Designing timber trusses in Belgium during the age of iron engineering

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ABSTRACT: This paper aims to trace back the design methods available to Belgian engineers for the construction of timber roof structures between 1840 and 1914. Based on the literature of that period, we investigate the evolution of the calculation methods, the innovative connection techniques and their impact on the built typologies. This study contributes to a better insight into the roots of timber engineering in Belgium, while positioning this evolution in an international framework. It demonstrates how iron engineering has inspired and speeded up the transition from traditional carpentry to timber engineering. Moreover, it provides valuable information to current professionals who are facing the structural assessment of these historic structures.

1 INTRODUCTION

The preservation of historic timber roof structures and the recognition of their heritage value require a thorough understanding of their structural behaviour. Unfortunately, this structural knowledge is too often lacking in current assessment campaigns, resulting in erroneous assumptions followed by inappropriate interventions (Yeomans 2008). In Belgium, this is particularly true for 19th- and early 20th-century timber roof trusses which are still under-recognized and under-researched compared to more ancient timber frames or 19th-century iron construction.

The complexity – but also the most interesting aspect – of these timber structures lies in the influence of iron construction on their builders' minds. Contrary to what one may think, timber was not simply replaced by iron: timber structures continued to be built without interruption, while benefitting from fast achievements in the building sector. This transition from traditional carpentry to timber engineering is characterized by an important use of structural iron in timber trusses, but also by innovative design methods wavering between craftsmanship and rational sciences.

In France and Germany, Stefan M. Holzer traced back the introduction of these new design methods in roof construction through the example of the mixed timber-iron Polonceau roof, which rapidly became an all-iron structure by the end of the 1840s (Holzer, 2010). In addition, Emanuele Zamperini has studied the influence of structural analysis on the design of 19th-century timber trusses in Italy (Zamperini 2015).

Yet in Belgium, where timber has always remained a widely used construction material for roof trusses, this has not been studied until now. Hence, the present paper aims at investigating the structural understanding of the Belgian engineers which designed timber roof structures between 1840 and 1914. By retracing this historical knowledge, one can reveal the available calculation methods, but also the innovative connection techniques which facilitated the evolution towards rationalized typologies. Moreover, the contemporary texts already shed light on the gap between the theoretical methods of analysis and their actual implementation in the building practice.

2 THE BELGIAN ENGINEER’S LIBRARY

In order to retrace the knowledge background of Belgian engineers, historic literature on timber construction which circulated in Belgian engineering circles has been investigated. Recent studies on the engineer’s profession in 19th-century Belgium (Linssen 2013 & Raymaekers 2013) has provided crucial information on the institutional and educational landscape of the studied period. In these works, a list of contemporary Belgian engineering schools has been established: Ecole des Mines in Liège (°1825), Ecole Royale militaire in Brussels (°1834), Ecole spéciale du génie civil in Ghent (°1836), Ecole provinciale des mines du Hainaut in Mons (°1837), Ecoles spéciales des Arts et Manufactures, du Génie Civil et des Mines in Leuven (°1864) and Ecole Polytechnique in Brussels (°1873).

All handbooks and lecture notes which have survived in the above-mentioned schools’ libraries and which deal with the design of timber roof trusses have been gathered and critically analysed. Besides local authors, many French and (in a smaller proportion) German publications were available in these Belgian engineering schools. Additionally, the articles written by Belgian engineers in the Annales des travaux publics de Belgique (official journal published by the Ministry of Public Works from 1843) complemented the overview. This technical literature – about 80 publications – can be considered as the
3 CALCULATION METHODS

3.1 Overview

Among the gathered literature, about 30 sources include precise calculation methods aimed at sizing timber roof trusses. These calculation methods have been associated to the “men of science” who can be considered as their inventors or major contributors, such as Eytelwein (1808), Navier (1826), Whipple (1847), Clapeyron (1857), Ritter (1862), Cremona (1872) and Müller-Breslau (1892).

Based on the literature, a historical framework assessing the evolution and dissemination of these calculation methods has been established, in such a way that each roof can be positioned within a technological timeline depicting the level of knowledge of Belgian engineers. Among the 19th-century methods of analysis, two main approaches can be distinguished: the analysis by component which considers the structural elements individually, and the statically determinate truss analysis which considers the structure as a whole (Holzer 2010).

3.2 Analysis by component

Being located just under the roof covering, rafters are usually the first elements which need to be sized. In most cases, they are continuous members submitted to compression and bending, generally supported by one or more intermediate supports (i.e. collar beam, struts, etc.). A rafter can thus be seen as a statically indeterminate beam on multiple supports. Once the support reactions are defined, the latter allow to determine the forces acting on the underlying members.

This problem was tackled as early as 1808 by Eytelwein, engineer in the Prussian administration of buildings, in his Handbuch der Statik. Eytelwein provided a set of formulas allowing to determine the support reactions of continuous beams loaded by distributed and concentrated loads (Fig. 1a). For example, he was able to determine the compression force transmitted by a continuous rafter to the underlying collar beam.

In France, Navier addressed the problem of the statically indeterminate beam in his Résumé des leçons données à l’Ecole des ponts et chaussées which was published in 1826. Navier was apparently not aware of Eytelwein’s pioneer work (Holzer, 2010); his approach is similar although Navier limited his examples to a two-span beam with concentrated loads at the middle of each span. However, Navier went further in the analysis by determining the bending moment in the loaded beam in order to obtain the internal stress in the beam’s section.

In 1840, Ardant, a French captain, was apparently not acquainted with Eytelwein’s handbook, but well aware of Navier’s work when he published his Etudes théoriques et expérimentales sur l’établissement des charpentes à grande portée upon request from the French Ministry of War. Not only did he use Navier’s theory of arches in order to quantify the stiffness of the famous Emly’s laminated timber arch roofs, but he was also inspired by Navier’s approach in order to determine the internal stress due to bending and compression in the rafters. Quite surprisingly, although he could have used Navier’s formulas for the sizing of rafters on three or more supports, he limited himself to the “rafter on two supports” case study.

Ardant’s willingness to make his results easily accessible is reflected by the handy semi-empirical formulas and tables he provided. These tools were used as such in later publications by Demanet (1847), Roffiaen (1858) and, even in the 20th century, by Launoy (1910). It is worth noting that Demanet attempted in his Cours de construction professé à l’Ecole Militaire de Bruxelles (1843 à 1847) to apply Ardant’s formulas to more complicated trusses (Fig. 1b). In order to do so, he had to carry out some heavy simplifications: the rafters were considered as if they had no intermediate supports; the collar beam was roughly sized in order to resist an axial force equal to half the weight supported by one rafter; eventually, the king-post was treated as if the collar beam’s weight fully hanged on it.

In Belgium, it took a while before Eytelwein’s and Navier’s methods were published or taught in order to size timber members on multiple supports. Although there are several examples of their correct application in German literature from the end of the 1830s (Holzer 2010), one has to wait until the 1850s to track down these methods in the Belgian schools’ libraries. The handbooks of Weisbach (1851) and Bresse (1859) are the two first examples (Fig. 1c).

In 1857, an alternative method was published by Clapeyron: the famous three moment equations permitted to directly determine the bending moments at the supports of a continuous beam, without computing the reaction forces. He had developed this method of analysis for the design of several iron railway bridges in France in the early 1850s (Kurrer 2008). Only two years after Clapeyron’s publication, Bourdais (1859) applied the three moment equations in order to size the tie-beam in a king-post roof. Apart from Bourdais’s treatise, Clapeyron’s three moment equations had practically no impact on the calculation methods of timber roof structures in the studied literature. Until the end of the 19th century, the methods of Eytelwein and Navier remained thus very common for the sizing of rafters on up to five supports, as shown by the publications of Behse (1864), Résal (1880), Oslet (1890), Boudin (1890), Madamet (1891), Combaz (1895), Pillet (1895) and Barré (1898).

These authors only considered symmetric loading cases; on the other hand, the calculation of asymmetric loading cases (e.g. wind pressure) is much more complex because the supports of the rafters cannot be
Figure 1. Schematic representation of the main calculation methods and their applications on timber roof trusses.

considered as rigid. On the contrary, the displacement of one side of the roof can be transferred to the other side via an internal element such as a collar beam. Such a situation was treated by Böhm (1911), who considered each rafter as a two-span continuous beam with a lack of alignment at the intermediate support (Fig. 1d). Böhm was able to consider the asymmetric loading case in the calculation thanks to the Müller-Breslau’s equation for continuous beams (1892) which takes the displacement of the supports into account.

3.3 Statically determinate truss analysis

The method of analysis by component was taught and published in Belgium from the 1850s onwards until at least the turn of the 20th century. However, another design method became very popular in the last decades of the 19th century: the statically determinate truss analysis, considering the structure as a layout of discontinuous members articulated at several nodes. This method was likely first used by Whipple, designer of the first all-iron trussed bridge in 1841; he calculated the forces in the members of his iron trusses by expressing the equilibrium of each node with the parallelogram of forces. This straightforward method, which does not consider bending and shear stresses in continuous members such as rafters and tie-beams, had little impact on contemporary handbooks on timber framing. Indeed, since each set of equilibrium equations needs to be solved node by node, the method becomes quite fastidious as soon as the structure reaches a certain level of complexity. Nevertheless, about 60 years after its publication, Whipple’s method was chosen by Claudel (1910) and Lambotte (1914) which were looking for simplicity in pedagogy rather than efficiency (Fig. 1e).

A quicker method of statically determinate analysis was published by Ritter in 1862. His method is a simple way of determining the forces acting on any truss member, using the equilibrium equations of a portion of the truss isolated from the whole by a well-chosen section. This method seems to have been much more popular for its applications on iron trusses than on timber ones. Nevertheless, one may notice that it was used by Collignon (1869), Madamet (1891) and Combaz (1895) for the analysis of timber and mixed iron-timber structures (Fig. 1f).

In 1872, Cremona provided 19th-century engineers a powerful graphical method which eased the analysis of isostatic trusses, by combining Maxwell’s theory of reciprocal diagrams and Culling’s theory for graphical statics based on projective geometry (Kurrer 2008). No mention of his methods has been retraced in the Belgian schools’ literature before Lévy’s famous publication La graphique statique in 1874: he seems to have popularized the method in France and Belgium (Chatzis 2004). The Cremona’s method allows finding the forces exerted on any truss member by drawing them on a scaled diagram in a particular order. Its applications on timber roof structures are well illustrated by the treatises of Oslet (1890), Boudin (1890), Aldebert (1896) and Zillich (1906) (Fig. 1g).

Even though the analysis by component remained present in the technical literature until the first decades of the 20th century, the statically determinate truss analysis – polarized through Cremona’s graphical method – enjoyed an advantage because of its easy and quick implementation, especially for complex structures which were modelled – at the cost of approximations – as isostatic trusses.

3.4 The influence of iron engineering

From the end of the 1840s onwards, it may be noted by looking at the very first applications of the theories of Whipple, Clapeyron, Ritter, Cremona and Müller-Breslau, that their methods had obviously been developed for the analysis of iron structures (Kurrer 2008 & Timoshenko 1965). Such an observation is not surprising since most technological advances were then driven by the fast introduction and large-scale application of iron. Contrary to timber trusses, there was no century-old tradition nor empirical rules that could be relied upon. These initial uncertainties were thus reduced thanks to a science-based approach embodied by engineers and mathematicians. Moreover, iron was
particularly well suited for the development of innovative and efficient structures: it was a man-made, highly resistant and extremely formable material.

The articles written by the public officers in the *Annales des travaux publics de Belgique* comply with this trend by providing key information on the professional practice and research fields of Belgian engineers. The analysis of these articles shows that timber structures remained a priority of concern until the end of the 1850s. Experiments and scientific calculation methods were frequently discussed in order to "substitute calculations for empiricism" (Lamarlé 1845). Although timber was commonly used in important civil works during the first half of the 19th century (e.g. railway bridges with laminated arches) the attitude towards timber radically changed in the following years. From the 1860s onwards, iron monopolized the Belgian engineers’ minds; innovative design methods were developed with a view of applying them to iron structures.

Consequently, from the mid-19th century onwards, once innovative calculation methods had been established for iron construction, the latter were simply applied as such to timber trusses.

### 3.5 From theory to practice

Besides the structural analysis itself, many contemporary texts discussed the differences between the results of these theoretical calculations and their application in building practice. Therefore, these sources also provide a first insight into the adjustments required for the practical use of structural analysis in timber construction.

Firstly, engineers had to deal with structures which were traditionally highly hyperstatic, while available calculation methods where only suitable for quite simple (for the analysis by component) and preferably isostatic (for the truss analysis) roof structures. In his *Traité de l’art de la charpenterie*, Emy (1841) already advised to only consider the main elements of a truss and to dismiss "all other elements contributing to the stiffness". Demanet (1847) also neglected most secondary elements in his calculation. In the same line of thought, Bourdais (1890) mentioned that "the forces acting on other truss elements – such as the struts – cannot be determined from the laws of static, the structure being at equilibrium with or without them, hence their dimensions cannot be determined with accuracy". In another approach, Launoy (1910) advised to size redundant elements which are positioned close to each other so that "each of these elements, taken in isolation, could resist the stress". The hyperstatic structure was thus calculated as a superposition of independent statically determinate trusses. Moreover, in the *statically determinate truss analysis*, continuous members were considered as interrupted at the joints and perfectly articulated. It was commonly thought that, in reality, their continuity would give more strength to the structure. Yet, this interpretation leads to a complete overlooking of secondary stresses.

Secondly, one may wonder to what extent the formulas were actually used in the building practice. Part of the answer is given by Oslet (1890) who advised to use empirical rules before any further calculation: for example, the height of tie-beams should vary between 1/24 and 1/20 of the truss’ half span, between 1/20 and 1/15 for rafters, between 1/20 and 1/12 for king-posts, etc. Moreover, many semi-empirical tables were available in the literature, suggesting that – at least for simple projects – designers could avoid any further calculations.

Thirdly, just as today, practical considerations also influenced the sizing of timber members. For example, in order to reduce labour, the calculated dimensions were logically increased to the closest trade sizes, providing additional safety (Emy 1841 & Combaz 1895). Furthermore, the optimization of material use through calculation was often hampered by stereotomic rules. Indeed, in order to ensure good assemblies between timber members, the sizes of the king-post, collar beam and tie-beam often had to correspond to the rafters’ dimensions (Roffiaen 1858, Adhémar 1861 & Pillet 1895). In such situations, the calculations were thus just limited to the sizing of the rafters. Commenting on Ardant’s formulas, Demanet already stated in 1847: “The dimensions provided by these formulas [...] cannot be fulfilled in the practice [...]. Nevertheless, they show that one usually uses too much material compared to the function served by these elements. The indications provided by the theory may undoubtedly be approached through some modifications of the connection techniques, which are not difficult to be discovered”. This stresses the fact that advances and optimizations in timber construction are closely related to the development of new connection techniques and innovative ways of transferring forces between truss members.

### 4 CONNECTION TECHNIQUES

#### 4.1 The benefits of iron assemblies

For centuries, traditional carpentry joints had been designed thanks to the knowhow of carpenters who mastered the effects of tensile and compression forces on timber as an anisotropic material. For example, bracing struts were always connected well above the king-post’s end, ensuring a sufficient bearing area (Fig. 2a). Also, because traditional tenon and mortice joints are weak in tension, iron straps and bolts were in general use to reinforce such connections already long before the 19th century. The stress that a timber joint can withstand – especially perpendicular to the grain – being quite limited, timber elements were commonly connected at a certain distance from each other or in several layers in order to avoid high stress concentrations. Despite these measures, timber assemblies often led to loosening and settlement of the structures (Richard 1848).

Although the first assemblies used in iron construction were largely inspired by timber ones until
the 1820s, builders quickly realized that they could achieve – thanks to the higher strength and formability of iron – new types of connections which were much more efficient (Fig. 2b). The assemblies used in iron construction – bolts, plates or rivets – had several advantages over timber: they permitted a universal load transfer in tension and compression, all forces could be acting on a single point, they could possibly allow some rotation, and the structural members could thus be sized independently from their assemblies. They were thus in perfect accordance with the theoretical models developed for structural analysis than traditional timber joints (Rinke 2010). In the light of these benefits, it is not surprising that substantial efforts were made during the 19th century in order to introduce innovative connection techniques in timber roof trusses. While the use of iron straps and bolts remained very common, new assemblies such as iron shoes and plates appeared.

4.2 Innovative techniques: shoes and plates
A very early use of cast iron shoes in timber structures is reported from the construction of the Moscow Manege in 1817. In order to achieve an exceptional span of 50 meters with slender elements, engineer Augustin Bétancourt used iron shoes at the junction between rafters and posts (Fig. 2c). Such connections became very present in the technical literature from the 1840s onwards when cast iron started to reach all construction fields.

All the above-mentioned advantages of iron connectors could straightforwardly be applied to timber trusses. Moreover, while traditional timber to timber joints required the cutting – and thus the weakening – of the members, the latter ones could now remain steady on their entire length. Such connections also eased the combination with wrought iron members which often replaced timber for tensioned elements (Fig. 2d). Last but not least, the economy in workmanship was considerable. According to their representation in technical handbooks, cast iron shoes remained a very common assembly technique until the first decades of the 20th century.

From the 1890s onwards, iron plates, widespread as connectors in iron construction, were implemented on timber trusses. The first example mentioned in the studied literature is the Laillet system produced by the Société métallurgique d’Amiens (Barré 1898). Two punched iron plates were maintained on each side of the timber elements using three pairs of bolts which insured the good adherence required for a diffused load transfer. This universal system could be used for transferring tension as well as compression (Fig. 2e). In the same spirit, another economical type of connection plate was generalized in the 1910s, which simply consisted of two timber planks nailed from both sides of the frame (Fig. 2f). These types of plate connectors are clearly the ancestors of the economical assemblies which are commonly used in current timber engineering.

4.3 Sizing the timber assemblies
The study of the Belgian engineering literature shows that builders relied upon empirical rules inherited from centuries of craftsmanship for the sizing of timber joints until the turn of the 20th century. As described by Zillich (1906): “It is not the custom to statically calculate the resistance of assemblies. Practice has shown that in common situations – that is to say according to craftsmen’s rules – their strength is sufficient; static calculations are thus only used when important loads are involved”. Therefore, it is not surprising that Oslet’s treatise (1890) which contained the first calculation encountered in the literature focusses on a heavily loaded connection: the rafter’s foot (Fig. 2g). Oslet determined the required shear area at the tie-beam’s end, admitting that “few experiments have been done on the shear resistance of timber, making it difficult to establish precise rules on this subject”. He advised to use a shear strength in the grain direction of 0.42 kg/mm$^2$ for softwood and 0.16 kg/mm$^2$ for oak. He then mentioned that, in the practice, an important safety factor of 10 was usually applied on these uncertain values. Five years later, for the same detail, Pillet (1895) confined himself to provide empirical design rules purely based on geometry. Even though semi-analytical calculations existed for riveted connections since the 1870s (Collette 2014), it was not until the 1900s that very similar design methods – based on shear and crushing failure modes – were applied for timber elements connected with bolts and straps (Zillich 1906 & Böhm 1911) (Fig. 2h).
5 TYPOLOGICAL EVOLUTIONS

5.1 A new design process

During the 19th century, Belgian engineers could use various calculation methods in order to test the feasibility of roof trusses projects. Instead of reproducing established typologies, they were now able to make a clean sweep from the past: a rational grasp on the structural behaviour could already be obtained in the early design stages. This structural understanding, combined with innovative connection techniques, opened the way towards a new design process.

This tabula rasa is comprehensively described in Oslet’s treatise (1890): first, a triangle composed of two rafters and a tie-beam had to be drawn based on the desired roof shape; then, the rafters could be divided into several nodes according to the number of purlins; eventually, each node had to be supported by sub-elements dividing the whole into smaller triangles. According to Pauporté (1909), the resulting truss had to be simple (easy mounting, low labour cost), light (limited material use) but as strong as possible. Moreover, timber had to be loaded in tension and compression only, in the grain direction. Denfer (1892) added that large timber sections should be avoided due to their higher price. Taking these factors into account, a rational and economical truss could be drawn, structurally analysed and fine-tuned for each building project.

5.2 A roof as a trussed beam

Although early 19th-century examples of rationalized truss structures were entirely made of timber (e.g. Town’s lattice truss in 1820, Long’s truss in 1830), timber was rapidly combined with iron (e.g. Polonceau’s truss in 1839, Howe’s truss in 1840). Later on, most innovative typologies were fully designed in iron (e.g. Whipple’s truss in 1841, Warren’s truss in 1848, Schwedler’s three-hinged arch in 1865). Therefore, as was the case for calculation methods and connection techniques, the role of iron, catalyst for innovation, cannot be underestimated during the studied period.

Based on the Belgian engineering literature, this rationalization is illustrated with one example – the roof as a trussed beam – although it is observable in many other typologies (king-post roofs, laminated curved roofs, pre-flexed roofs, etc.).

Italian architect Palladio illustrated as early as 1570 what is certainly the first known example of a trussed bridge (Timoshenko 1965) (Fig. 3a). By connecting three simple triangular trusses, which he knew were not deformable, he understood that the strength of the whole truss “lies in the fact that each part is supporting each other” (Palladio 1650). To create a pitched roof, a small triangular frame resting on the Palladio truss could be added on top. Such a typology is represented in Demanet’s lecture notes (1847), where the 19th-century improvements are clearly introduced: tensioned members are out of wrought iron while the assemblies are ensured by cast iron shoes (Fig. 3b).

Because the contribution of the small upper frame to the overall truss’ stiffness was unclear, more efficient roof trusses quickly replaced this typology.

The development of economical railway bridges in America during the second quarter of the 19th century had a great influence on European builders. Well-known examples were illustrated in the literature. For example, the Howe’s truss systems used in 1850 for Munich’s Propylaea (Fig. 3c). In 1880, a version without all counter members (called “English roof truss” in Germany) was built for Frankfurt’s opera house (Fig. 3d) (Böhm 1911). From the 1890s onwards, very efficient structures known as “American trusses” – already in widespread use in iron construction since the 1830s – appeared in the literature available in Belgium and dedicated to timber construction (Fig. 3e). With a very clear structural behaviour, such trusses were ideal for a precise sizing of all members. Their tensioned elements were usually connected by mean of iron straps or iron bolts. Sometimes, these members were replaced by iron (Fig. 3f). According to Pauporté (1907), the resulting mixed-trusses were, in the Belgian context of the 1900s, advantageous for roofs spanning 10 to 20
meters. Beyond that, timber trusses were too expensive and too heavy; therefore, full-iron trusses were preferred.

Instead of designing one single truss, another option was to build the rafters as two inclined trusses. This idea was already present in Krafft’s treatise (1805) where each rafter was doubled and bounded to the other with perpendicular posts (Fig. 3g). A famous example is the Cirque d’Hiver built in 1852 in Paris, where the technique was applied on a much larger scale (Denfer 1892). The connection between the upper and lower chords was improved by several diagonal bracings which allowed the truss to work as a whole (Fig. 3h). The 19th-century advances in timber engineering are obvious if one compares this last structure to the Dresden’s feast hall built in 1900 (Fig. 3i). Each rafter forms a Warren truss made of thin planks which were bolted to the upper and lower chords.

As can be seen from the historic sources, there is little mention of specific built structures which were actually applied in Belgium. Even in the Belgian handbooks and lecture notes, most examples were issued from the surrounding countries. This gap of knowledge can thus only be bridged by further on-site and archival investigations.

6 CONCLUSIONS

This paper sheds light on the roots of timber engineering in Belgium, through a survey of 19th- and early 20th-century technical literature dedicated to timber roof structures which circulated in the Belgian engineering landscape.

In the first place, the influence of iron as a structural material is indisputable. Although a scientific approach had already begun with timber structures in the early 19th century, iron structures quickly became a driving force behind innovation in engineering sciences. Timber construction benefited from these advances, but only in a second phase, as shown by the dissemination of the calculation methods. Moreover, compared to iron structures, empirical design rules and craftsmanship remained relied upon until much later, especially for the sizing of the assemblies.

Furthermore, even though the history of timber engineering calls for the above-mentioned nuances, it is clear that timber was not simply forgotten and replaced by iron during the 19th century. To the contrary, timber structures evolved considerably during the studied period. Therefore, modern timber engineering cannot be fully understood without considering these earlier developments.

The resulting overview provides additional material for the structural and heritage assessment of historic timber roofs. Indeed, knowing their builders’ technological background makes it easier to point out the characteristics, strengths and weaknesses of these structures.

Finally, little research has been carried out on roof trusses in 19th- and early 20th-century Belgium. For example, the respective contribution of each construction actor (engineer, architect, contractor and carpenter) on the design decisions still has to be studied. Therefore, although the historic literature is a crucial and unavoidable source of information, further onsite and archival investigations are still needed in order to learn from the built structures themselves.

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