Standardisation: an essential enabler for the circular reuse of construction components? A trajectory for a cleaner European construction industry

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Title
Standardisation: an essential enabler for the circular Reuse of construction components? A trajectory for a cleaner European construction industry

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Abstract
The concept of a circular economy has been proposed as a key component of a solution for the finiteness of earth’s resources. As one path, the research on the direct reuse of construction components focusses on strategies for designing buildings for disassembly in the end-of-life stage. This is of particular importance because it can reduce the environmental impact of the construction industry. The recently published ISO 20887 also advocates to design buildings for disassembly and to use standard-sized components. However, to the authors’ knowledge the role of standardisation in this process remains unexplored. Therefore, in this paper the evolution of standardisation is studied in order to identify the drivers for standardisation and currently available standards that aid and support the claims of the ISO 20887. This study concludes that most standards are introduced from an economic, rather than an environmental point of view. Also, ISO 20887 seems to be the first actual standard addressing the idea of reusing building components. Through an integrative discussion of the available types of construction standards, the problem areas obstructing the required further standardisation are identified: protectionism of contractors whom perceive standardisation as a threat, protectionism of manufacturers whom are reluctant to change the organisation structure, and designers whom seem least aware of the need to implement the circular economy in the construction sector. Finally, a corresponding trajectory is proposed for future standardisation to tackle these problem areas and to actually perform its role as an essential enabler for circular Reuse in the construction sector.

Keywords
Construction; circular economy; design for disassembly; Reuse; reverse logistics; standardisation

Highlights
- No written standards aiding the circular Reuse of building components are available
- Standards are introduced from an economic, rather than an environmental perspective
- The development of standards for circular Reuse concerns all construction stakeholders
- Standardisation can enable circular Reuse and effectuate a cleaner construction industry
1. Introduction

Material demand has risen sharply in the last century. According to De Wit et al. (2018) there has been a considerable increase in materials mining from 1960 onwards due to the exponential growth of our economy and urbanisation. In 1960, around 21 billion tonnes of raw materials were mined, an amount which has been multiplied by four over the next six decades, resulting in about 84 billion tonnes of raw materials annually mined today. If this trend continues, this number will keep increasing to around 180 billion tonnes of annually mined raw materials by 2050 (de Wit et al., 2018). Half of all the annually excavated raw materials worldwide are destined for the construction industry (de Wit et al., 2018), rendering this a critical industry for the depletion of earth’s resources. Additionally, considering that with the current mining practices and consumption rate, earth’s resources such as zinc will be depleted by 2025 and will be entirely unavailable by 2030 (Circular Flanders, 2019), it becomes clear that our material demand poses a crucial problem that requires immediate action. The European Commission (2018) reported that approximately 25-30% of all waste generated in the European Union (EU) is Construction and Demolition Waste (CDW). They ascertained the high potential for reusing and recycling this CDW, as well as the high resource value of some of the components in CDW, which led to the identification of CDW as a priority waste stream by the EU (European Commission, 2018).

Primarily, the concept of a Circular Economy (CE) has been proposed as a solution for the abovementioned problem (D’Amato et al., 2018). The essence of the CE can be brought back to the four R’s - Reduce, Reuse, Recycle, Recover- signifying the desired order of the value retention of products and materials, and this on three levels – the micro-, meso- and macro-scale (Anastasiades et al., 2020; Kirchherr et al., 2017). Pomponi and Moncaster (2017) considered the three levels of the CE within the built environment. The Cradle-to-Cradle principle represents the micro-scale, the scale of the material/building component itself (Pomponi and Moncaster, 2017). The Cradle-to-Cradle philosophy reflects the idea of endless recyclability of resources (McDonough and Braungart, 2002). The meso-scale is represented by the entire building or construction in general, an assembly of components. The highest level, the macro-scale, considers eco-cities - fully self-sustaining, carbon neutral cities (Pomponi and Moncaster, 2017). Note that the macro-scale is in fact again the general CE, rather than its application to the building sector.
Most of the available research in the field of circular construction has generally focussed on materials recycling (e.g. Akanbi et al., 2018; Gálvez-Martos et al., 2018; Ghisellini et al., 2018b, 2018a; Huang et al., 2018; Jiménez-Rivero and García-Navarro, 2018; Nußholz and Milios, 2017) or more specifically recycling through reverse logistics (e.g. Chileshe et al., 2018; Hammes et al., 2020; Li et al., 2018; Wijewickrama et al., 2021). Also improving the environmental profile of construction materials and components through the incorporation of waste streams from other production processes has gained attention (e.g. Asim et al., 2021; Carvalho et al., 2014; Marvila et al., 2021; Mendes et al., 2019; Mohan et al., 2021). Hence, the primary research focus is on Pomponi and Moncaster’s micro-scale, the scale of the material and the component, and thus the cradle-to-cradle principle. For CDW, a 95% recycling rate can be achieved, but the majority of this CDW is recycled as foundation material in road construction and thus downcycled (Reike et al., 2018). This is not the value retention as propagated in the CE paradigm. The currently best available approach for CDW is to recycle as many of the materials as possible into new products. However, when it comes to new construction projects, it will be important to actually make them future-proof. In this, not only the environmental profile of the materials and the entire construction needs to be improved, but also the way the construction is designed and built. The latter is where the approaches of Design for Disassembly (DfD) and Design for Adaptability (DfA) come forward, acting as an important symbiosis between the micro-scale of the material and the meso-scale of the building or construction in general. In the DfD approach, none of the building components are permanently fixed. Instead, the use of reversible connections is advocated, which eases the disassembly and replacement of a particular element in the end-of-life stage. Additionally, this facilitates the dismantlement of the complete building in the end-of-life phase so the salvaged building components can be directly reused in new buildings elsewhere, in order to extend their lifespan at their highest value. If this is deemed impossible, because of e.g. deformation, they can be reused in a lower value application or recycled as raw material (Cruz Rios et al., 2015; Guy et al., 2005; Hood et al., 2005; Metin and Aydin İpekçi, 2015; Webster and Costello, 2005).

A complete knowledge on the building over its complete life span, including all changes that have occurred, which may have affected the building components, is necessary to facilitate this direct reuse of components (Guy et al., 2005). A promising tool for effectuating this knowledge transfer of building components and materials is the materials passport. It is of primary importance that the materials passport contains all relevant information that defines their residual value for construction. These data should also be shared in a centralised platform, accessible by all stakeholders (Heinrich and Lang, 2019).

In the DfA approach, a building is designed to be adaptable in order to prolong the building’s lifetime. The idea is that a building, serving its present purpose, can easily be adapted to the changing requirements, conditions and demands of future generations instead of being completely or partially demolished (Estaji, 2017; Geldermans, 2016; Jakšić et al., 2017; Kelly et al., 2011; Schmidt III et al., 2010). In this way, a lot of energy and materials can be saved (Estaji, 2017). In DfA, it is thus of primary importance that architects learn and understand how buildings tend to change and evolve over time in order to improve their designs to meet the DfA principles (Kelly et al., 2011). The Reuse aspect in DfA is practically focussed on the building in its entirety but seeks to allow each functional layer to be updated and changed independently. Therefore, the lifetime of the building is prolonged by increasing the probability of new configurations of functions. These shearing layers should be detangled to allow simple access as they age at different rates and must be replaced more or less frequently due to changing boundary conditions and needs (Brand, 1994). Additionally, three categories of changeability of buildings and their spaces could be considered when designing adaptable buildings: the alterable, the extendable and the polyvalent (Leupen, 2004). The adaptation of the building over time and the possible replacement of certain components is embedded in this
system, it reflects a certain volatility that is inherent to every building. The component replacement, at least for certain functional layers or parts of the building, can be approached with DfD concepts.

Recently, the International Organisation for Standardisation (ISO) (2020) published the “ISO 20887:2020 Sustainability in buildings and civil engineering works - Design for disassembly and adaptability - Principles, requirements and guidance”. This standard provides a general vocabulary, definitions and guidelines for DfD and DfA, corresponding to the descriptions provided above. The general purpose is to allow components to be more easily reused and their materials recycled when reuse is not possible anymore. The ISO 20887 advocates the importance of building documentation and the registration of the material constituents. This registration can help to assess the reusability of the elements at the moment of disassembly. In addition, the environmental impact and the identification of potentially hazardous materials also need to be mapped out (International Organisation for Standardisation, 2020). Note that this is in fact a direct reference to the materials passport. The ISO 20887 emphasises that it would be completely meaningless to set objectives towards DfD and DfA if it is not possible to measure the progress against the business as usual scenario. Therefore, it is also important to visualize the current scenario both qualitatively and quantitatively (International Organisation for Standardisation, 2020).

An important aspect that the ISO 20887 discusses is standardisation. It is argued that the use of “standardised parts […] can support aspects of simplicity, adaptability and further re-use”.

Advantages such as the fact that these materials can be purchased more easily and the reduction of cutting losses on site, which saves material, are brought forward. It is argued further that the standardisation of dimensions, components, connections and the compatibility with other construction systems, both dimensionally and functionally, will benefit their reuse capabilities (International Organisation for Standardisation, 2020). However important this argument on standardisation and however important the ISO 20887 in its entirety may be, these guidelines remain general and vague. Consequently, their applicability in practice remains questionable.

Nevertheless, the focus on the reuse capabilities of construction components in a CE is of particular importance, because it is environmentally more beneficial than merely recycling materials (Buyle et al., 2019; Densley Tingley et al., 2017). Several authors (e.g. Cruz Rios et al., 2015; Densley Tingley et al., 2017; Iacovidou and Purnell, 2016) have also investigated and discussed the barriers to the circular Reuse of construction components which lead to the identification of the following six important aspects: the perceived risk in reusing components, reusing components could be more expensive, composite construction (for example concrete on steel deck flooring with shear studs) may prevent circular Reuse, the same counts for inaccessible/irreversible joints in general, there is a lack of reuse markets and supply chains, and time constraints may favour demolition over deconstruction. However, the lack of standards and their significant role as an enabler for circular Reuse, and thus the aforementioned environmental benefits, is barely mentioned and, to the authors’ knowledge, remains unexplored. Therefore, in this study the existing types of construction standards will be reviewed and discussed in order to identify which available standards contribute to effectuate the envisaged circular Reuse of components when DfD/A is implemented in the construction industry, and thus contribute to effectuate and enable the actual application of the ISO 20887 in practice. Additionally, the limits and shortcomings of the currently available construction standards will be identified and a trajectory for future standardisation will be proposed. An overview of this paper is shown in Figure 1.
Figure 1: Article overview
2. Material, methods, scope and goals

An overview of the evolution of standardisation in construction will be given, starting from the very beginning of standardisation till the present. The literature that is consulted in order to fill in this overview is kept as wide as possible. The sources range from science and history books, over scientific articles, to professional websites of construction stakeholders. The used search terms in order to attain a general overview are: construction standards, construction standards history, history of standardisation, history of building codes. From there onwards, more targeted searches were carried out to obtain more information on specific types of construction standards.

The standardisation mapping framework, as proposed by Ho and O’Sullivan (2018), serves as base for the overview of the available kinds of construction standards. The framework addresses strategic questions - i.e., ‘what’, ‘why’, and ‘when’ - and tactical questions - i.e., ‘how’, ‘who’, and ‘where’. Strategic questions are principally related to key dimensions of standardisation - i.e., technology and innovation elements relevant to standardisation, their roles and functions, and timing. Tactical questions, on the other hand, may address additional important issues like modes of coordination and types of SDOs (Ho and O’Sullivan, 2018). For further details, the authors refer to Ho and O’Sullivan’s full publication.

The aim is to find, on the one hand, answers to why standardisation is called upon -what drives the standardisation process. On the other hand, the kind of standards that were developed in response, will be evaluated in terms of their contribution to the enablement of the circular Reuse of construction components, as advocated in the ISO 20887. The aim is not to list all available construction standards, as many construction standards deal with the same matter. Enumerating all available construction standards will therefore not contribute to answering the abovementioned questions. The aim is rather to provide an overview of all kinds of constructions standards that are important for and influenced the European context, organised in a chronological order. Of each kind, a number of representative examples will be listed. Often, these are the first of their kinds or the best documented ones. Other, unmentioned examples can be considered as similar.

In a subsequent section, the overview of the available kinds of construction standards will be discussed in an integrative way. The aim in this section is to identify the problem areas obstructing the further development of standards enabling the circular Reuse of construction components.

3. Results

In order to understand how standardisation currently enables DfD/A and ultimately Reuse in a circular construction industry, as advocated in the ISO 20887, it is important to provide an overview of the available types of construction standards. By examining the relevant dimensions (what, why,...) of this standardisation process, a clear view can be obtained on how and why standardisation is relevant and what drives standardisation. It was chosen to organise and divide the overview of the available types of construction standards into six different periods in time, which correspond to key events in regulatory contingency:

1. From regional punishments to the art of construction (3000 B.C. – 1660 A.D.)
2. The need for new cities (1660-1840)
3. Industry 1.0 and 2.0 - New materials and globalisation (1840-1940)
5. The emergence of the Eurocode (1990-2005)
6. Industry 4.0 - The awareness of the importance of a sustainable world (1987-)

The first period is the longest. It starts with the available standards of the earliest developed civilisations and ends at the end of the renaissance. In this period written standards are rare as they were not common practice, hence the extensive time-span. The second period mainly concurs with
the era of colonisation. The four subsequent periods correspond to the Industrial Revolution phases from Industry 1.0 to 4.0.

A full overview of the standards included in the framework, is shown in Table - A in the appendix and in Figures 2 to 7 in the following subsections. These Figures are a visual representation of Table - A. They show the problem that rose and the code of the corresponding standard that followed. The standards themselves are further elaborated in Table - A. In this table, only written standards are included. In the following subsections, each phase will be discussed, each time with a brief reflection in terms of standardisation enabling circular Reuse. Also pre-modern and pre-industrial local practices of standardisation, of which only architectural evidence but no written records remain, will be discussed.

3.1 From regional punishments to the art of construction (3000 B.C. – 1660 A.D.)

One of the first forms of codified standardisation, relevant to construction, can be found as early as the 4th millennium B.C. with the standardisation of measuring systems in the ancient Eastern world. The most prominent ones are the standardised measurement of lengths with the Egyptian cubit, based on the length of a man’s forearm, and the standardised weight system developed by the Indus Valley Civilisation to control the trade of goods (Kenoyer, 2006; O’Connor and Robertson, 2003; Science Learning Hub, 2020). Aside from these standards, introduced by local governments, the archaeological evidence in the Indus Valley shows that bricks were highly morphologically standardised as all domestic and public architecture was constructed of bricks with the same strict proportions. Here however, the standardisation is probably the result of craft specialisation and the migration of brick masters throughout the region (Kenoyer, 2006). Note that all these standards serve the economy, as they provide a reference base for the trade of goods.

The next prominent, historical form of construction standard can be found in 1750 B.C. in the Hammurabi code. This code imposed various penalties on the contractor if buildings collapsed, ranging from damage compensation to death penalties if there were fatalities as a result of the collapse (Anwar and Najam, 2015; Denton, 2018; Farnam Street Media Inc., 2020; Harper, 1904; Vaughan and Turner, 2013; Winkel et al., 2007).

Ching and Winkel (2018) stated that the main reason for this form of standardisation is that it allows the government to guarantee a kind of accountability and protection for its people. This protection refers not only to the safety of the people but also to the health and welfare of the society. These core values –safety and economy- are still visible today in the underlying motivation for standardisation (Ching and Winkel, 2018).

Hammurabi’s code remained the most elaborate known concept of codified standardisation for a long time -see Figure 2. Even though there were several standardised forms in ancient Greek architecture, as Greek architects formalised beam and column proportions which were subsequently adopted by the Romans (Senseney, 2014), these were not formally codified until the Roman architect and engineer Vitruvius published his 10 books in the second half of the first century B.C., all together forming the treatise “De Architectura” (Jones, 2014). In these books, Vitruvius documented the state-of-the-art in Roman building technology and architecture. Standardisation was applied here as a tool to codify the ideal aesthetic proportions in architecture, to control and apply successful and reliable methods and schemes, again to guarantee people’s safety, but also urban planning schemes. This allowed to quickly and effectively expand the infrastructure in the Roman Empire and thus ensure its economic welfare (Encyclopaedia Britannica, 2020; Vitruvius, 1999). While Hammurabi mainly focused on the meso-scale and considered each building separately, Vitruvius for the first time looked at standardisation on the macro-scale as well by looking at urban planning.
Neither Hammurabi’s code, nor Vitruvius’ De Architectura mention anything on the reuse of building components. However, Frangipane (2016) stated that in ancient times, reusing materials has always been common practice for economic reasons, as well as to transfer their symbolic value, thus for cultural appropriation. Since buildings, often also important ones, were frequently destroyed by earthquakes or war, it was common practice to reuse elements in new buildings or new applications.
(Frangipane, 2016). Kinney (2001) explained that these reused elements, “spolia”, consisted of column shafts, capitals, bases and lintels. The fact that Vitruvius codified their aesthetic principles and proportional composition benefitted their reuse until the early middle ages of Charlemagne (8th century A.D.) (Kinney, 2001).

Later on in medieval times, the age of the stonemasons, the Greco-Roman architectural language was largely abandoned. In this period, the direct reuse of building components was fairly limited, as components were rather downcycled and recut, for stone, or remelted, for metals, into new components (Frangipane, 2016). According to Ralls (2015), medieval stonemasons, also referred to as master builders, had their own set of regulations of which no written records remain before the mid-fourteenth century. The stonemasons’ craftsmanship was treated in a highly protective way and stonemasons’ training was conducted orally. From the mid fourteenth century onwards, guild records and ordinances appeared to control and protect the stonemasons’ trade. On the one hand, this protective stance was to maintain the stonemason’s economic position, but certainly also because errors in the construction of a building could be fatal for both workers and public. In terms of morphology, only few written documents are known, all referring to cathedral construction. The more famous of these is the mid-12th century account by Abbot Suger of Saint-Denis on the new choir of his abbey church (Ralls, 2015). However, there is no knowledge of any recorded construction standards at that time as construction was based on experience, and fine examples of architecture were often developed and refined through repetition. At the beginning of the renaissance, Tavernor (2009) explained, Vitruvius was rediscovered which resulted in the revival of the classical orders. The numerous architectural treatises that followed, starting with architect Alberti’s “De Re Aedificatoria” in 1485, are all based on or inspired by Vitruvius (Tavernor, 2009). All these treatises may have resulted in a fairly unified architectural style, but not necessarily in a constructional standardisation. The rediscovery of Vitruvius did, however, lead to the reuse of ancient Roman spolia in the contemporary 15th to 18th century buildings. Public authorities allowed complete Roman buildings to be reused with a different function, or completely dismantled and sold on the antique market. The latter occurred despite several unsuccessful preservation acts against the abuse of spoliation (Frangipane, 2016).

3.2 The need for new cities (1660-1840)

Because of various city fires in the 17th century, of which the Great Fire of London in 1660 is the more famous example, several cities had to be rebuilt (Noorthouck, 1773). As colonization also became more important, new cities were built all over the world (1911 Encyclopædia Britannica, 1911; Encyclopaedia Britannica, 2018). After these events, local authorities established broad regulations, many of which based on standardisation, depicted in Figure 3.

![Figure 3: The need for new cities (1660-1840)](image)

Considering the proven usefulness of urban planning, this form of standardisation on the macro scale was elaborated with the Laws of the Indies in 1680, a comprehensive set of regulations for the colonies which also comprised urban planning regulations. They were updated and rewritten several times until they lost their importance in the 19th century (1911 Encyclopædia Britannica, 1911; Encyclopaedia Britannica, 2018). The reuse of building components was still not standardized in any form other than the common practice as in previous periods. However, it is important to note that
even without standards and regulations, until the early 19th century this reuse of building components and recycling of materials has always been common practice.

3.3 Industry 1.0 and 2.0 - New materials and globalisation (1840-1940)

The Industrial Revolution was a catalyst for standardisation, see Figure 4. Not only did the Industrial Revolution lead to various new building materials (de Bouw et al., 2009), it also led to an enormous increase in population density, making people live closer together than ever before (Clarke Annez and Buckley, 2009). This in itself induced various threats such as diseases and city fires (Winkel et al., 2007), as a result of which local authorities had to focus their attention again on urban planning standards. In the mid-19th century, the idea of urban planning was further elaborated, for example for London and Paris, to meet the ensuing needs. For the first time, also the conservation of important roads and monuments, which were part of these cities, was considered (Clarke Annez and Buckley, 2009; CreateStreets, 2019; Loew, 1998). Additionally, as urban planning increases the living standards in cities, it is beneficial for these cities’ economies.

Another aspect was the growing demand for cheap building materials, causing the demand for standardisation to increase at the micro scale. Wermiel (2009) explained that steel gradually became the most important construction material during this period, due to its believed fire resistance and strength, even though it was not a cheap material, certainly not in the beginning. A lot of competition between manufacturers was created, each one of them developing their own set of standard profile sections, starting with the typical rail-type and quickly expanding to very particular composite profiles (Wermiel, 2009). This competition also led to the establishment of the first facilities for mass-production, each hosting its independent quality controls (Bates, 1984; Encyclopaedia Britannica, 2019). Local, manufacturer-dependent, morphological standards emerged to make mass-production more effective and more economic, which eventually resulted in the creation of the I-profiles that are now known worldwide (Bates, 1984; Beal, 2011). Mass production itself provides additional benefits like an increase in quality, due to the increased possibility of control, and a reduction in price. Mass production can therefore be seen as another crucial reason to apply standardisation, which is in fact again economy-driven.

During this period, the collection and recycling of scrap metal for the production of new steel elements became common practice, arising entirely from an economic point of view (Medina, 2007). Nevertheless, there are no records of the direct reuse of steel elements, even though this would be
perfectly possible since steel elements with the same cross-section may serve different applications. Additionally, provided they are correctly attached and maintained regularly, the lifetime of steel elements may exceed 200 years (InterNACHI, 2020).

In the 18th century, concrete re-emerged as a construction material. It was known from Vitruvius’ descriptions, and from many surviving Roman buildings, the Pantheon in Rome as the greatest Roman example. Newby (2001) explained that several engineers in the 18th and 19th century picked it up again as an interesting construction material because of its high fire-resistance and underwater performance. Concrete was investigated more elaborately and its properties fine-tuned. Of these engineers, Smeaton was the first who experimentally managed to actually understand the properties of the Roman pozzolana in the mid-1750’s. Several engineers followed to produce derivatives of this natural hydraulic cement, but it was Aspdin who managed to produce the artificial ‘Portland cement’ in 1824. However, it was only in the second half of the 19th century that serious advances were made in the research and application of concrete. After many serious attempts, one of which by Joseph Monier, it was Hennebique’s method of construction, calculation and typical reinforcement details, which he patented in 1892, that proved to be most effective (Newby, 2001). In the further decades, standardisation focussed on the material use and construction process of concrete, starting with local and later national regulations at the turn of the century. Nothing is known about the reuse or recycling of concrete, presumably because of its durability and consequent long life-expectancy. Also its low cost made its reuse economically redundant.


The absolute pioneer in the theory of elasticity as we know it today was Navier. Bistafa (2018) explained that Navier’s publication of the equations for the equilibrium and motion of an isotropic, one-constant, elastic solid in 1821 can be seen as the birth of the modern theory of elasticity. Afterwards, several mathematicians like Cauchy, Poisson and Saint-Venant arrived at the same equations, but failed to acknowledge Navier’s pioneering work (Bistafa, 2018). Navier and his contemporaries set up a new engineering education regime at the new polytechnic in Paris making the emerging natural sciences and mathematics the basis of structural design as we know it today. In this standardized process, all boundary conditions and the design process were considered in a popularized pattern which ideally led to the choice of standardized structural members. This was particularly important for the new structural typologies and loads together with the new material iron (later steel) for all of which no direct experience was available and applicable (McKeon, 2020). Until the first half of the 20th century, these calculations were done manually. The developments made were fundamental but rather slow, and it was only in the second half of the 20th century that mathematical models to approach structural behaviour became the main focus of attention (Hansen, 2007; Todd, 1944). In this period, the focus shifted from the scale of the individual component to the scale of the entire structure. With the arrival of the computer, vast leaps forward could be made in the optimisation of components and entire structures, as shown in Figure 5.

![Figure 5: New mathematical theories (1940-2015)](image_url)

Further knowledge in probability calculation ultimately contributed to the development of safety factors and partial safety factors (Galambos, 1998). Note that these are again focussed on guaranteeing people’s safety. There is no real focus on the reuse of structural components in this
period, but it is nevertheless crucial to gain insight into the behaviour of building materials in order to gain a good understanding of their lifetime. Also, these insights in material characteristics and new calculation models allowed for structures to be more correctly calculated, raising certainty and thus reduce overestimation. Consequently, from an economic point of view, this meant a relative reduction of material use.

3.5 The emergence of the Eurocode (1990-2005)

In the middle and certainly towards the end of the 20th century, another reason why standardisation is useful gained importance. With the establishment of the Benelux, the Treaty of Rome and eventually the EU, free transport of both construction professionals and building materials became possible (Spaak et al., 1957). Consequently, a standardized system to demonstrate a certain level of quality became increasingly important. That is why the Eurocode (EC) was created, ultimately becoming one of the most important construction standards worldwide at the beginning of the 21st century (Calgaro, 2006; Denton, 2018; Linssen, 2018; Schaerlaekens, 2000). Since this is such an important standard, it was decided to consider this period -shown in Figure 6- completely separately, although in many respects it corresponds to the development of new mathematical theories and could therefore be merged with the previous period.

![Figure 6: The emergence of the Eurocode (1990-2005)](image)

The European Commission will always release a new EC first in the form of a European pre-Standard (ENV), after an evaluation they become a part of the EC. Finally, each Member State can add a national annex to take into account, for example, the climate in that particular Member State (Schaerlaekens, 2000).

Within the EC, there has not been any standardisation with regard to reuse. The focus here is mainly on being able to guarantee a certain quality that can be achieved uniformly across different countries. Of course, this again goes back to a certain level of safety which needs to be guaranteed.

3.6 Industry 4.0 - The awareness of the importance of a sustainable world (1987-)

The true pioneer for the CE was K.E. Boulding in 1966 with his publication of “The Economics of the Coming Spaceship Earth” (Boulding, 1966), followed in 1968 by the establishment of the Club of Rome striving for a sustainable world (Club of rome, 2020). However, it was in the Brundtland report, published in 1987, that guiding principles were established for sustainable development as it is generally understood today. Therefore, 1987 is seen as the beginning of a broader awareness of the importance of sustainability (Commission on Environment and Development, 1987; Jarvie, 2016).
Figure 7: The awareness of the importance of a sustainable world (1987-).
Ever since, sustainability is being addressed and is gradually being standardised, as shown in Figure 7, resulting in a last reason why standardisation is useful. Standardisation effectuates the ability to obtain an objective impression of the sustainability of buildings (International Organisation for Standardisation, 2020). However, the sustainability of buildings is a very broad issue and thus something that is extremely difficult to quantify. To this end, governments have already attempted to standardise sustainability quantification by means of the Life Cycle Assessment (LCA), the Energy Performance of Buildings Directive (EPBD) or Building Research Establishment Environmental Assessment Method (BREEAM) (International Organisation for Standardisation, 2020; Tsimplokoukou et al., 2014). These make it possible to assess and compare different constructions in terms of their energy performance in the operation phase, or their environmental footprint. Unfortunately, this is not oriented towards circular construction principles or the reuse of building components, more specifically. In fact, the first standard dealing with this issue is the ISO 20887, in which DfD and DfA are standardized for the first time (International Organisation for Standardisation, 2020). However, as mentioned before, this remains a vague collection of definitions and requirements, and none of the currently available standards aid or support the ISO 20887. As such, we may now be on the verge of a new standardisation phase which will practically translate the DfD and DfA principles in the construction sector.

4. Discussion
In order to start this discussion, it is appropriate to provide an abstraction of the previous results section. In the overview of the evolution of standardisation, four main drivers for standardisation were identified. Each of these drivers came with its own types of standards, which in their turn were developed by different actors. This is presented in Table 1.

Table 1: Abstract of standardisation overview

<table>
<thead>
<tr>
<th>Reason, goal</th>
<th>Type of standard</th>
<th>Actors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Guarantee people’s safety</td>
<td>Product Quality/Reliability</td>
<td>Researchers, Contractors, Manufacturers, Governments</td>
</tr>
<tr>
<td>Construction Quality/Reliability</td>
<td>Researchers, Contractors, Manufacturers, Governments</td>
<td></td>
</tr>
<tr>
<td>Urban Planning</td>
<td>Manufacturing/Characterisation</td>
<td>Manufacturers, Researchers, Governments</td>
</tr>
<tr>
<td>Terminology/semantic</td>
<td>Manufacturers, Designers, Contractors, Researchers, Governments</td>
<td></td>
</tr>
<tr>
<td>Aesthetics</td>
<td>Optimal proportions</td>
<td>Designers, Researchers</td>
</tr>
<tr>
<td>Economic benefit</td>
<td>Manufacturing/Characterisation</td>
<td>Manufacturers, Researchers, Governments</td>
</tr>
<tr>
<td>Urban Planning</td>
<td>Designers, Contractors, Governments</td>
<td></td>
</tr>
<tr>
<td>Optimal proportions</td>
<td>Designers, Researchers</td>
<td></td>
</tr>
<tr>
<td>Product Quality/Reliability</td>
<td>Researchers, Contractors, Manufacturers</td>
<td></td>
</tr>
</tbody>
</table>
The first and foremost driver for standardisation is the guarantee of people’s safety, both on the meso-scale of the building, and on the macro-scale of the city layout. Aesthetics are another reason for standardisation. This was very apparent in ancient Greek and Roman architecture, but also later in gothic architecture. During the Industrial Revolutions, mass-production became a very important driver for standardisation from an economic standing point. Morphological standardisation allowed production to be faster and cheaper, but also measurable quality standards were introduced. Only in the last four decades, sustainability consciously became a driver for standardisation. However, until now these standards mainly focus on the energy-consumption or carbon footprint of buildings throughout their lifetime.

An interesting observation is that reusing building components, either directly or through downcycling, has always been common practice since ancient times until the 19th century. It seems that in the age of concrete and mass-production, the direct component reuse was abandoned, probably also because concrete elements are not easily reusable, nor recyclable, and because construction components can now be more easily manufactured than ever before.

In short, standardisation provides reliability and safety by lowering risks, creates a common level of knowledge and practices, facilitates processes, and provides a universal view on different issues and is therefore a common practice in the construction industry. It is that universal view that is now needed to address the problem of material resources being finite. This problem has been known for a long time, but in recent years is becoming more apparent and showing increasingly severe consequences. Until now, however, the latest ISO 20887 is the only standard that addresses the reuse of building elements in new constructions. This finding is in fact striking, as DfD, DfA and the circular Reuse of building elements have been and are still discussed extensively in literature (e.g. (Arora et al., 2019; Chileshe et al., 2018; Cruz Rios et al., 2015; Durmisevic and Brouwer, 2002; Estaji, 2017; Guy et al., 2005; Hood et al., 2005; Iacovidou and Purnell, 2016; Metin and Aydin İpekçi, 2015; Schmidt III et al., 2010; Webster, 2007; Webster and Costello, 2005)). Unfortunately, the current collection of standards does not address the practical implementation of the circular Reuse of components. Mostly, standardisation was driven by an economic rather than an ecological point of view and thus the guidelines in ISO 20887 have yet to be developed further. Standardized sizes are only available in terms of profile sections, but they can still be produced in any length, and connection compatibility between elements is virtually non-existent. This lack of further standardisation is partly due to protectionism of the manufacturers of building materials and components whom are reluctant to change their organisation structure and business routines (Hosseini et al., 2014). Moreover, the additional operations needed to reuse construction components may hold a risk in the form of profit loss (Dunant et al., 2018). However, by refurbishing or remanufacturing returned components, added value can be gained by putting in much less effort and energy compared to manufacturing using virgin materials (Hosseini et al., 2014). Furthermore, this protectionism may obstruct the development of standard-sized components with increased
interconnectivity with other construction systems. Yet, this is needed to make the circular Reuse of components profitable (Hosseini et al., 2014). Additionally, building documentation, e.g. materials passports, are brought forward as a facilitator for the circular Reuse of building components. However, current building documentation is mainly developed to reduce unnecessary damage during future renovation works, e.g. through documenting the exact location of electricity cables and water pipes inside walls and floors.

Also contractors often perceive standards as a threat. Polesie (2013) explained that the uniqueness of projects is their key argument against increased standardisation. The contractors argued that each project required a different approach in planning, organisation and execution due to the differences between construction sites, the buildings themselves, customers, subcontractors, etc. All these contribute to the unique conditions for each project and different ways to reach the final goal.

However, the reduction of the number of products used in buildings is perceived as a beneficial kind of standardisation. This is an indication of an attempt to standardise by decreasing the variability in choice of materials and components, but also simplifying the building process (Polesie, 2013).

However, the culturally embedded negative perception of reused materials and components being of inferior quality (Cruz Rios et al., 2015) remains. Additionally, for a component to be reused, there needs to be an actual economic demand for that type of component (van den Berg et al., 2020). On the other hand, designing structures is still too often done in the traditional way: the architect focuses primarily on the overall design and shape of a construction and the structural engineer is only called in at a later stage to assure the overall stability of the structure (Christensen and Klarbring, 2009). The engineer’s task is thus reduced to the optimisation of the already chosen structural typology. This may lead to an optimal version of this type of structure, but not necessarily to the optimal solution to the problem, as the structural typology itself may not be optimal. Additionally, due to the fact that just about any component size or connection is available, designs oriented towards the use of standard-sized components are still rarely considered. A reason may also be the fact that designers are, along with clients and subcontractors, the most important parties lacking a CE awareness (Adams et al., 2017).

In this discussion, three problem areas obstructing the circular Reuse of building components in the construction industry were identified:

1. Protectionism on the contractors’ side, as they perceive standardisation as a threat, even though they do see a benefit in standardisation which decreases the variability in choice of materials and products. However, due to the lack of standard-sized components, there is no demand for deconstructed components, available for reuse.
2. Protectionism on the manufacturers’ side, as they are reluctant to change the organisation structure and business routines. This may obstruct the development of standard-sized components with increased interconnectivity with other systems. Additionally, contractors distrust reusing building components.
3. Designers, whom seem least aware of the need to implement the CE in the construction sector and thus do not take any of the CE’s four R’s duly into account.

The significance of these findings is that governments and SDOs will be able to develop new, appropriate standards considering these problem areas. In this way, new standards can truly effectuate the DfA/D design strategies and the circular Reuse of building components. Hence, the environmental benefit of the circular Reuse of components over recycling the materials they are made of, will truly occur.

5. Proposed trajectory for future standardisation enabling circular Reuse

In correspondence to the identified problem areas, the authors propose the following standardisation trajectory:
A further morphological standardisation is needed. This morphological standardisation should not focus solely on profile sections. The focus should be broader and also lengths and heights of building components should be standardised. Even more important, the interconnectivity between different building components, the interface, should be investigated, meaning that standard connection systems should be developed. This further morphological standardisation does not apply merely to structural components, but also to components for the architectural finishing. Of great importance here is that architectural freedom should not become too limited. This will be important for both contractors and designers not to perceive this type of standardisation as a threat to their work. By standardising building component dimensions and connections, the demand for these building components will increase and consequently their reuse will be enabled and facilitated. Additionally, there is an opportunity for the social pillar of sustainability, as the increased labour-intensity of deconstruction brings opportunities for creating jobs for unskilled workers (Cruz Rios et al., 2015).

Standard procedures and certification schemes for the reuse of building components are missing. Materials passports will be of primary importance for effectuating the necessary knowledge transfer of building components and materials. Their use and application should be standardised, instead of merely being a vague guideline. Subsequently, when deconstructing a building in the end-of-life phase, a possible procedure could be that the deconstruction contractor returns the deconstructed building components to the concerning manufacturers. The manufacturer can then perform a (yet to be) standardised series of non-destructive tests in order to check whether the building component is directly suited for reuse, alternatively in need of repair, or maybe refurbishment, or completely rejected for reuse, disassembled and recycled as raw materials. Standardising these procedures will thus facilitate reverse logistics and induce new business models for both manufacturers and contractors. Additionally, this will facilitate the creation of supply chains for reusable components, which can counter the fear of economic loss. The certification of reused components can counter the fear of the quality of these components not being up to standard.

All construction stakeholders should be involved in the development of these morphological standards and standard procedures for circular Reuse. Hence, also designers’ awareness of their important role in effectuating the implementation of the CE in the construction sector will increase. The involvement of all construction stakeholders -designers, contractors, researchers, manufacturers, governments- is of particular importance because each and every construction party should support the newly introduced standards. In this sense, it will be important for all construction stakeholders to first agree on a theoretical standardisation framework that can serve as the basis for the development of the needed standards. Subsequently, these newly developed standards can serve as the start of the needed mind-shift to truly change the linear construction sector into a circular construction sector. Note that construction education will play an important role to establish this mind-shift as well.

Additionally, governments will play an important role in larger construction projects, like public buildings and bridges, to encourage all designers -architects and engineers- to cooperate right from the start of a project in order to reach both aesthetical and structurally optimal designs. In this, it is worthwhile mentioning the concept of Green Public Procurement (GPP) which was already introduced by the EU in 2005 (Bouwer et al., 2006), but only recently has gained increasing attention and importance. The idea of GPP is that Europe’s public authorities as major consumers are encouraged to “procure goods, services and works with a reduced environmental impact throughout their life cycle when compared to goods, services and works with the same primary function that would otherwise be procured” (European Commission, 2019). Hence, GPP is the EU’s encouragement for governments to indeed take their responsibility in society to set the example. However, it should be extended to also incorporate the CE and the circular Reuse of building
components. Additionally, instead of merely being an encouragement, GPP should evolve into a standard.

6. Conclusions

In this paper, the evolution of standardisation is investigated in order to determine what drives standardisation and which standards are already supporting the recently published ISO 20887. This standard provides guidelines for DfD and DfA and advocates the use of standard-sized building components as well as the interconnectivity between different building components. The aim is that this will enable the circular Reuse of deconstructed building components from end-of-life constructions because this is environmentally more beneficial than merely recycling materials. However, the lack of standards and their significant role as an enabler for circular Reuse, and thus the aforementioned environmental benefits, is barely mentioned and, to the authors’ knowledge, remains unexplored. Therefore, a historical overview of the evolution of standardisation in the construction sector was compiled in search for types of standards that could aid and support the practical implementation of ISO 20887. However, it was found that there is no currently available standard that defines these ‘standard-sized components’, nor ‘standard connection systems’ of which the ISO 20887 claims they should be applied. Additionally, in the discussion of this review, different problem areas obstructing the formation of these morphological standards were identified and a responding action plan was defined. A summarising overview can be found below in Table 2.

Table 2: Summary of the proposed standardisation trajectory

<table>
<thead>
<tr>
<th>Problem</th>
<th>Standardisation - action point</th>
<th>Actors</th>
</tr>
</thead>
<tbody>
<tr>
<td>No demand for deconstructed components, available for reuse</td>
<td>A further, broader morphological standardisation, focussing on lengths and heights of building components</td>
<td>Designers, Manufacturers, Contractors</td>
</tr>
<tr>
<td>The interconnectivity between building components should be investigated, standard connection systems should be developed</td>
<td></td>
<td>Designers, Manufacturers, Contractors</td>
</tr>
<tr>
<td>Protectionism from the contractor’s side, standardisation is perceived as a threat</td>
<td>A further morphological standardisation should allow enough architectural freedom</td>
<td>Designers, Manufacturers, Contractors</td>
</tr>
<tr>
<td>Protectionism from the manufacturer’s side due to fear of economic loss</td>
<td>Standard procedure for the reuse of building components in which the deconstruction contractor returns the deconstructed building components to the concerning manufacturers</td>
<td>Manufacturers, Contractors, Researchers, Governments</td>
</tr>
<tr>
<td>Contractors distrust the reuse of building components</td>
<td>A standardised series of non-destructive tests on deconstructed building components is necessary in order to declare and certify their aptitude for reuse</td>
<td>Manufacturers, Contractors, Researchers, Governments</td>
</tr>
<tr>
<td>Designers are the least aware of the need to implement the CE in the construction industry</td>
<td>The concept of GPP should be extended to also include the CE.</td>
<td>Designers, Governments</td>
</tr>
<tr>
<td>GPP should evolve into a standard instead of an encouragement</td>
<td></td>
<td>Governments</td>
</tr>
</tbody>
</table>

Of primary importance is that all construction stakeholders should be involved in the development of these morphological standards and standard procedures for circular Reuse. In this sense, it will be important for all construction stakeholders to first agree on a theoretical standardisation framework that can serve as the basis for the development of the needed standards. That is because each and every construction party should support the newly introduced standards. Only in this way, standardisation is able to perform its role as an essential enabler for circular Reuse in the construction sector.
### 7. Appendix

#### Table - A: Overview of the types of construction related standards which are relevant for and influenced the European context, organised according to Ho and O’Sullivan’s framework

<table>
<thead>
<tr>
<th>Phase</th>
<th>Code</th>
<th>Standard</th>
<th>Subject</th>
<th>What</th>
<th>Why</th>
<th>When</th>
<th>How</th>
<th>Where</th>
<th>Who</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>M1</td>
<td>Egyptian cubit</td>
<td>General construction</td>
<td>Generic technology</td>
<td>Measurement/Characterization, Quality/Reliability</td>
<td>~3000 B.C.</td>
<td>Anticipatory/Participatory</td>
<td>Government-based, Publicly available specifications</td>
<td>Governmental bodies</td>
<td>Government</td>
</tr>
<tr>
<td></td>
<td>M2</td>
<td>Weight system</td>
<td>Trade</td>
<td>Market/Customer, Policy/Regulation</td>
<td>Measurement/Characterization, Quality/Reliability</td>
<td>~3000 B.C.</td>
<td>Anticipatory/Participatory</td>
<td>Government-based, Market-based</td>
<td>Governmental bodies</td>
<td>Government</td>
</tr>
<tr>
<td></td>
<td>Q1</td>
<td>Code of Hammurabi</td>
<td>General construction</td>
<td>Policy/Regulation, Proprietary-technology</td>
<td>Quality/Reliability</td>
<td>~ 1750 B.C.</td>
<td>Anticipatory/Participatory</td>
<td>Government-based</td>
<td>Governmental bodies</td>
<td>Government</td>
</tr>
<tr>
<td></td>
<td>Q2, T1, A1</td>
<td>Ten books of architecture (Vitruvius)</td>
<td>General construction</td>
<td>Policy/Regulation, Proprietary-technology</td>
<td>Quality/Reliability, Terminology/Semantic, Aesthetics</td>
<td>~ 200 B.C.</td>
<td>Anticipatory</td>
<td>Market-based, Performance-based, Solution-describing</td>
<td>Private companies</td>
<td>Designer, Contractor</td>
</tr>
<tr>
<td></td>
<td>Q3, T2, A2</td>
<td>Account by Abbot Suger of Saint-Denis</td>
<td>General construction</td>
<td>Proprietary-technology</td>
<td>Quality/Reliability, Terminology/Semantic, Aesthetic proportions</td>
<td>~1150 Participatory</td>
<td>Performance-based, Solution-describing</td>
<td>Private companies</td>
<td>Researcher</td>
<td></td>
</tr>
<tr>
<td>II</td>
<td>Q4</td>
<td>Sir Matthew Hale’s Act</td>
<td>City planning</td>
<td>Policy/Regulation, Product/Application</td>
<td>Quality/Reliability</td>
<td>1667 Responsive</td>
<td>Solution-describing, Government-based</td>
<td>Governmental bodies</td>
<td>Government, Designer, Contractor</td>
<td></td>
</tr>
</tbody>
</table>

1 (Kenoyer, 2006; O’Connor and Robertson, 2003; Science Learning Hub, 2020)
2 (Kenoyer, 2006; O’Connor and Robertson, 2003; Science Learning Hub, 2020)
3 (Anwar and Najam, 2015; Denton, 2018; Farnam Street Media Inc., 2020; Harper, 1904; Vaughan and Turner, 2013; Winkel et al., 2007)
4 (Denton, 2018; Encyclopaedia Britannica, 2020; Vitruvius, 1999; Wilde, 2004)
5 (Rails, 2015)
6 (Tavernor, 2009)
7 (Noorthouck, 1773)
8 (1911 Encyclopædia Britannica, 1911; Brillenburg, 2020; Encyclopaedia Britannica, 2018)
<table>
<thead>
<tr>
<th>No.</th>
<th>Q/R</th>
<th>Description</th>
<th>Industry</th>
<th>Government</th>
<th>Quality/Reliability</th>
<th>Solution-describing</th>
<th>Governmental bodies</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>III</td>
<td>Q6</td>
<td>London Building Act</td>
<td>City planning</td>
<td>Policy/Regulation, Product/Application</td>
<td>Quality/Reliability</td>
<td>1844</td>
<td>Anticipatory/Participatory</td>
<td>Solution-describing, Government-based</td>
</tr>
<tr>
<td>Q7</td>
<td>Paris Decree</td>
<td>City planning</td>
<td>Policy/Regulation</td>
<td>Quality/Reliability</td>
<td>1852</td>
<td>Participatory</td>
<td>Solution-describing, Government-based</td>
<td>Governmental bodies</td>
</tr>
<tr>
<td>V1</td>
<td>Bessemer process</td>
<td>Steel production</td>
<td>Industry-environment, Production</td>
<td>Variety-reduction</td>
<td>1856</td>
<td>Responsive</td>
<td>Market-based, Solution describing</td>
<td>Governmental bodies</td>
</tr>
<tr>
<td>V2</td>
<td>Art of Building</td>
<td>Brickwork</td>
<td>Product/Application</td>
<td>Variety-reduction</td>
<td>1857</td>
<td>Responsive</td>
<td>Market-based, Performance-based</td>
<td>Governmental bodies</td>
</tr>
<tr>
<td>Q8</td>
<td>City of Baltimore’s building code</td>
<td>City planning</td>
<td>Policy/Regulation, Product/Application</td>
<td>Quality/Reliability</td>
<td>1859</td>
<td>Participatory</td>
<td>Solution describing, Government-based</td>
<td>Governmental bodies</td>
</tr>
<tr>
<td>M3, Q9</td>
<td>The chemical composition and physical properties of steel rails</td>
<td>Steel</td>
<td>Production, Infratechnology</td>
<td>Measurement/Characterization, Quality/Reliability</td>
<td>1878</td>
<td>Participatory</td>
<td>Publicly Available Specifications</td>
<td>SSO, Private Company</td>
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<tr>
<td>T4</td>
<td>Francois Hennebique</td>
<td>(Reinforced) Concrete</td>
<td>Production, Product/Application</td>
<td>Terminology/Semantic</td>
<td>1892</td>
<td>Anticipatory</td>
<td>Market-based, Performance-based</td>
<td>Private companies</td>
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<tr>
<td>Q10</td>
<td>ASTM A7</td>
<td>Steel</td>
<td>Science base, Product/Application</td>
<td>Quality/Reliability</td>
<td>1901</td>
<td>Participatory</td>
<td>Technical Specifications</td>
<td>SSO</td>
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<td>Q11</td>
<td>Standard No. 1 (NACU)</td>
<td>(Reinforced) Concrete</td>
<td>Product/Application</td>
<td>Quality/Reliability</td>
<td>1906</td>
<td>Participatory, Responsive</td>
<td>Technical Specifications</td>
<td>SSO</td>
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<td>T5</td>
<td>Standard Building Regulations</td>
<td>(Reinforced) Concrete</td>
<td>Production</td>
<td>Terminology/Semantic</td>
<td>1910</td>
<td>Participatory, Responsive</td>
<td>Technical Specifications, Marked-based</td>
<td>Private companies</td>
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</tbody>
</table>

References:
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11 (Bates, 1984; de Bouw et al., 2009; Dudley, 1878; Encyclopaedia Britannica, 2019)
12 (Adell-Argilés, 1994; Coates, 2017)
13 (Anwar and Najam, 2015; Inc., 2020)
14 (ASTM, 2020; Dudley, 1878)
15 (Bates, 1984; Beal, 2011)
16 (Adams et al., 2017; Beal, 2011; Newby, 2001; Timperley, 2018; Verma and Raghubanshi, 2018)
17 (Gustafson, 2007)
18 (Wilde, 2004)
19 (ACI, 1920; Todd, 1944)
20 (Montanstahl AG, 2019)
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<th>IV</th>
<th>Q12</th>
<th>DIN 4114</th>
<th>Steel</th>
<th>Science base</th>
<th>Quality/Reliability</th>
<th>1952</th>
<th>Anticipatory</th>
<th>Performance-based</th>
<th>FSO</th>
<th>Researcher, Designer, Government</th>
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<tbody>
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<td></td>
<td>Q14</td>
<td>ETV (Reinforced) Concrete</td>
<td>Science base</td>
<td>Quality/Reliability</td>
<td>1970</td>
<td>Anticipatory</td>
<td>Performance-based</td>
<td>FSO</td>
<td>Researcher, Designer, Government</td>
<td></td>
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<tr>
<td></td>
<td>Q15</td>
<td>DIN 1045-1 (Reinforced) Concrete</td>
<td>Science base</td>
<td>Quality/Reliability</td>
<td>2011</td>
<td>Participatory</td>
<td>Performance-based</td>
<td>FSO</td>
<td>Researcher, Designer, Government</td>
<td></td>
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<tr>
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<td>T8</td>
<td>EN 1993-2 Steel bridges</td>
<td>Science base, Generic technology, Market/Costumer</td>
<td>Terminology/Semantic</td>
<td>2006</td>
<td>Anticipatory/Participatory</td>
<td>TR, Solution describing</td>
<td>FSO</td>
<td>Researcher, Designer, Government</td>
<td></td>
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</table>

21 (Galambos, 1998)  
22 (Proiske and Van Gelder, 2009)  
23 (Calgaro, 2006; Harrison et al., 2015; Proiske and Van Gelder, 2009; Schaerlaekens, 2000)  
24 (Beal, 2011; Calgaro, 2016; Denton, 2018; Proiske and Van Gelder, 2009; Schaerlaekens, 2000)  
25 (Beal, 2011; Calgaro, 2016; Denton, 2018; Proiske and Van Gelder, 2009; Schaerlaekens, 2000)  
26 (Harrison et al., 2015)
| Q16 | ISO 15392 | Sustainability principles | Science base | Quality/Reliability | 2008 Anticipatory | IS, Solution-describing | FSO | Researcher |
| T18 | CEN/TR 15941 | EPD selection of generic data | Science base | Terminology/semantic | 2010 Anticipatory | TR, Solution-describing | FSO | Researcher, Designer, Government |
| T20 | EN 15978 | LCA calculation procedure | Science base, Production | Terminology/Semantic Measurement/Characterization | 2010 Anticipatory, Participatory | TR, Solution-describing | FSO | Researcher, Government |
| T21 | ISO 15686 | Service life planning | Science base | Terminology/semantic | 2011 Anticipatory | IS, Solution-describing | FSO | Researcher, Designer |
| T22 | ISO 20887 | DfD and DfA | Science base, System | Terminology/semantic | 2020 Anticipatory | IS, Solution-describing | FSO | Researchers, Designers |

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