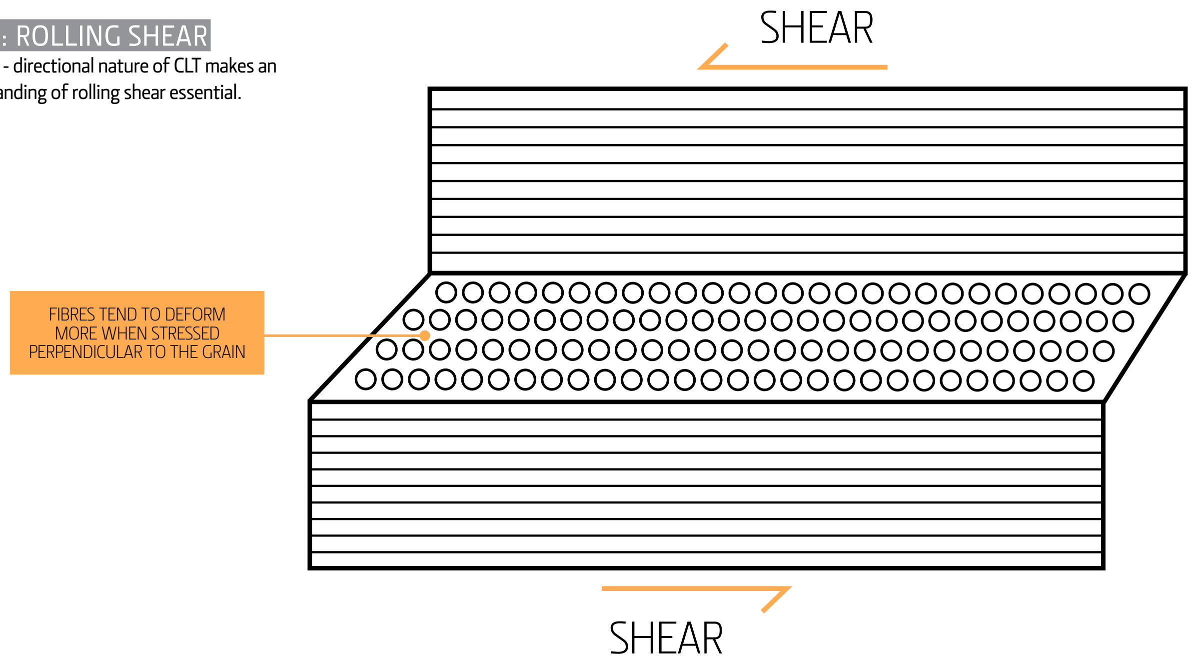
Even softwood CLT had never been used in such a complex way. As Andrew Lawrence, Arup’s timber specialist, explained, ‘Most CLT buildings are very simple. The CLT is just used to make walls and floors. No-one has ever attempted something as complex as this.’

To realise this project, Arup engineers undertook a three-fold approach: engineers studied the latest information available; performed sophisticated analysis and calculations; and commissioned testing to demonstrate that the theoretical performance would be achieved in practice.

This was a tremendous opportunity to illustrate how engineering from first principles could bring to fruition the architect’s concept in an elegant and efficient manner, while at the same time promoting the use of a completely new timber material.

FIG 1: ROLLING SHEAR

The two - directional nature of CLT makes an understanding of rolling shear essential.



UNDERSTANDING TULIPWOOD CLT

Understanding the behaviour of tulipwood CLT, especially in 'rolling shear', was the first challenge. CLT is made by gluing small planks together in two directions, thus enabling very large panels to be manufactured from small trees. Unlike in a floor joist where all the wood fibres run in the span direction, in cross-laminated timber approximately half run crossways. Therefore, when a CLT floor panel deforms under load (Figure 1), the cross-fibres tend to roll over each other. This rolling increases the amount of deformation.

Until CLT was invented, very little testing had been undertaken on rolling shear for any wood species. Eurocode 5, for instance, simply recommends taking the rolling shear as twice the tension strength perpendicular to grain, and there is little or no guidance on rolling shear stiffness. For Endless Stair, testing at the University of Trento utilised the test method in the provisional European standard for CLT (pr EN 16351) to determine more accurate values.

Three CLT panels were made and tested. The results were incredibly exciting. They demonstrated that tulipwood was approximately three times stronger and stiffer in rolling shear than softwood. This evidenced Arup's original hypothesis that tulipwood was an ideal material to use for CLT. Understanding the rolling shear properties allowed the design of Endless Stair to proceed with increased confidence as to how the overall structure would behave.

DURABILITY

CLT is not suitable for permanent use outside. Rain and humidity cause the wood to swell, and that can, in turn, place stress on the glue lines. Tulipwood is not durable enough for external exposure without treatment. To improve durability and limit swelling, two coats of lacquer were applied to the faces and end grain of the panels. In addition, any standing water was removed from the sculpture, to reduce the possibility of moisture ingress.

The bottom tread of each flight was made of concrete to avoid the timber having unnecessary contact with the ground, which could have potentially led to moisture uptake and swelling.

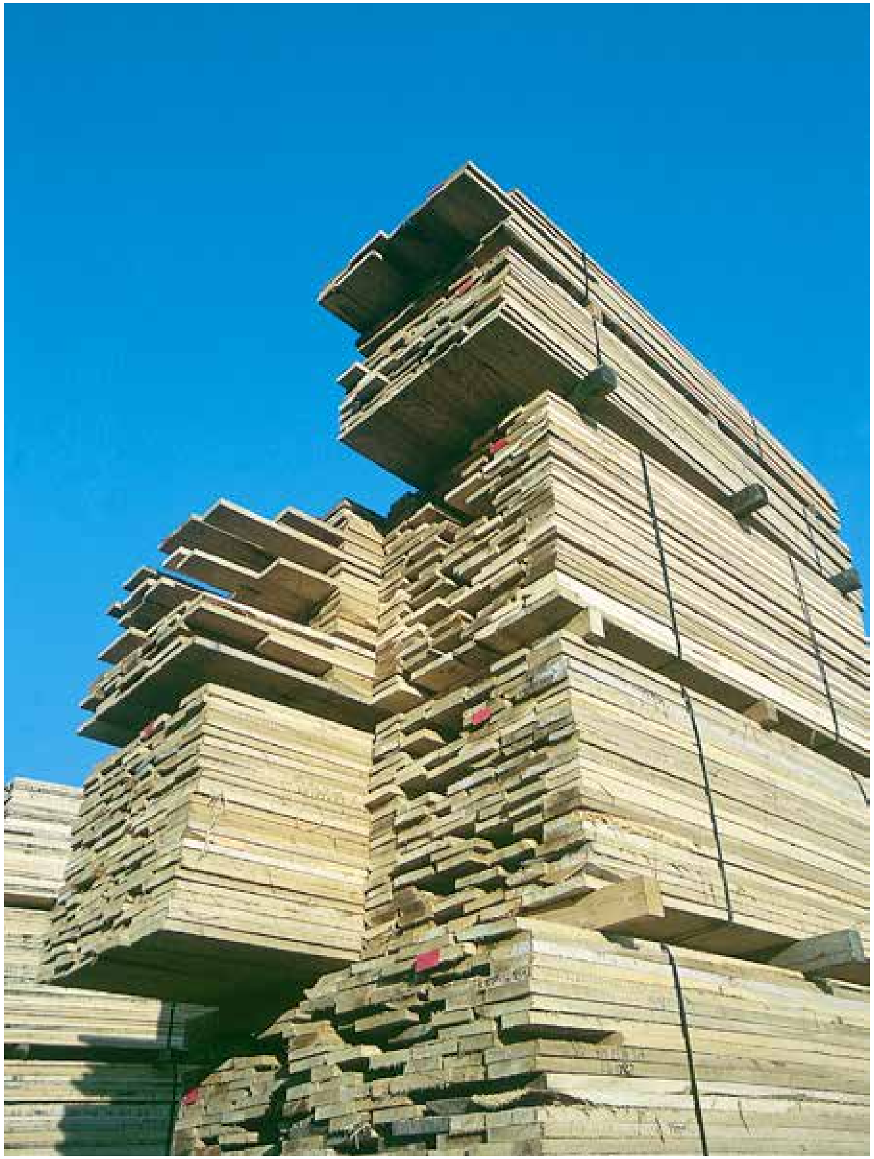


FIG 2 American sawmills cut timber in random widths and lengths, which may pose a challenge for traditional CLT manufacturers.

MANUFACTURING HARDWOOD CLT

One of the challenges of manufacturing hardwood CLT is the size of the available raw material. Softwood CLT producers usually source planed, kiln-dried timber. All the pieces have an identical thickness, width and length. In contrast, American hardwoods are generally shipped in random widths and lengths (Figure 2). For tulipwood, the width can vary from 95mm to 350mm and the length from 1.8m to 4.8m. A higher degree of wastage would have occurred had boards been cut down to standard lengths and widths to suit a typical softwood CLT manufacturer. For future commercial development of tulipwood CLT, it may be possible to source fixed width lumber. The solution however for this project was to identify a company that could edge-glue the random-width boards together into large flat sheets. Imola Legno was identified as the preferred manufacturer.

Edge-gluing is the application of glue between the boards that make up each individual layer of a CLT panel. Normally edge-gluing is not required. For Endless Stair, however, the CLT panels had to be cut into relatively small elements and edge-gluing was, therefore, essential. This treatment ensured unglued joints did not appear in sensitive locations. To add further strength, Imola Legno created a finger-joint between the edge-glued boards. (See pages 34-35 for images).

Identifying the appropriate glue was also essential. The PVA joinery glue which Imola Legno normally used was not suitable for structural use outside. When exposed to the elements, PVA quickly loses strength and, therefore, would not be suitable for a sculpture that carrying loads. The normal solution for CLT is to use polyurethane glue. Testing was undertaken by Purbond, a company specialising in adhesives for timber construction, proving that tulipwood glues very easily. Polyurethanes, however, set relatively fast and, therefore, require specialist equipment that Imola Legno could not obtain in time. It was decided instead, to use an epoxy resin (Lamset by Rotafix). This particular epoxy resin is much easier to apply by hand. In the future it will make sense to use standard polyurethane glue as this will be more economic.

> The solution was to identify a manufacturer that could edge-glue the random-width boards together into large flat sheets.

STRUCTURAL CONCEPT

The overall structural concept for the stair is relatively simple. The flights tend to act partly as arching elements, with compression carried both through the solid balustrades and from tread to tread down to the ground (Figure 3). The overall shape of the sculpture allows flights to lean against each other.

The behaviour of the stair is similar to Georgian 'cantilever stairs', a slightly misleading term as the stairs do not actually cantilever. Vertical loads are actually transmitted down to the ground by one tread supporting the one above (Figure 4). Bending in the thin CLT panel connecting adjacent treads must be carried by just a 20mm thick layer of tulipwood. The connection between treads is, therefore, one of the most highly stressed parts of the sculpture. The balustrades help to stiffen the structure rather than just the treads on their own. The stiffness of the side balustrades is controlled by the 'rolling shear' properties and the amount of overlap between one balustrade panel and the next.

The use of hardwood CLT panels means that the structure's geometry has been maintained as envisaged by the architect in the conceptual designs.

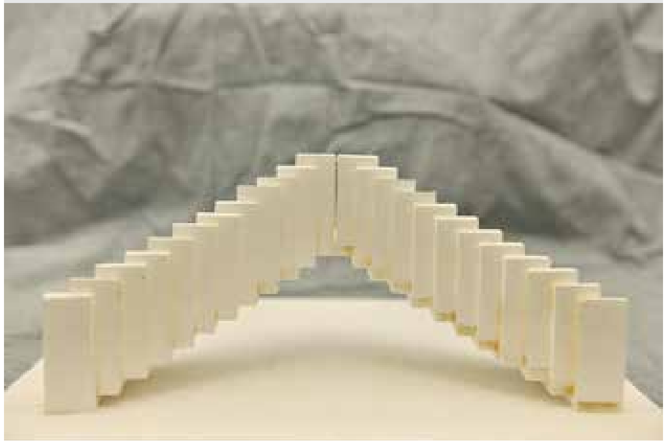


FIG 3 The pairs of flights act as arching elements.

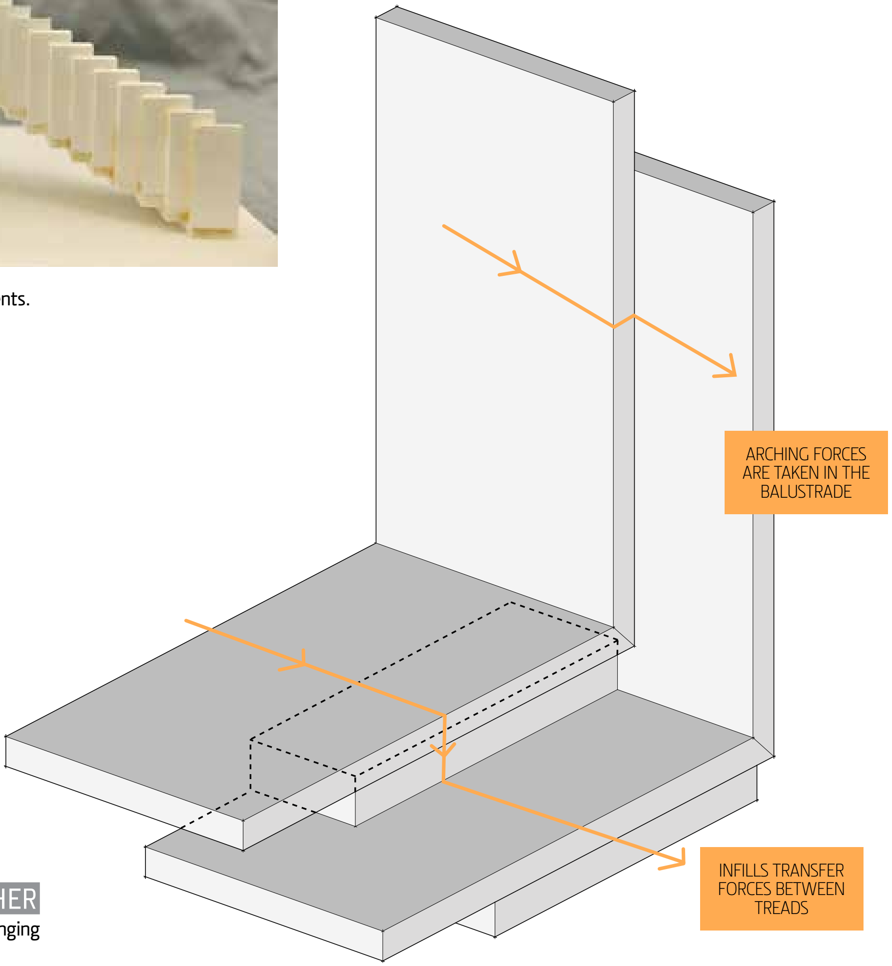


FIG 4: WORKING TOGETHER
Each tread supports the one above, bringing the load to the ground.

> By examining how people queued on busy stairs, Arup defined an appropriate level of loading.

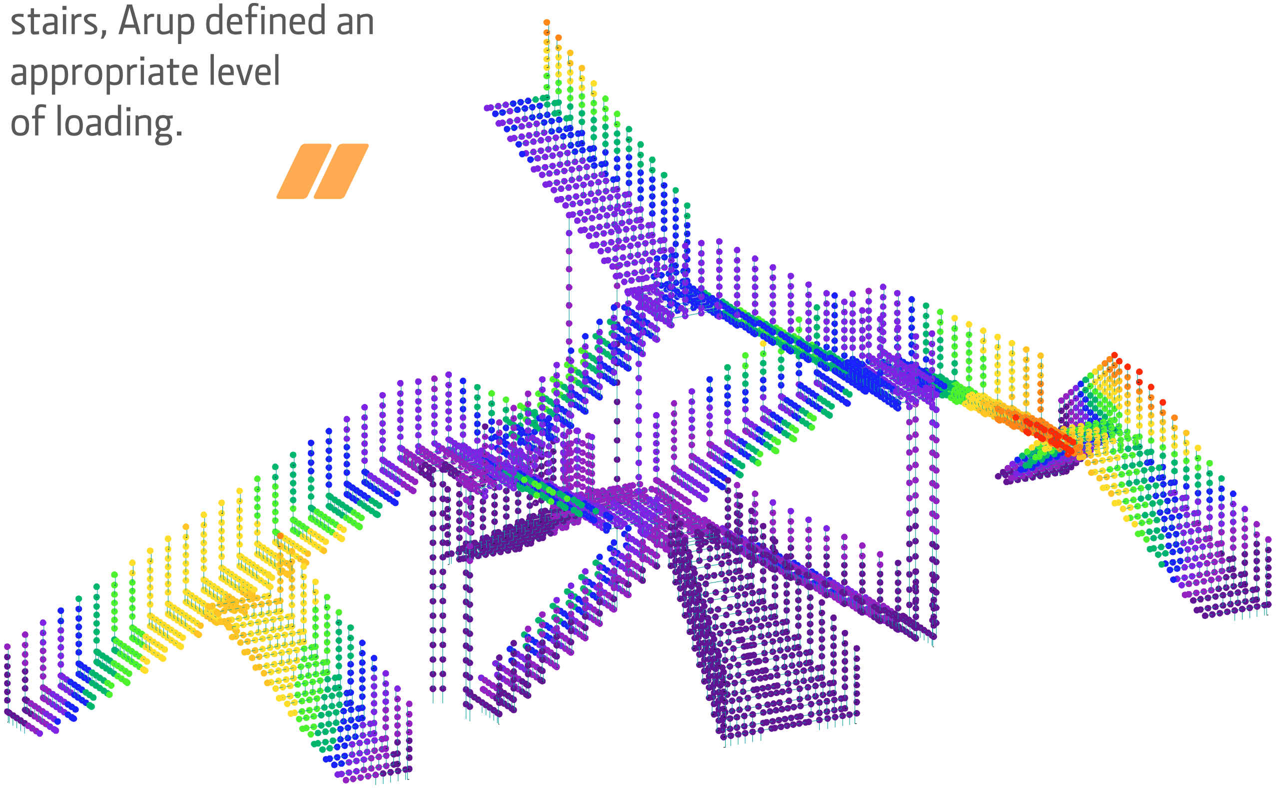


FIG 5 Predicted deflections of the sculpture under a uniform load of $2kN/m^2$ on every tread. Red shows the largest lateral deflections.

DESIGNING FOR PERFORMANCE

Since the installation was designed to be interactive and people were encouraged to climb the stairs, the sculpture had to be safe to use, while not compromising the overall aesthetics of the design.

With little guidance on how a structure of this type would perform, Arup had to identify the appropriate engineering design criteria to assess its performance. By examining how people queue on busy stairs, with one person standing on every other tread, Arup defined an appropriate level of loading. In typical loading terms this equated to approximately $2kN/m^2$ (i.e. $200\ kg/m^2$). In addition, Arup predicted that there might be times when people would stop and assemble in groups. For these concentrated patch loads, Arup assumed having one person on every tread. This is equivalent to nearly $4kN/m^2$. Figure 5 shows the deflections of the sculpture under a uniform load of $2kN/m^2$ on every tread.

It was also important to set a limit on how much the structure could move. The analysis model showed that no part of the structure would ever move by more than 20mm, which was acceptable. In most areas, the movement would be far less than this (See figure 6 over the page).

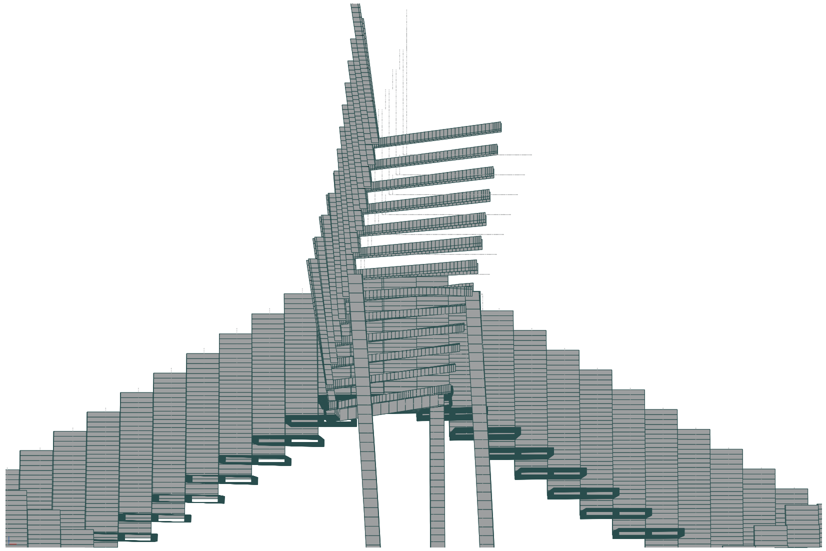


FIG 6 Exaggerated picture of how the top cantilevering flight will distort.

COMPUTER MODELLING

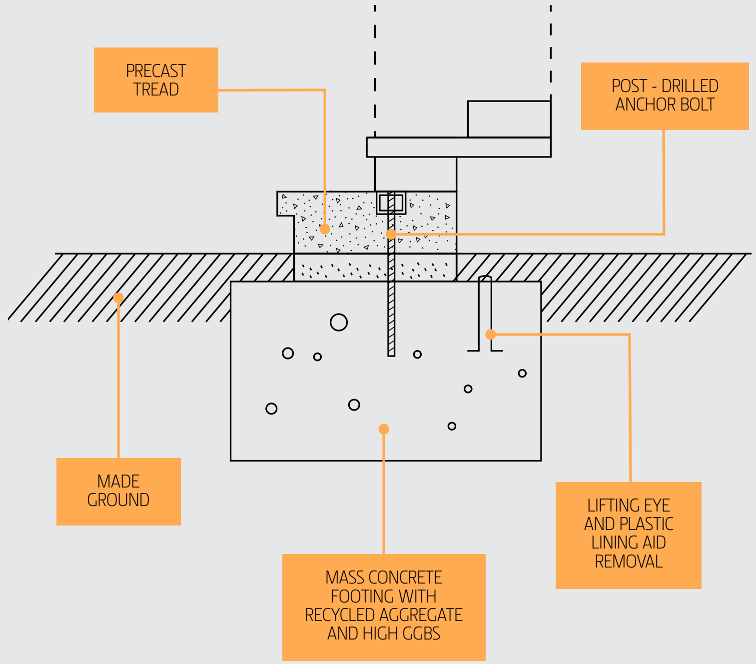
As the sculpture could be more flexible than a conventional structure, this would inevitably lead to larger than normal deflections. The sculpture was, therefore, designed to resist non-linear second-order deflection and buckling effects.

Notwithstanding the computer modelling, confidence in designing such a complex structure had to be verified to evidence how the structure would behave. Arup therefore asked Nüssli to manufacture a test flight and to compare its performance with the computer model. Weights were loaded onto the test flight (see pages 36-37) and the resulting movements were sufficiently close to provide increased certainty that the computer modelling was accurate.

Similarly, the complexity of the design meant that the overall vibration behaviour could not be easily predicted through analysis. The completed stair was tested, in situ, before the formal opening in order to measure its performance. The monitoring information gathered during the de-propping sequence showed that the structure is stiffer than anticipated, suggesting that with further materials testing, improved rolling shear characteristics could be adopted for future designs in tulipwood.

FOUNDATIONS

Endless Stair was supported on concrete pads to suit the particular site conditions. The foundations were designed to resist not only the vertical loads of the sculpture and people but also the horizontal thrust imposed by the arching forces. In legacy mode, different solutions will be required with respect to foundations.



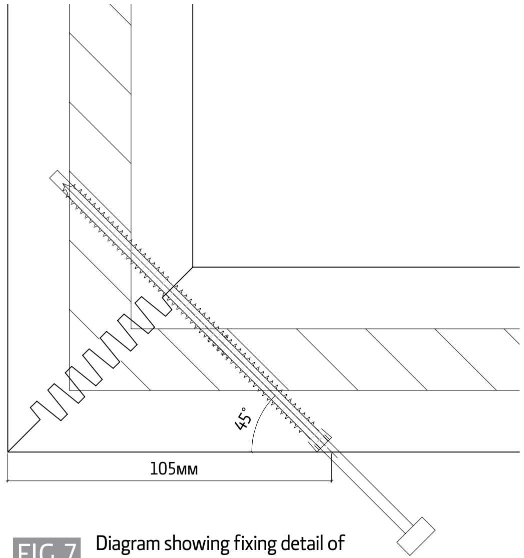


FIG 7 Diagram showing fixing detail of tread to balustrade panels.

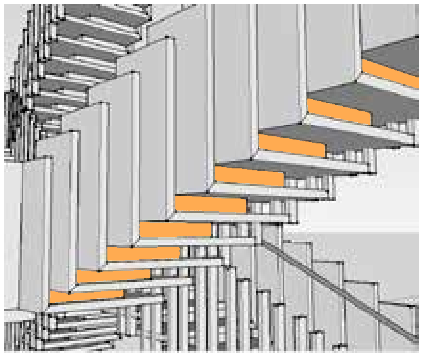


FIG 8 Final proposal for the glulam infill block connecting one tread to the next.

CONNECTIONS

Good connection design is a vital element for all timber projects. The connections between treads and balustrade panels were critical to both the design and the ease of construction (Figure 7). In dRMM's initial design, the infill between adjacent treads consisted of two small blocks and was relatively transparent. Arup settled on one longer block (Figure 8), made from five layers of tulipwood glulam (glued laminated timber), to allow the forces to flow down through the treads. The connecting tread was, nonetheless, one of the most highly stressed parts of the stair, using the full bending stiffness of the tulipwood.

The individual flights were glued and screwed together off site in controlled factory conditions, to provide a strong and stiff connection. The landing connections were also critical in allowing for fast on-site installation and later disassembly. This was achieved by connecting together the prefabricated flights on site with long tensioned bolts.

PROVISIONAL DESIGN DATA FOR TULIPWOOD CLT

The table below provides some of the key structural properties for tulipwood and compares these to standard C24 softwood. Most of the values are based on testing previously carried out by Arup and AHEC at the UK's Building Research Establishment (BRE), using FAS joinery-grade tulipwood material that was re-graded to comply with structural grade TH1 of BS 5756. The strength of wood is dominated by density, knots and slope of grain. Tulipwood grows as fast and straight as softwood but is about 30% denser and practically knot free up to 20 – 25m from the ground. Tulipwood is therefore approximately 70% stronger in bending than a typical grade C24 softwood, as illustrated in the table below.

		Tulipwood	**C24 softwood**
Bending	N/mm²	**41.7**	**24**
Tension parallel	N/mm²	**25**	**14**
Tension perpendicular	N/mm²	**0.5**	**0.4**
Compression parallel	N/mm²	**26.8**	**21**
Compression perpendicular	N/mm²	**6.8**	**2.5**
Shear	N/mm²	**4.0**	**4.0**
Rolling shear (*provisional)	N/mm²	**2.7**	**0.8**
Mean density	N/mm²	**552**	**420**

*The rolling shear values are based on project-specific testing for Endless Stair and should not be used for other projects. These impressive values can, however, potentially be achieved.

03 | MANUFACTURE

ITALIAN JOB: MAKING THE CLT PANELS

The lumber that arrived at Imola Legno was transformed efficiently into uniform panels of CLT.

Imola Legno, a family-owned timber firm based in northern Italy, made the tulipwood CLT panels. The biggest challenge for production director, Chad Cole, was working as efficiently as possible with the different widths and lengths of tulipwood that arrived from the producers in North America. The grade of timber specified for this project is known as 'No. 2 Common' a relatively low grade, which is usually reserved for the domestic market. No. 2 Common timber has a higher incidence of knots and other defects. The whole point of the process of making CLT is that this lower grade of timber can be used without jeopardising the strength of the panels but providing cost savings. With material coming from a number of suppliers, there was also considerable variation in colour, which enhanced the attractive appearance.

Imola Legno took the 1" thick (American measures) strips of hardwood and cut out the larger defects to create planks of various widths of wood. It cut them, and created a 'jigsaw puzzle' of pieces (although all the timber was aligned in the same direction) in order to make the sheets of CLT. Then it edge-glued between the strips with vinylic glue. Finally, it planed the sheets down to 20mm thick.

Not all layers were alike. Cole deliberately made three types of sheet, an sheet - A, B and C. 'A' was the best quality in terms of finish, 'B' the next best, and 'C' the least attractive visually, although still structurally sound. The 'C' sheet became the centre of the sandwich, with the others providing the exterior faces. The very best would be the surface seen from close up, and the second best seen from underneath or outside of the structure. Cole said, 'This means that, from a sustainability point of view, waste can be minimised by using all of the material's natural colour and grain variations.'

The company also made the five-layer glulam for the infill blocks. It used a 'brick-laying' technique, ensuring that the joints in adjacent layers did not line up, to increase the structural strength.

01:LUMBER ARRIVES

American hardwoods are generally shipped in random widths and lengths. Only the thickness is constant. For tulipwood, the width typically varies from 95 to 350mm, and length from 1.8 to 4.5m. This means that the manufacture of CLT from tulipwood is a very different process, requiring a more considered approach than when using softwood which is cut to standard widths and lengths.

02:CUTTING & PLANING

A softwood CLT producer would have created a large amount of wastage to achieve standard timber dimensions. Fortunately Imola Legno, a leading Italian importer of hardwoods, is used to working with these random elements. It created a 'jigsaw' of timber, cutting the lengths and widths appropriately to minimise wastage, and then planing the 1" timber to a thickness of 20mm.

03:EDGE-GLUING

Edge-gluing, which is the gluing of the sides of the planks together to form the sheet, is not done by all CLT manufacturers. Some rely on the bond between the sheets to hold the elements in place. But in this case, where there are points of high loading and with the possibility that an edge joint could be near the edge of an element, it was considered essential. Imola Legno used a modified finger joint and a vinylic glue.

04: SINGLE LAYER

Once the planks had been edge-glued together to form the single sheets that would be combined to make the CLT, they were placed in clamps for setting. Each monolayer sheet measured 1135mm by 560mm. The planks ran the opposite way in the sheets that would form the 'filling' for the timber sandwich. Imola Legno consigned the least visually appealing timber to this hidden role.

05: RESIN SPREADING

Because Imola Legno usually makes panels for joinery, it uses a non-structural PVA glue. This would not have been suitable for bonding the layers of CLT for the stair, since it would be exposed to moisture in the external environment. Test data showed that polyurethane glue (PUR) would be an appropriate solution, but there was not enough time to set up the equipment that would be needed for its use. Instead Rotafix Lamset Epoxy was used.

PHOTOS: MAXILLA FOTOSTUDIO

06: THE PRESS

Completed panels were placed in a press while the epoxy resin reached its full strength. Once this happened, the task was complete. After some final finishing, the panels were packaged ready for road transport from northern Italy to Nüssli in north-east Switzerland ready for the next stage in the making of Endless Stair.

SEE MORE PRODUCTION IMAGES IN THE iPAD EDITION

Search for 'Endless Stair' in the App Store

MASTERS OF MAKING

At a manufacturing facility in a rustic Swiss village, Nüssli fabricated Endless Stair with exemplary attention to detail.

Nüssli received the CLT panels, glulam panels and timber for the upright posts, and then set about assembling them into flights of stairs – minus the balustrade posts, which had to be fixed on site, as they would have made the flights too bulky for transport.

The first task was to cut and mould the solid timber columns. Then the CNC machine cut the treads and the side elements, putting in all the fixing points.

Next came the cutting of the special diagonal finger joint, and of holes for screws to prevent the stair from pulling apart. After this was the cutting of the infill elements, and of the balustrade posts.

With all the elements now cut, the process of assembly could begin (although of course, these happened alongside each other once production was going at full tilt). The first step was to glue the treads and the sides together in pairs, with a polyurethane glue. Then the flights themselves were assembled, and finally, the landing elements. The black tubular steel handrails, through which the cables for the lighting travelled, were also fixed.

There was a great deal of handwork involved in the process, which was done with the greatest precision. For example, the company cut special slots into the treads to help with the positioning of the infill blocks, to ensure that this was done with total accuracy each time.

Nüssli also assembled a test flight, loaded it and measured the deflection, finding that it was well within the expected limits.

Once all the assembly was complete, the flights and ancillary elements were packed into four trucks to travel to the site, outside Tate Modern in London.

01

Cutting and moulding of a solid timber column.

05

Joining treads and balustrade elements.

02

CNC machine cutting treads and balustrades and putting in fixing points.

03

Finger joints having just been cut.

04

Cutting the infill elements from five-layer glulam.

06

Assembling a flight.

07

The test flight assembled, complete with balustrade posts which for the other flights were fixed on site.

08

Test flight, loaded to simulate occupation in use.

WELCOME TO LONDON

Prefabrication paid off when the structure arrived on site, with simple and rapid erection.

Nüssli's own team was in charge of the erection process. The first stage of the work, once all the material had been unpacked on site, was to carry out some final gluing of the landings, since creating a complete double landing in the factory would have been too ungainly for transport. At the same time, the shallow foundations were constructed and trenches laid for the electrical cables.

Nüssli used a crane to erect and fix the stairs, with cherry pickers used for limited support tasks (using these too freely would have had a damaging effect on the grass), and some scaffolding to support the flights until they were joined together, forming the self-supporting arches.

The screws that Nüssli used for fixing on site had much larger heads than those it used in the factory. This was because in the factory it was able to use fully threaded screws, which resist pull-out forces far better than partially threaded screws. But they require elements to be clamped together in a manner that was not practical on site. For on site fixing of the balustrade posts the company, therefore, used partially threaded screws, with the large heads providing the extra resistance needed.

DYNAMICS AT NIGHT

Subtly changing lighting provided another way of seeing Endless Stair at night.

SEE MORE NIGHT IMAGES IN THE iPAD EDITION
Search for 'Endless Stair' in the App Store

The complex form of Endless Stair lent itself to imaginative lighting, and that is what SEAM Design provided. 'We worked with the architect's vision of an Escher-esque piece,' explained Marci Song, director of SEAM, 'to bring out the juxtaposition between solids and voids, solids and surfaces, and play on disorientation.'

The lighting scheme used LED luminaires supplied by Lumenpulse. These were a combination of linear grazers and spotlights hidden within the sculpture. With the use of special programming, these were dynamic lights, which could be controlled individually to reveal different aspects of the structure and to perceptually reconfigure the spaces within. The effect of light movement was slow and subtle, giving a feeling of changing mood and definition. Additionally, the light scheme incorporated presence detectors to trigger light sequences, which gave an added degree of interest and enhanced the security of the sculpture at night. 'This allowed us to experiment with the relationship and interactivity between people and the sculpture,' Song said.

The lighting system was designed in advance, with the final programming carried out once Endless Stair was installed.

04 | LIFE-CYCLE

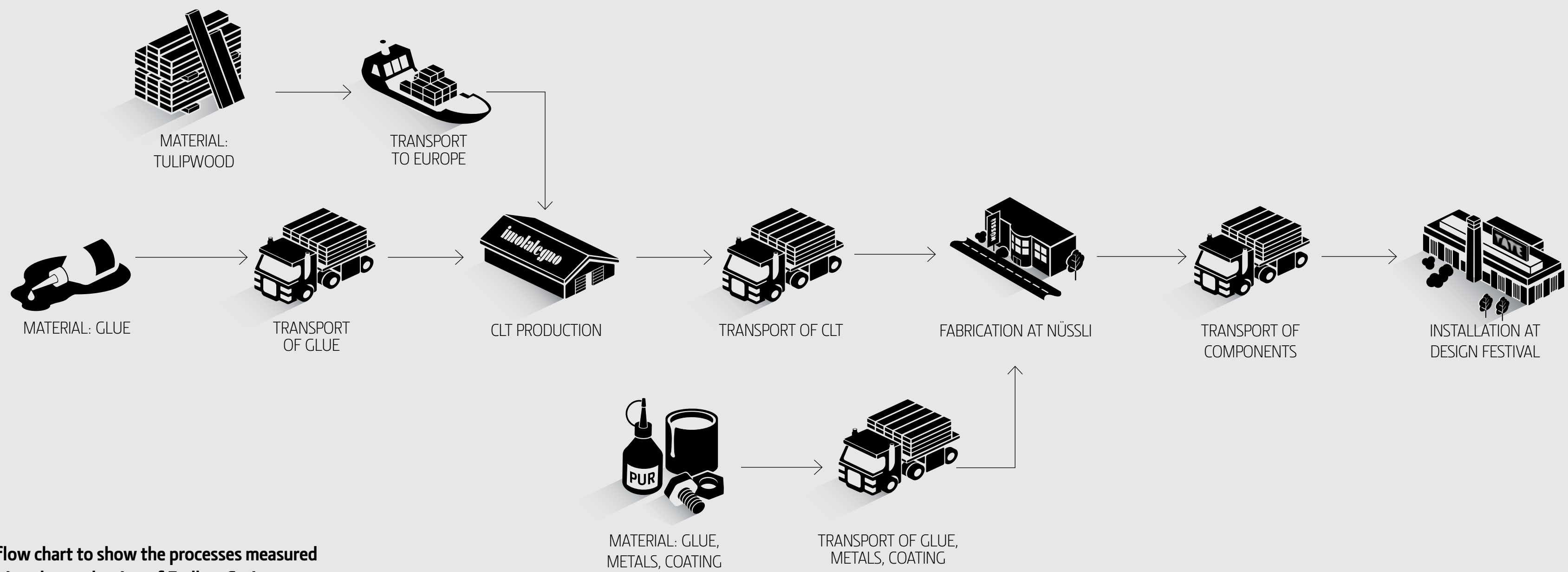
LIFE-CYCLE ANALYSIS

Detailed analyses of six major impacts make it possible to determine the contribution of every part of the process.

The following pages show the main environmental impacts involved in the production of Endless Stair, from the forest to installation on site. All information has been provided by PE International. It is worth noting the considerable off-setting of some impacts that come from the manufacturing processes. This is because both Imola Legno and Nüssli use hardwood waste to produce thermal energy. This is common practice in the wood manufacturing industry and helps to avoid the consumption of natural gas as fuel with its consequent impacts, particularly for global warming. In this way the manufacturing process can actually help offset the impacts of a product.

Impacts of glues are high, higher, in fact, than they would be with industrial-scale production. This is because of the logistical need (explained on page 27) to use epoxy resin for the face gluing in the CLT production, rather than the polyurethane glue that would normally be used and which has around 30% less global warming potential and primary energy demand.

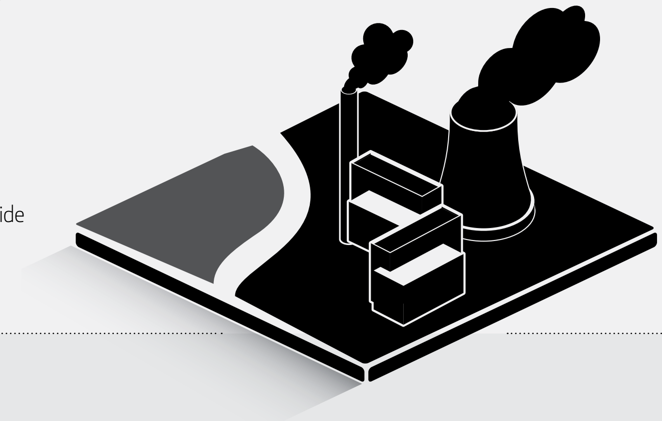
These analyses do not go beyond the installation of Endless Stair to its end of life. Biogenic carbon stored in biomass will – sooner or later – be released at the end of the product's life-cycle, one hopes with a beneficial result such as burning for energy. There are different ways to account for the embodied carbon, but for simplicity and transparency, in these analyses the stored (biogenic) carbon has not been subtracted from the global warming impact of Endless Stair. For information, however, a reasonable estimate is that about 14.5 tonnes of CO_2 are stored in the structure.

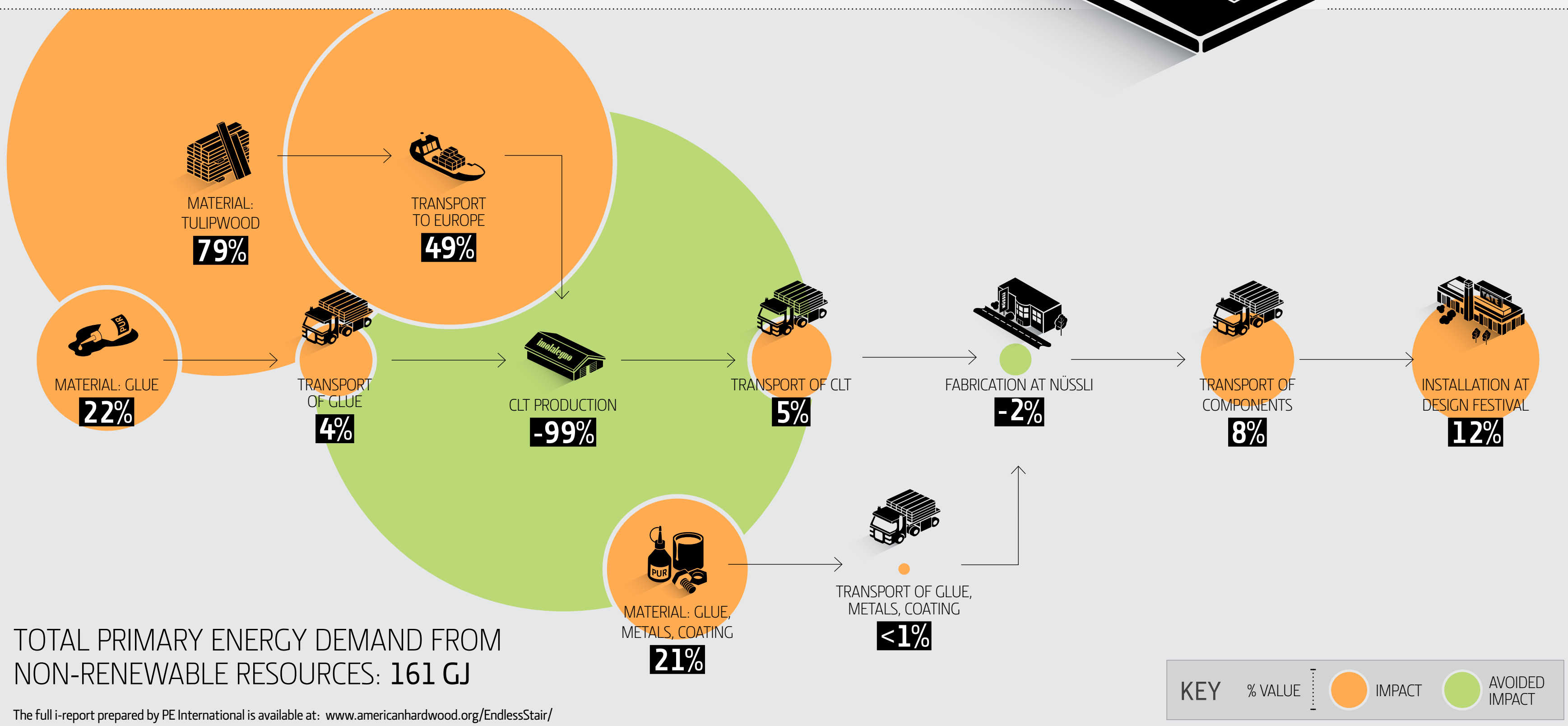


A flow chart to show the processes measured during the production of Endless Stair.

PRIMARY ENERGY DEMAND
(NON-RENEWABLE RESOURCES)

This is a measure of the total demand of primary energy that comes from non-renewable resources, such as oil and natural gas. Measured in gigajoules (GJ), the primary energy demand takes into account the conversion efficiencies from the primary energy to, for example, electricity. The generation of carbon dioxide from the production of energy is one of the major causes of global warming.





TOTAL PRIMARY ENERGY DEMAND FROM NON-RENEWABLE RESOURCES: 161 GJ

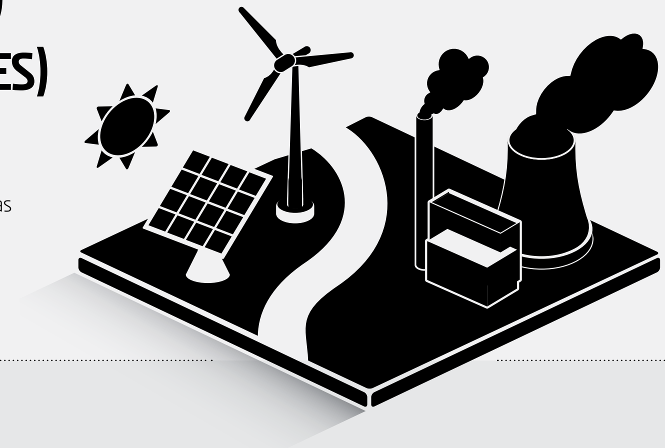
The full i-report prepared by PE International is available at: www.americanhardwood.org/EndlessStair/

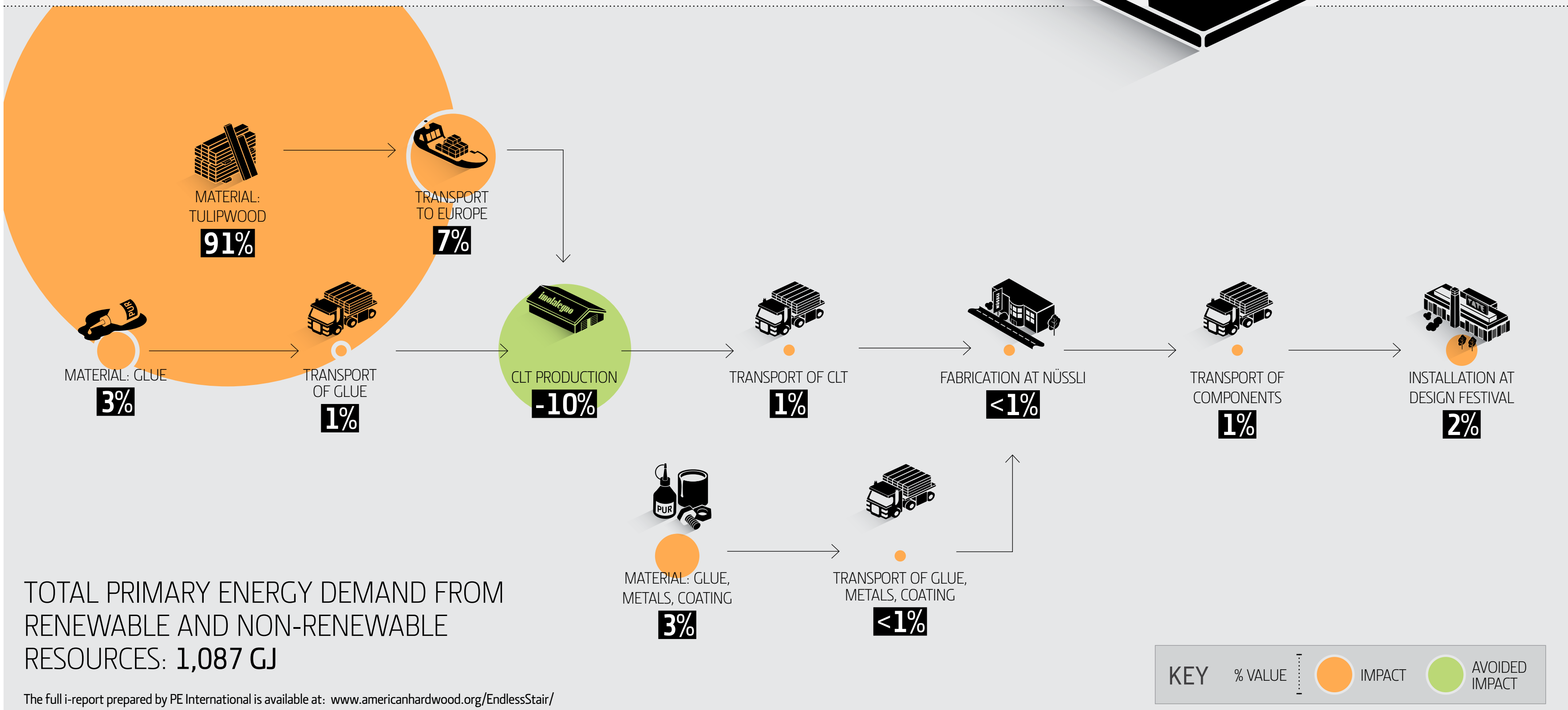
COMMENT

Hardwood production and transport are the most important elements in this category, largely because of the energy required to kiln dry the timber and petrol consumption for transport. The glues used for the CLT, the metalwork and the concrete for installation at the festival are also significant. Imola Legno makes an important avoided non-renewable energy demand because of the thermal recovery from wood waste.

PRIMARY ENERGY DEMAND
(RENEWABLE & NON-RENEWABLE RESOURCES)

Like the primary energy demand from non-renewable resources, this is a measure of the total amount of primary energy, but in this case, derived from both non-renewable resources and renewable sources such as hydropower and wind energy. Again, it takes conversion efficiencies into account where appropriate.





TOTAL PRIMARY ENERGY DEMAND FROM RENEWABLE AND NON-RENEWABLE RESOURCES: **1,087 GJ**

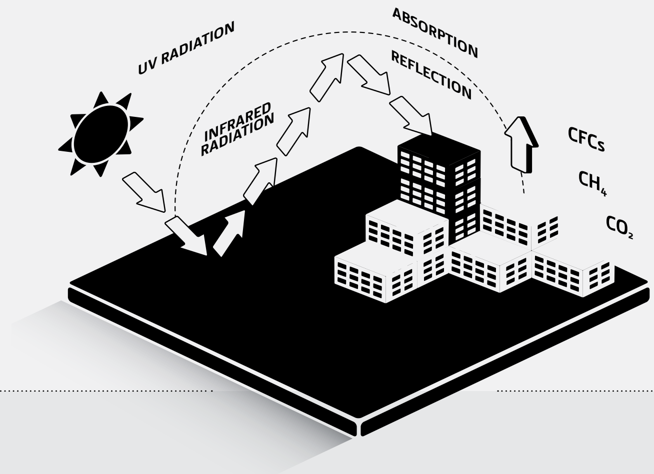
The full i-report prepared by PE International is available at: www.americanhardwood.org/EndlessStair/

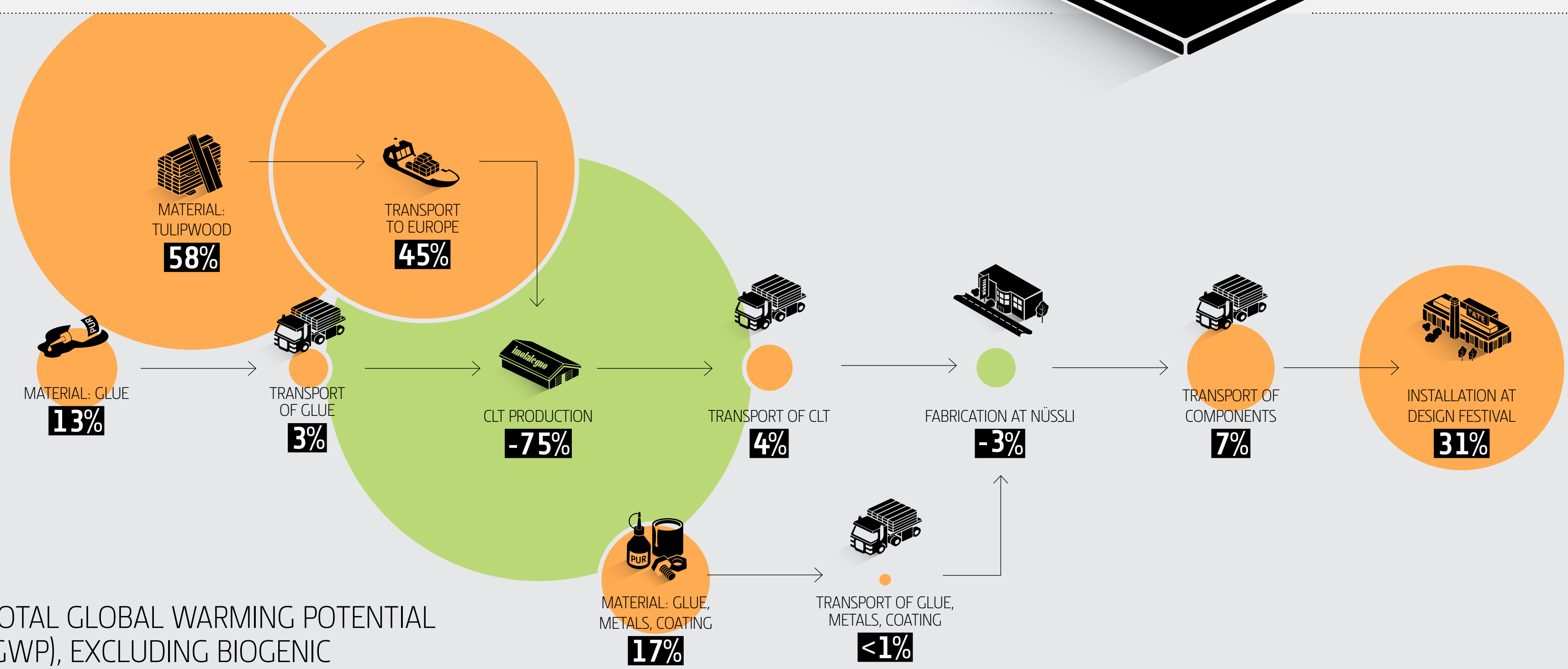
COMMENT

If it seems odd at first that the hardwood accounts for more than nine-tenths of this, it becomes clearer once you realise that the figures include the solar energy that trees absorb for photosynthesis. The avoided energy demand in the CLT production process is a result of thermal recovery from wood waste.

GLOBAL WARMING POTENTIAL (GWP)

Global warming is usually regarded as one of the most significant environmental issues. Global Warming Potential, measured in kg CO2 equivalent, is also a good marker for other environmental impacts. It is calculated from the volumes of greenhouse gases, such as carbon dioxide and methane, emitted during a process.





TOTAL GLOBAL WARMING POTENTIAL (GWP), EXCLUDING BIOGENIC CARBON: **13 tonnes CO_2 - equiv**

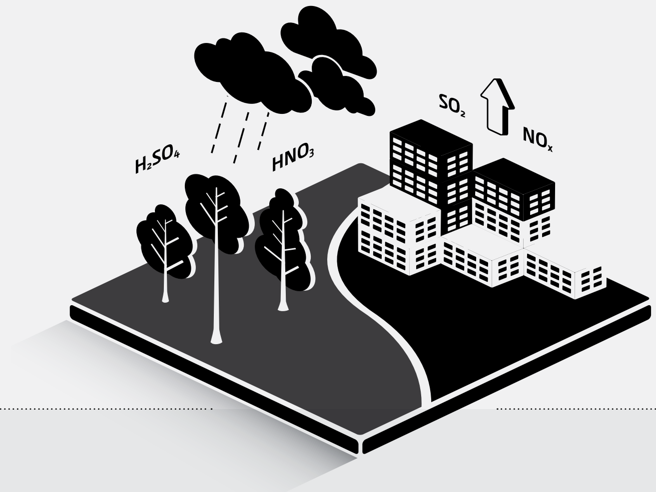
The full i-report prepared by PE International is available at: www.americanhardwood.org/EndlessStair/

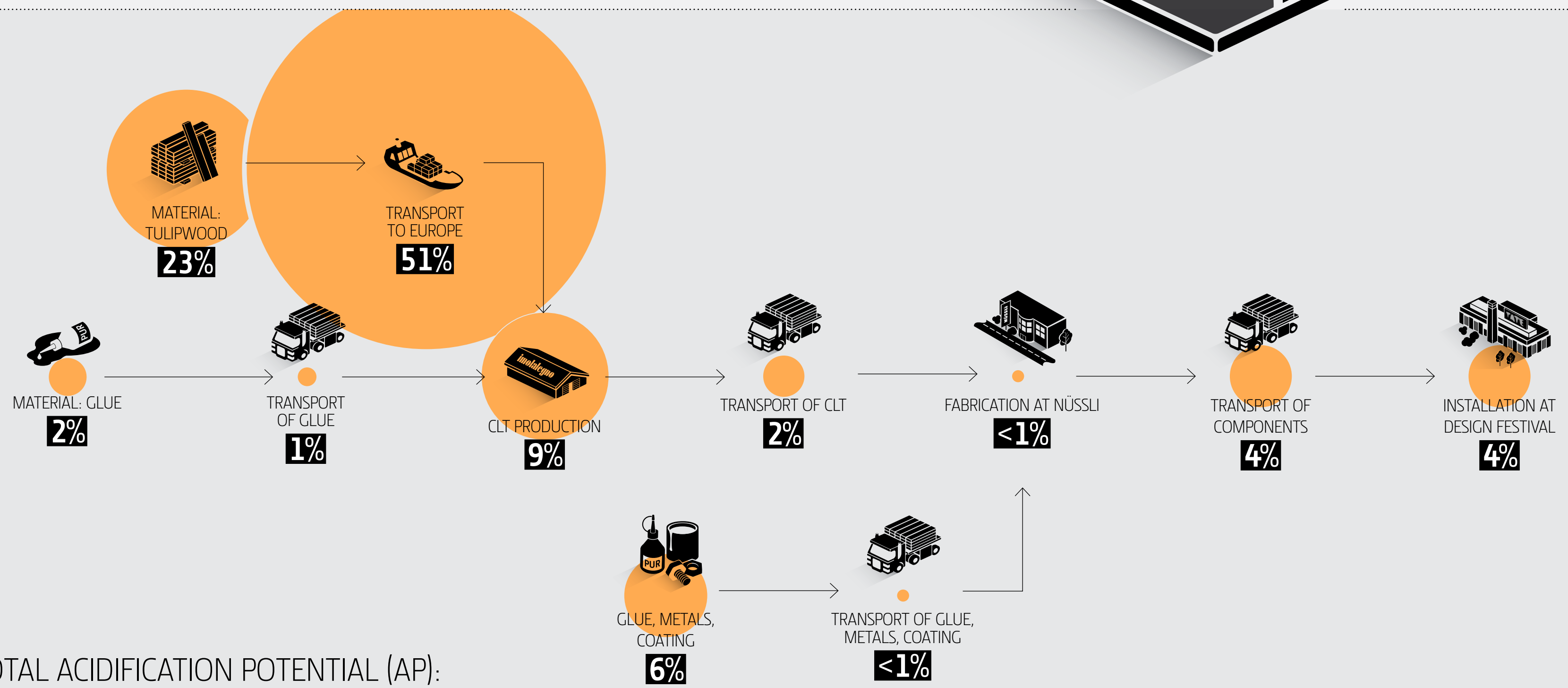
COMMENT

Imola Legno's operation has a large offset to the global warming potential, because of the on-site heat recovery from the wood waste. Nearly a third of the GWP impact comes from the installation process at Tate Modern, this is mainly due to the concrete used for the bottom steps and shallow foundations. Similarly, the metal elements used at Nüssli have a significant role because of the large volume of screws used in the connections.

ACIDIFICATION POTENTIAL (AP)

This is a measure of the emissions that cause acidifying effects to the environment, which can cause imbalances and the death of species. Emissions of sulphur dioxide and nitrous oxide result in acid rain which can fall some way from the place where the emissions occur. Acidification potential is measured in kg of sulphur dioxide equivalent.





TOTAL ACIDIFICATION POTENTIAL (AP):
172 kg SO_2 - equiv

The full i-report prepared by PE International is available at: www.americanhardwood.org/EndlessStair/

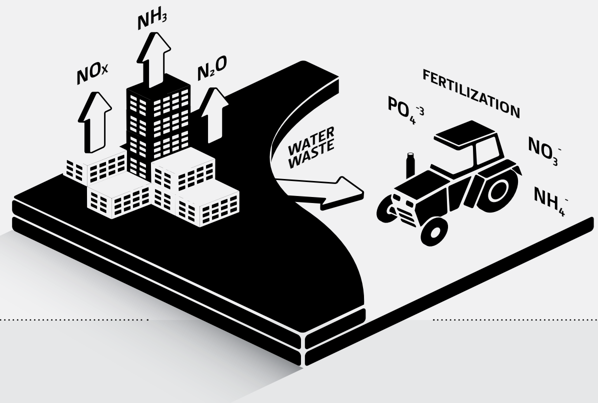
KEY: % VALUE | IMPACT | AVOIDED IMPACT

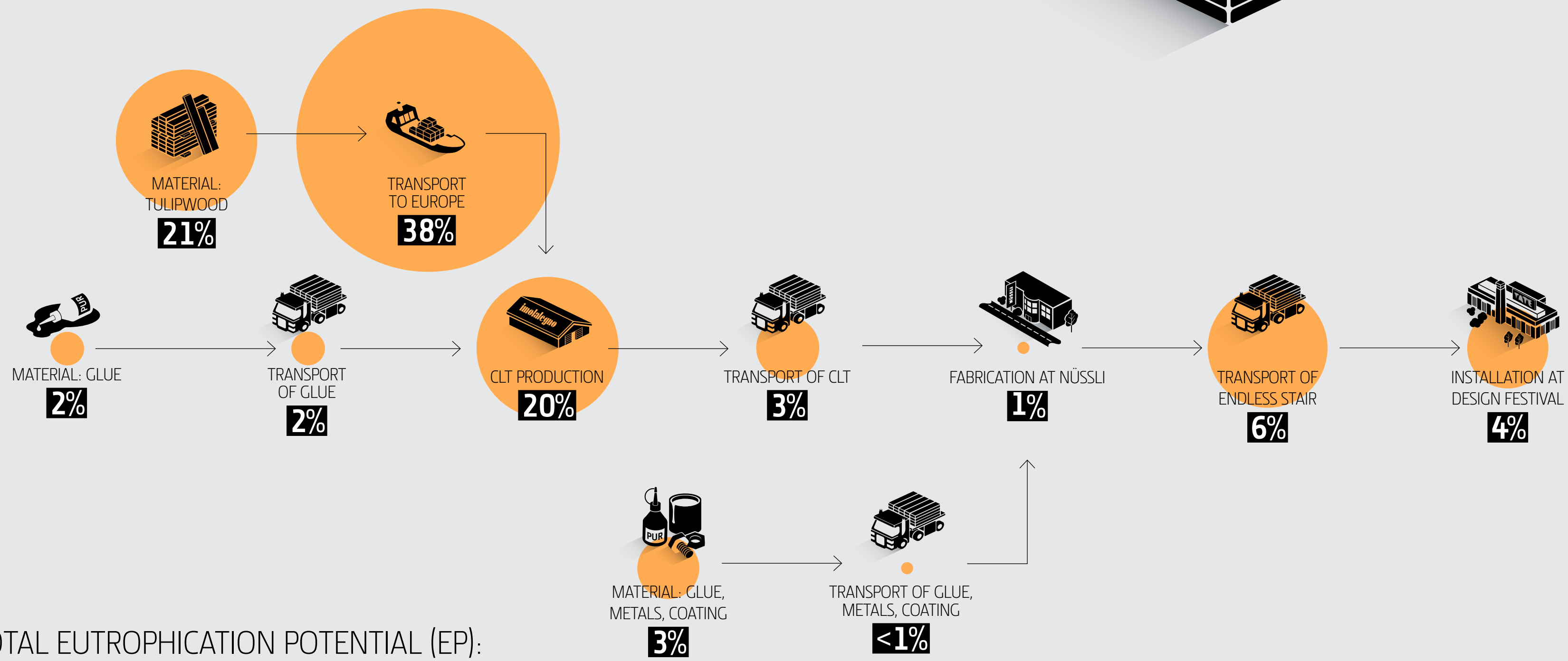
COMMENT

Transport makes the greatest contribution to the acidification potential, because of the sulphur dioxide (SO2) and nitrous oxide (NOx) emissions from the ships carrying the hardwoods to Europe. The significant contribution from the hardwood results from the processing before shipping – cutting, drying etc. Nearly 10% is calculated to come from CLT production – this is a conservative estimate based on a 'worst-case' scenario in terms of boiler emissions.

EUTROPHICATION POTENTIAL (EP)

Eutrophication is the process by which water receives an excessive amount of nutrients, particularly phosphates and nitrates. These nutrients, which typically come from run-off from fertilisers, lead to algal blooms which, in turn, deprive the water of oxygen and lead to imbalances and deaths in the aquatic populations. Eutrophication is measured in terms of kg of phosphate equivalent, and kg of nitrogen equivalent.





TOTAL EUTROPHICATION POTENTIAL (EP):
24 kg Phosphate - equiv

The full i-report prepared by PE International is available at: www.americanhardwood.org/EndlessStair/

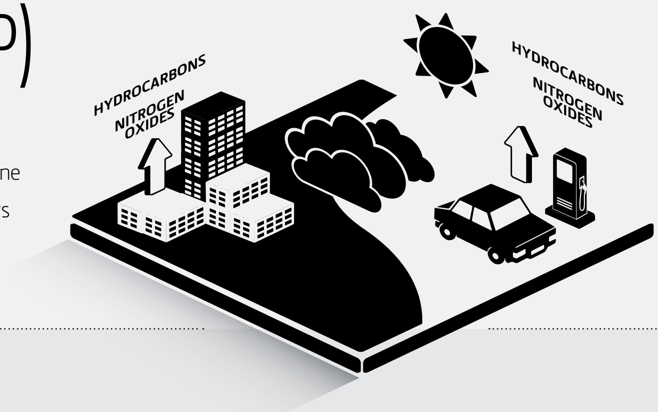
KEY % VALUE IMPACT AVOIDED IMPACT

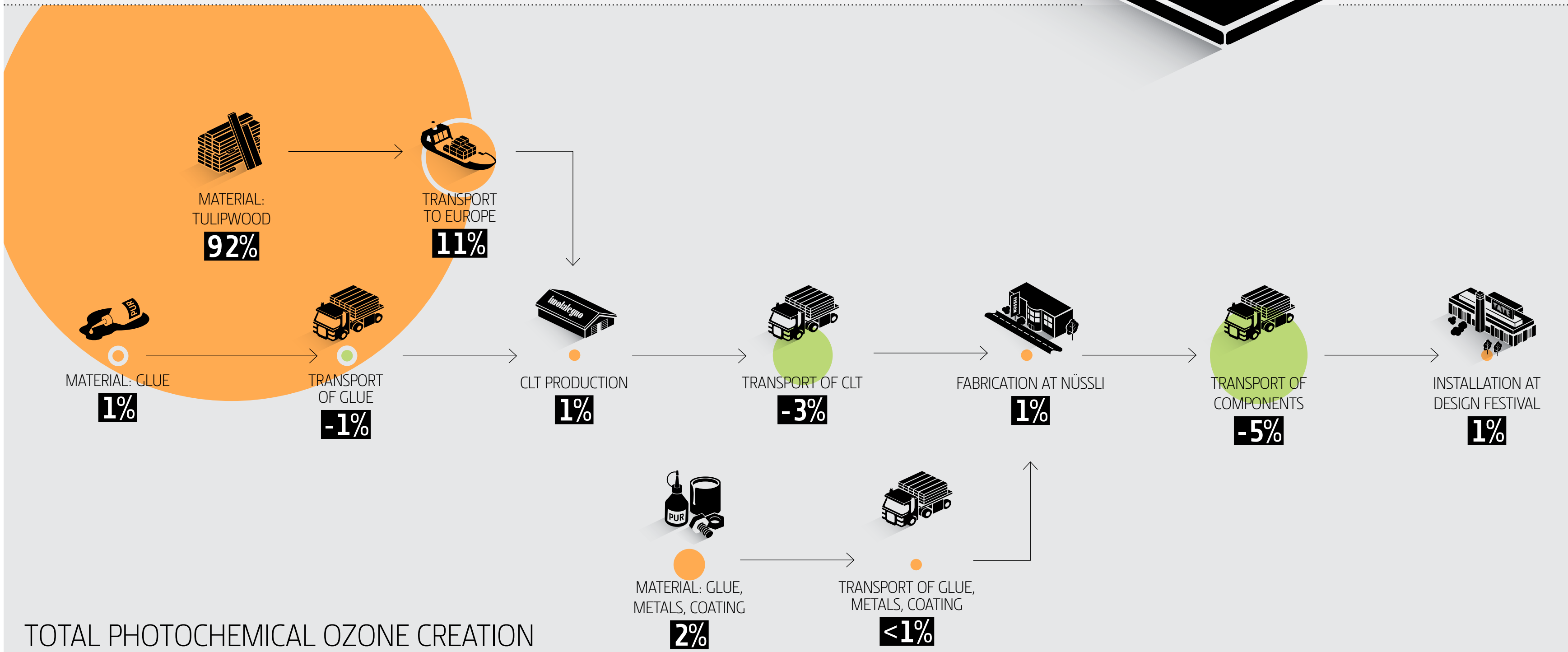
COMMENT

Fertiliser is very rarely used during the growth of American hardwoods and therefore material production contributes only one-fifth of total eutrophication potential. As with the acidification, transport by ship makes the largest contribution – in this case well over one third of the total. The 'worst case' scenario for the boiler at Imola Legno is even more significant here than in the case of acidification, because of the potential NOx emissions. For this reason it counts for one-fifth of the total figure.

PHOTOCHEMICAL OZONE CREATION POTENTIAL (POCP)

This is a measure of emissions or precursors that contribute to low-level smog. It is measured in kg of ethene equivalent. Ozone layer depletion potential (ODP) is also part of the i-report but is not included in the charts because the effect is negligible. There may seem to be a contradiction between these two impacts but, put simply, high-level ozone is good and should be protected, whereas ozone at ground level is a pollutant.





TOTAL PHOTOCHEMICAL OZONE CREATION POTENTIAL (POCP): **47 kg** Ethene - equiv

The full i-report prepared by PE International is available at: www.americanhardwood.org/EndlessStair/

KEY % VALUE IMPACT AVOIDED IMPACT

COMMENT

The large percentage of POCP during material production is due to emissions of terpene, a type of volatile organic compound (VOC) released from wood resins during kiln drying. In contrast, the transport has a negative figure, because of the assumptions applied by the reference impact assessment method (CML) that in some cases the emitted NO is oxidised to NO2, actually removing ozone locally.

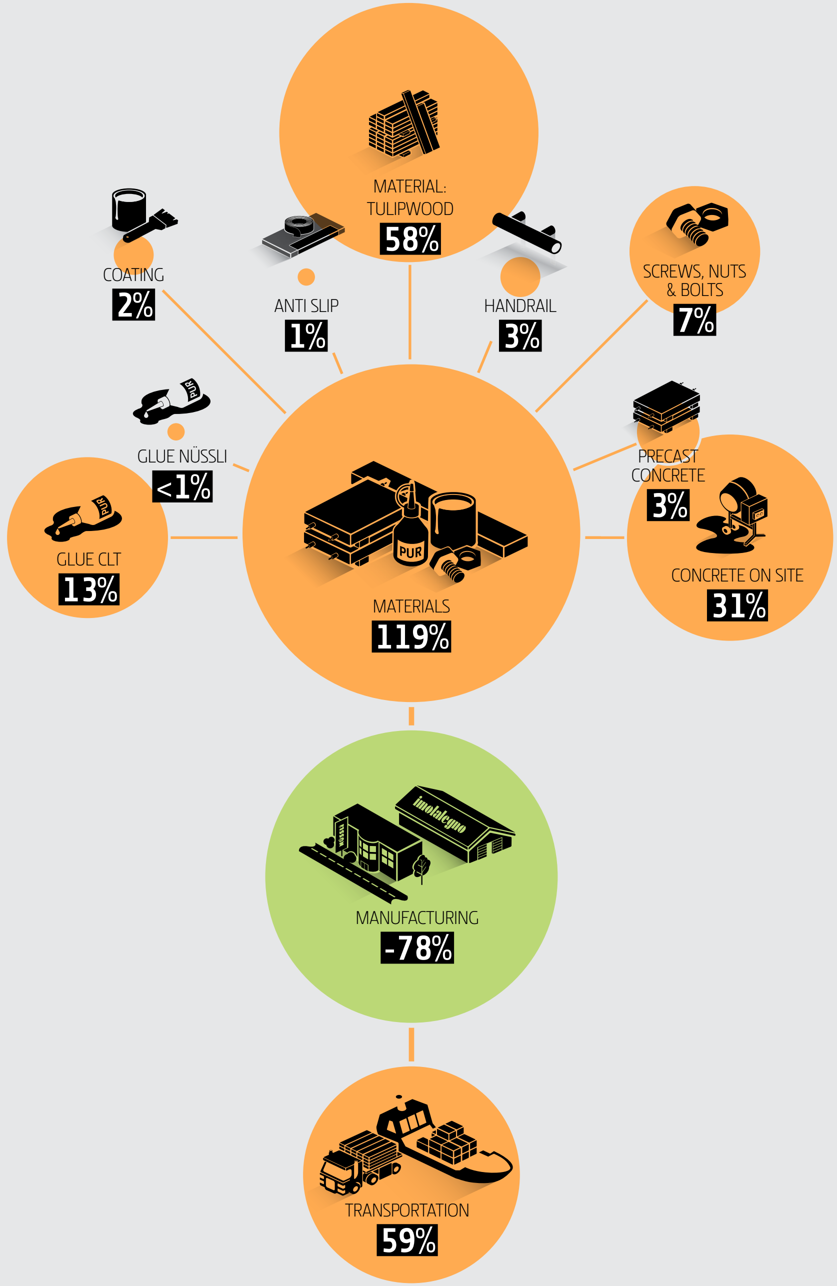
MATERIAL, MANUFACTURING AND TRANSPORT– WHERE DO THE IMPACTS LIE?

This section of the analysis looks at one of the categories – global warming potential – and assesses where the impact comes from. Materials make the largest contribution, with tulipwood, not surprisingly, dominating, since it is the primary material used in Endless Stair. In terms of the hardwood, as the breakdown opposite on page 51 for a square metre of CLT shows, the major contribution comes from kiln drying.

It is interesting to see the scale of the contribution made by concrete, glue and screws. On-site concrete, in particular, makes a massive contribution of 31%, despite the fact that it has only been used for pad foundations. PE International used data for industry standard concrete.

Transport has less of an impact than materials. The lion's share of it comes from transport of the hardwood to Europe, which is shared between truck transport within the U.S. and transport by ship between the U.S. and Europe.

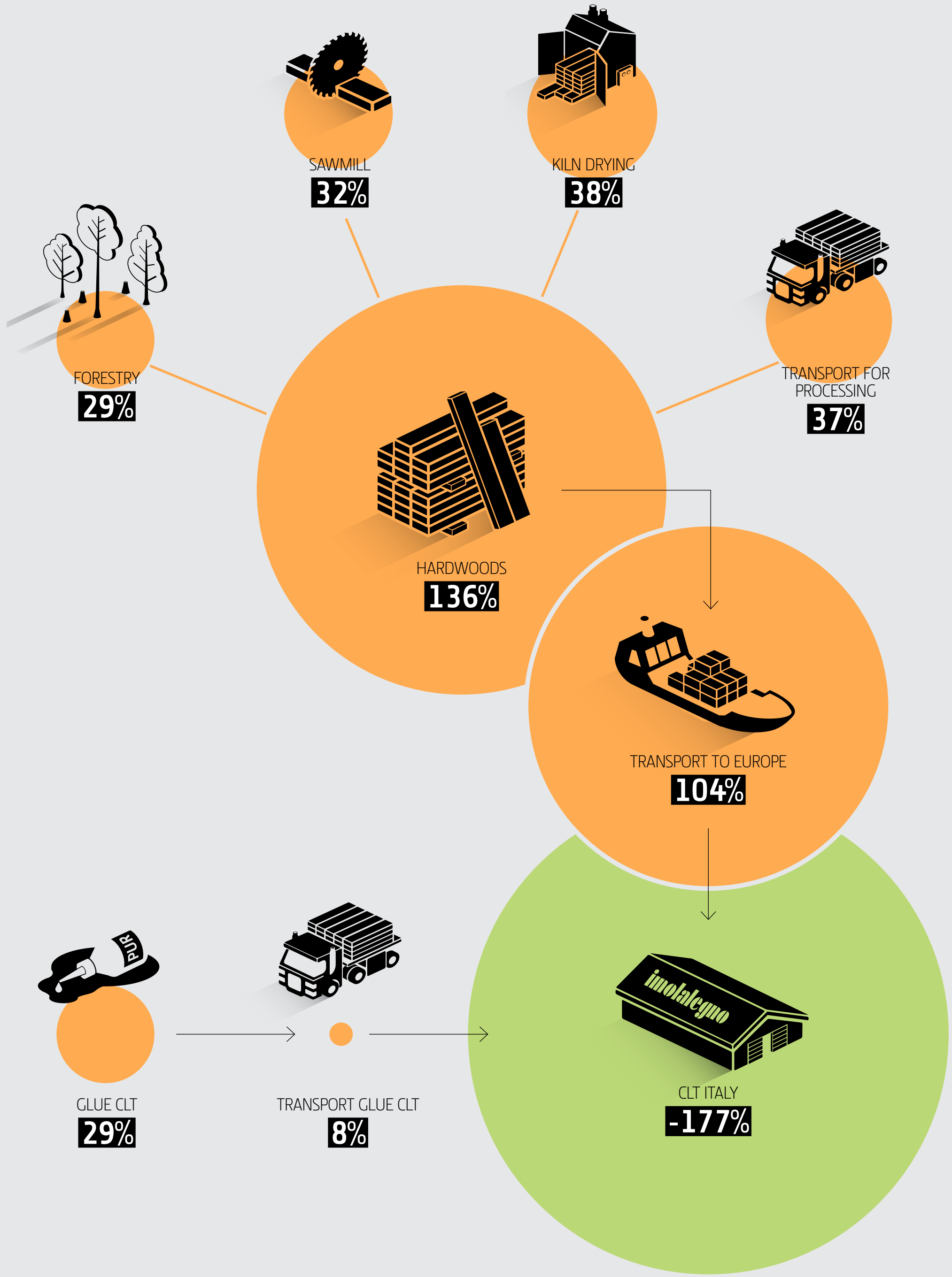
Manufacture actually has an important offsetting role in the global warming potential. This is thanks to the use of wood waste to generate energy, avoiding the use of natural gas which would have an important global warming potential.



IMPACT FOR 1m² OF 60mm 3-LAYER CLT

This chart shows the global warming potential of the production of 1m² of 60mm thick CLT. In terms of the hardwood, which again has the largest impact, it is worth noting that the effect of kiln drying is lower for tulipwood than for many other species, since it is one of the fastest-drying hardwoods, needing only six to eight days in the kiln (based on 1" thick lumber). Most of the impact of gluing comes from the epoxy-resin based face glue. Using PUR glue as originally intended would have reduced this figure significantly. Again, the highly efficient operation at Imola Legno, with its re-use of wood waste for heat generation, has a considerable offsetting effect. The table below shows the absolute impacts in the other five categories.

Impact Category	**Absolute value**
Global Warming Potential (GWP)	**14.6** kg CO_2-Equiv.
Acidification Potential (AP)	**0.38** kg SO_2-Equiv.
Eutrophication Potential (EP)	**0.05** kg Phosphate-Equiv.
Photochemical Ozone Creation Potential (POCP)	**0.13** kg Ethene-Equiv.
Primary energy demand from renewable and non renewable resources (net cal. value)	**2610.79** MJ
Primary energy demand from renewable resources (net cal. value)	**226.58** MJ



SPONSORED BY:

www.americanhardwood.org

For over 20 years the American Hardwood Export Council (AHEC) has been at the forefront of global wood promotion, successfully building a distinctive and creative brand for U.S. hardwoods. AHEC's support for creative design projects such as Endless Stair, for the London Design Festival, demonstrates the performance potential of these sustainable materials and provides valuable inspiration.

FOR:

THE LONDON DESIGN FESTIVAL

www.londondesignfestival.com

HOSTED BY:

TATE

www.tate.org.uk

IN COLLABORATION WITH:

DESIGN:

www.drmm.co.uk

www.arup.com

PRODUCTION:

LIGHTING:

seam

www.seam-design.com

lumenpulse™

www.lumenpulse.com

American tulipwood kindly donated by:

Allegheny Wood Products - www.alleghenywood.com
Blue Ridge Lumber - www.blueridgelumber.com
J&J - jjlog@aol.com
Northland Corporation - www.northlandcorp.com
Northland Forest Products - www.northlandforest.com
Pike Lumber Company - www.pikelumber.com
Shenandoah Hardwood Lumber Co - www.shlco.net
Verde Wood International - www.verde-wood.com

With thanks to:

TMX Shipping - www.tmxship.com
PE International - www.pe-international.com
Trento University - www.unitn.it
Rotafix - www.rotafix.co.uk
Purbond - www.purbond.com

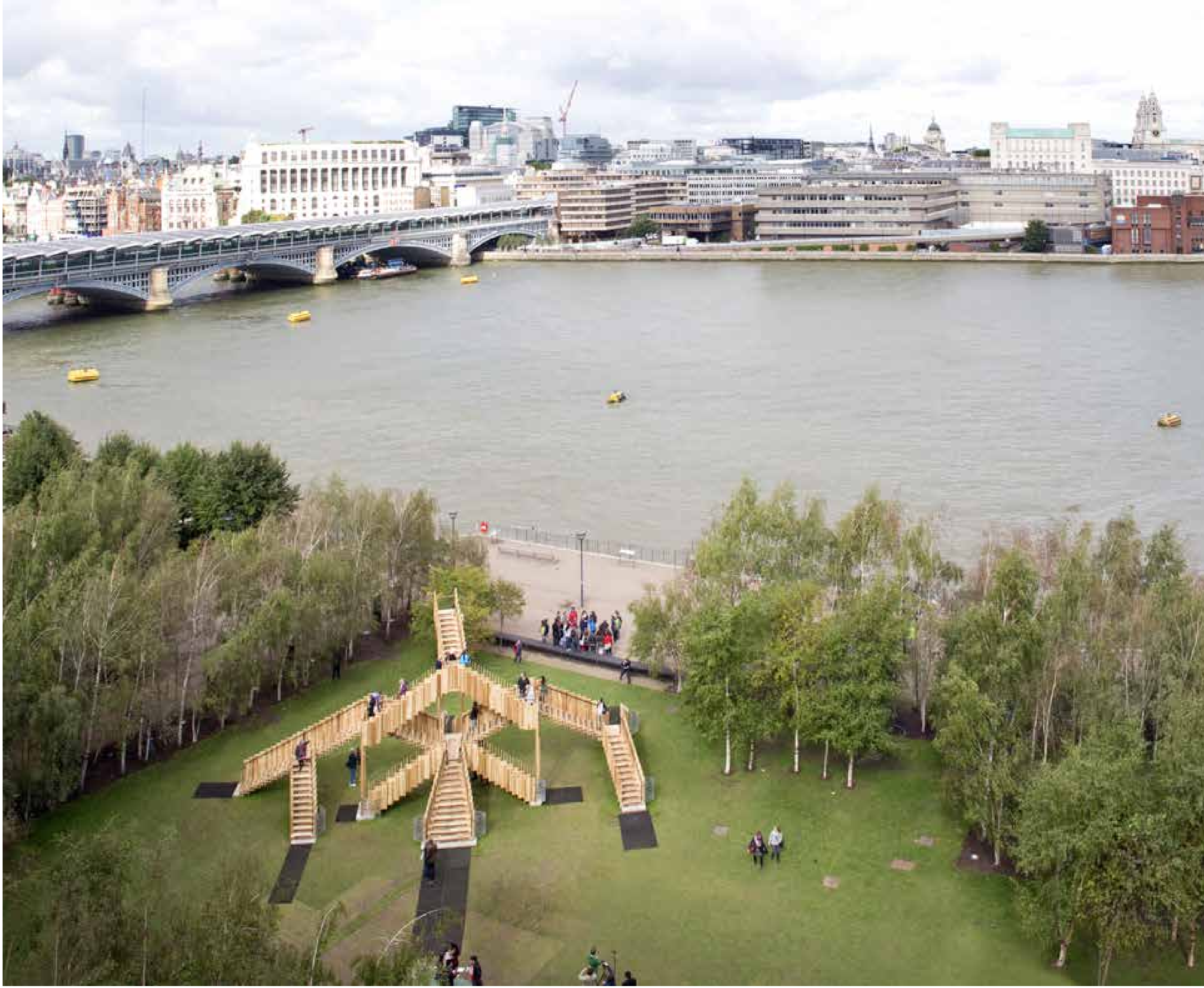
E N D L E S S   S T A I R

Produced by Nick Watts Design for the American Hardwood Export Council (AHEC)

Author: Ruth Slavid
Art Director: Nick Watts
Editor: Belinda Cobden-Ramsay
Designing in detail written by Arup
Sub-editors: Farrah Hassan-Hardwick, Ann Dingli, Catriona Maclean

Photography: dRMM
Technical drawings provided by Arup and dRMM
Printed by Greenshires

nickwattsdesign.co.uk



This publication tells the story of Endless Stair, a towering Escher-like structure that was erected outside Tate Modern in September 2013 for the London Design Festival. Made from American tulipwood CLT, it was an exciting exploration of space and form that also pioneered the use of a new material, and acted as a research project. It was designed by dRMM and engineered by Arup.

THE iPAD EDITION OF THIS PUBLICATION CONTAINS VIDEO, IMAGE GALLERIES AND INTERACTIVE CONTENT.
Search for 'Endless Stair' in the App Store