Seven digital technologies for structural engineers – Pathway to net zero

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Digital technologies are increasingly being used in the built environment. An overview of seven digital technologies for structural design is given and their applications and values on projects at various scales are discussed. The potentials and opportunities of digital technologies to contribute to sustainable designs are also addressed with the aim of achieving a net zero built environment.

Key words: Circular design, digital design, digital technologies, holistic design

1 Introduction

In the coming decade there are several global challenges that need to be addressed in the building industry. By 2030, three billion people will require new housing [UN-Habitat, 2018]. This huge demand conflicts with an increasing resource scarcity. Today's buildings and construction are responsible for 39% of energy-related CO_2 emissions [GABC Global Status Report for Buildings and Construction, 2019], are using 50% of all materials consumed in Europe [Herczeg et al., 2014] and are creating 36% of the total waste in the European Union [Eurostat, 2021]. The built environment urgently needs to improve the way buildings are built, designed, and operated. Structural engineers can significantly influence the environmental impact of construction. From the 39% energy-related CO_2 emissions, half is due to the embodied carbon of the building, and two-thirds of that is accounted for by the structure [Arnold, 2020]. As operational energy performance is increasing and as we get closer to the 2050 target deadline for a 0-carbon society there will be an increased relevance to develop zero embodied carbon solutions for the built environment.

By implementing digital technologies, the structural engineering discipline is radically transforming from conventional labour-intensive intuitive to automated and data-based design. Project stakeholders hugely benefit from this significant shift, by having improved

visualisation, increased productivity, better data sharing, reduction in building waste, sustainable performance, and safety improvements [Manzoor et al., 2021]. Besides these benefits, digital technologies have also gained rising attention due to the growth of concepts like digitalisation and automation in Industry 4.0 [Alaloul et al., 2020]. Finally, due to the significant importance of climate change, agreements and visions were presented on how to get to a sustainable and net-zero globe in 2050 [Paris agreement, European deal, 2015]. The EU CE Action Plan [European committee, 2020] and the 'Europe's Digital Decade' [European committee, 2020] describe that digital transformation and technologies are key to this transition. Çetin et al [2021] described that the implementation of digital technologies is an essential enabler of the circular economy in industries like the Architecture, Engineering, and Construction (AEC) industry.
This article addresses the following research question: which digital technologies are available to structural engineers and how could they be used to contribute to the design and engineering process and to achieve a net zero built environment? What challenges are faced in this process? And what is the future role of the structural engineer? Throughout the article the technologies are described, project examples are provided, and the potentials and challenges are discussed.

2 Digital technologies for structural design and engineering

The implementation of digital technologies on structural design and engineering started from the middle of last century. Arup's pioneering application of computers on the Sydney Opera project pushed the limits and revolutionised engineering practice at that moment when computers were seldom used for structural analysis (Fig. 1). With the use of the Ferranti Pegasus Mark 1 computer from 1957, a breakthrough pace of work was introduced to integrate computer calculations in the structural design work of the roof, as well as for the fabrication and construction planning. Estimates of the computer hours used on the project up to 1962 reveal that if done manually, the calculation work would have taken Arup engineers a further ten years [White, 2016]. The Opera House could simply not have been built without the help of computers.

With the more recent development, many other emergent digital technologies are available for the AEC industry (Fig. 2). Building information modelling (BIM), virtual reality (VR), augmented reality (AR), geographic information systems (GIS), artificial intelligence (AI), robotics, block chain, digital twins, and the internet of things (IoT) are some of the

Figure 1. Left: Ferranti Pegasus Mark 1 computer, 1957 (©Mary Evans Picture Library/Alamy Stock Photo); Right: Model of Sydney Opera House roof undergoing stress distribution testing at Southampton University, 1960 (© Henk Snoek/Courtesy Arup)

technologies that have transformed the built environment industry [Manzoor et al., 2021]. However, for structural engineers, not all of these are directly related to the engineering practice. In this chapter, seven key digital technologies for engineers will be elaborated, showing the advantages of using them in structural design and the potentials to contribute to sustainable designs and our pathway to net zero.

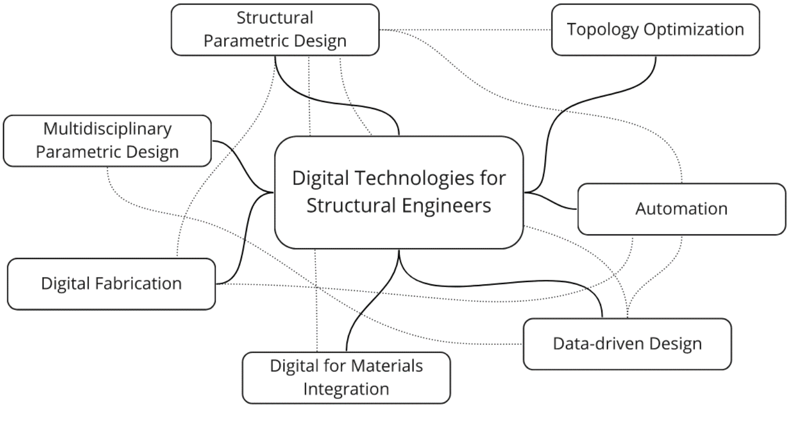

Figure 2. Seven digital technologies for structural engineers (© Arup)

2.1 ***Structural Parametric Design***

The traditional process of structural design and engineering is linear in most cases. This workflow, although most of the time including several design iterations of empirically-based interaction between architect and engineer, is limited on many cases when the interaction between architectural form and rational structural logic is required. In such a linear design process, the transformation of a huge amount of numeric data into a coherent design-relevant feedback loop in the iterative design process requires close interaction between analysis and the process of design development [Ren, 2015].

Figure 3. Camp Adventure Tower, Denmark (© Sydkyst Danmark)

With Arup's project Camp Adventure observation tower in Denmark, an integrated parametric workflow has been used to bridge the gap between architectural design and structural engineering (Fig. 3). The observation tower is a 45 m tall hyperboloid steel lattice structure featuring straight structural steel elements, and a spiralling walkway made of locally sourced oak wood that takes visitors up and above the trees for a panoramic view of the surrounding forests (Architect: EFFEKT). The project opened to the public in 2019.

Arup worked with the architect to take the design from inception to delivery with a total structural parametric workflow, which promoted ease and speed in generating, evaluating, and eventually optimising a large amount of design alternatives through various stages from form-finding of the hyperboloid shape at early stage to rationalisation of the steel connections. As shown in Figure 4, the process integrated the architectural drivers of the hyperbolic diagrid and the spiral ramp ring with the structural logic through a process of generative design and optimisation of the structural members including five offset layers. Automated structural static and dynamic analysis including Eurocode design checking

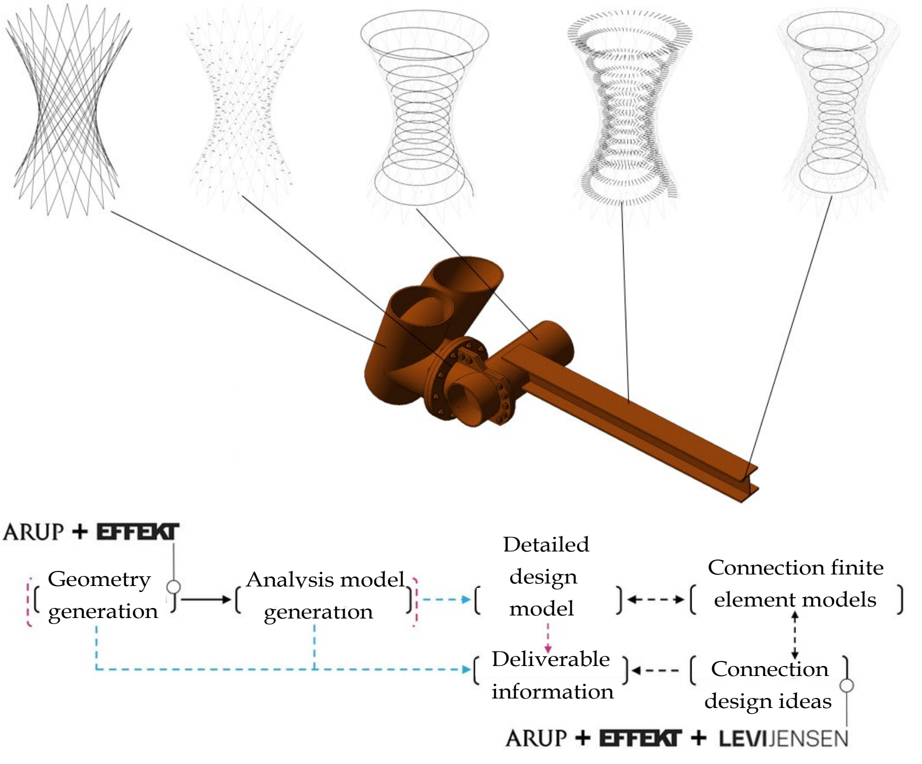

Figure 4. Parametric workflow developed for Camp Adventure Tower (© Arup)

were embedded in the parametric framework, allowing the engineer and architect to collaborate through the entire design, supported by numerical simulation and engineering rationalisation in a collaborative digital environment responsive to the design decisions for each step.

Parametric design was a perfect fit for this boundary-pushing design, until arriving at the final optimal structural concept that would offer the best solution against a set of performance indicators, including budget and sustainable impact. The entire design process serves as a novel example of digital best practice and demonstrates how the parametric design environment can promote engineer-architect collaboration and holistic thinking in the design of ambitious architecture.

As shown in the example above, applying parametric design on structural projects can help engineers to explore the design space, allow flexibility in the design, rationalise the structure, and optimise for certain objectives. Minimising structural weight has been an objective for quite some time, however there is exciting potential to include other objectives which can help achieve our pathway to net zero, such as minimising embodied carbon or maximising reusable members in the design. The two figures below show project examples of how to incorporate these objectives. Figure 5 shows an option study during the design process where the embodied carbon of a building structure was calculated and compared between different integral floor build-ups and structural spans. By digitally

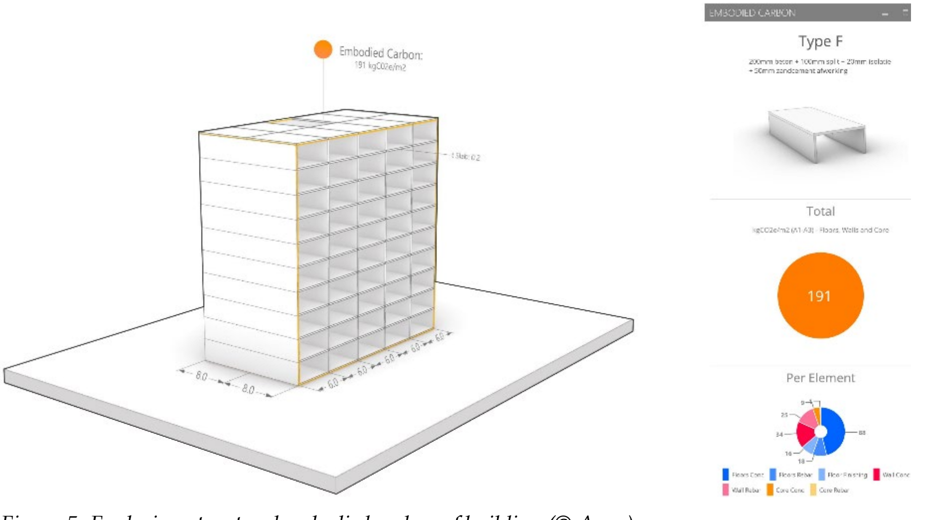

Figure 5. Exploring structural embodied carbon of building (© Arup)

generating and evaluating different alternatives, the most efficient option could be found based on structural, acoustical, and environmental demands. Figure 6 shows a study where parametric design was used for exploring reusability of steel structural platforms. With the establishment of the database of the waste material and exploration in a digital process, the case study shows that 62% of the new designed beams and 35% of the new designed columns could be built from existing steel profiles. Both examples highlight the potential of incorporating structural parametric design for a sustainable built environment.

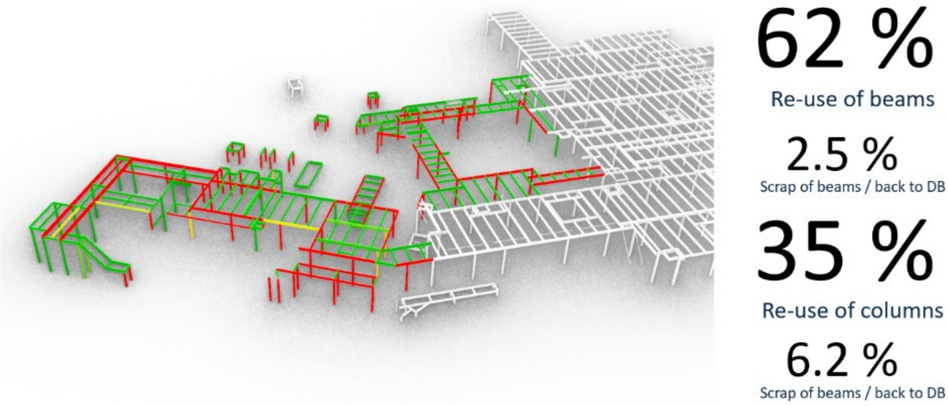

Figure 6. Designing steel structure with reusable steel members (© Arup)

2.2 ***Multidisciplinary Parametric Design***

The benefits of applying multi-objective multidisciplinary optimisation in building design have been increasingly recognised in the recent decade [Yang et al., 2018]. Often clients, architects and engineers want to explore numerous options and optimise their design based on usually more than one Key Performance Indicator (KPI). This can be quite a challenge when typically, the KPIs are based on more than one discipline and are conflicting each other. Using multidisciplinary parametric design helps the design team to programmatically explore the design space (the range of viable solutions) by searching for the best answer. This methodology has been proven to be time and cost-efficient compared to traditional design methods [Christodoulou et al., 2018]. Due to the time saving, more design iterations can be explored, resulting in increased quality.

Another great benefit of using multidisciplinary parametric design is to facilitate an informed communication among the design team, with regard to the relationship and relative weighting of distinctive design objectives [Titulaer et al., 2019]. Using this approach, the quantifiable improvement can be communicated to the design team and helps to incorporate sustainable objectives in the concept design stage, compared to their considerations later in the design process traditionally.

Standing by the river Amstel in Amsterdam, Elements is a new residential building developed by Kondor Wessels Vastgoed, Koschuch Architects, Boom Landscape, Buildung and Arup, shown in Figure 7. The 70-metre-tal timber hybrid structure is shaped by the elements: daylight, sun, wind, and structure. The main design challenge was to design this 14.800 m2 building for optimal daylight, wind comfort, green spaces, and energy generation whilst creating a design that carefully fits in the urban context.

Figure 7. Render of the final design (© Beauty and the Bit)

The design team carefully selected the KPIs and used parametric design to generate, explore, and evaluate hundreds of design variants (Figure 8). The result of this process was a design that achieved a satisfactory trade-off between the conflicting objectives as well as providing a quantifiable improvement over a rectangular reference design.

The final design of the building is energy-neutral, and by building a hybrid structure the MPG (MilieuPrestatie Gebouwen) score achieved on the design was 0.5 compared to a normal building design that in the Netherlands should have a maximum MPG of 0.8 to 1.0. The MPG is a Dutch mandated calculation method for indicating the environmental impact of the materials used in a building. A lower the MPG score, indicates a more sustainable the building.

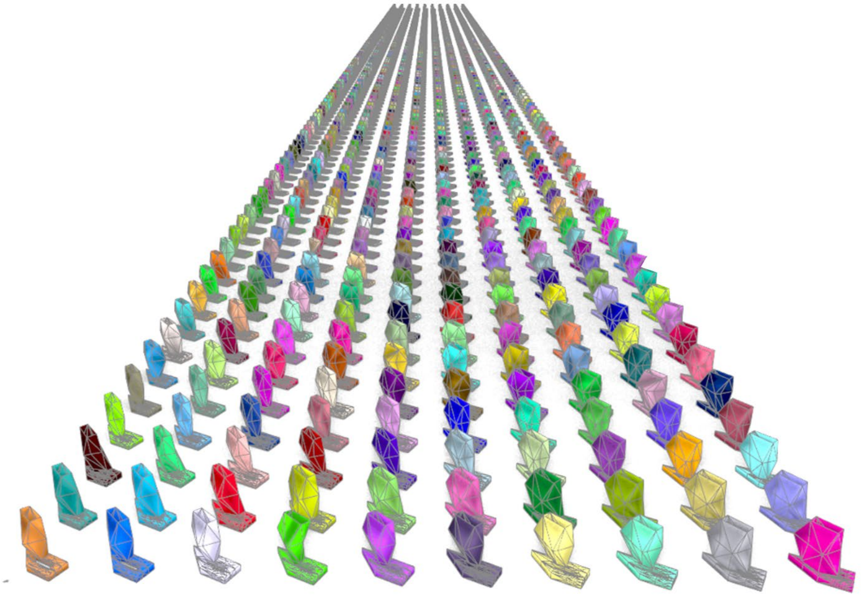

Figure 8. Design variants (© Arup)

The greatest benefit of a multidisciplinary parametric design is that you can add and assess as many KPIs as required. Engineers could include circular economy principles and regenerative objectives into our designs. Making use of multidisciplinary parametric could be the enabler of this. Designers could eliminate waste and pollution, by implementing modular and/or prefabricated systems into our framework, by building up our massing or geometry by using these systems. In this way waste and pollution can be reduced [WRAP]. Making use of informed visualisation dashboards could help in making those design decisions. In Figure 9 a multidisciplinary modular design is explored and rated on multiple KPIs. The dashboard helped the design team to choose the most suitable design.

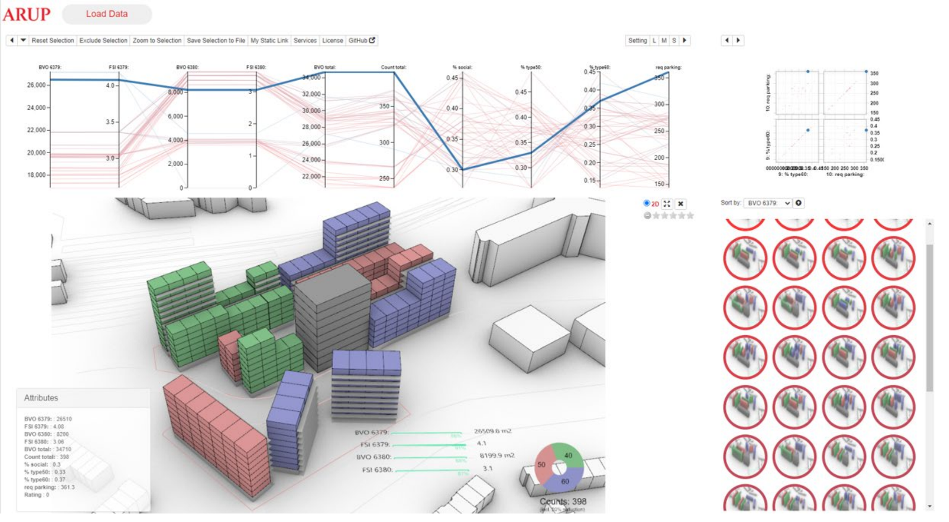

Figure 9. Informative visualisation dashboard of modular design (© Arup)

2.3 *Topology Optimisation*

By observing the evolution of natural structures such as osseous tissue, it becomes obvious that the material distribution of such structures achieves their optimum over a long evolutionary period and adapt to the environment (Jeronimidis, 2004). Imitating this adaptive process of biological structure, topology optimisation has been developed to optimise material layout with various techniques and theories (Michell 1904, Schmit 1960). The well-developed gradient-based optimisation algorithm has been adopted by many optimisation packages to optimise mechanical or structural objects (Schumacher 2005). By assuming a design domain subject to a set of boundary conditions, the optimal form can be predicted with iterative computation subject to the prescribed performance targets when all the design constraints are satisfied.

The application of this method within a complex design context was explored by Arup in 2014 with the Arup node research, focusing on bespoke steel node design connecting the cables to the struts of a tensegrity structure (Fig. 10). The interest in the usage of topology optimisation method to redesign the conventional node relies on the fact that by employing such techniques, it is possible to consistently integrate customised node design, structural efficiency, and weight reduction.

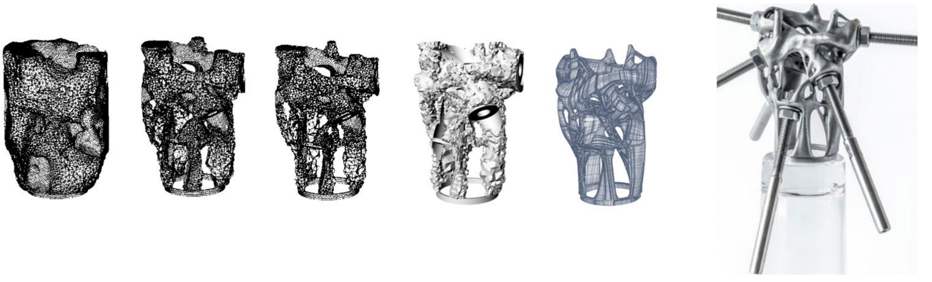

Figure 10. Topology optimisation process of the Arup AM metal node (©Arup)

The central volume in the shape of a cylinder was defined as the main design space with several internal access openings. Topology optimisation was performed with the design objective of minimising the total structural weight. As shown in the figures, starting with a solid 3D mesh within the entire design space, elements which were less loaded were identified at each generation. The node gradually evolved to an organic form with the most efficient load path for the given design forces. In this iterative way, topology optimisation allows for an integrated design and optimisation process achieving high level of material efficiency (Ren, 2015). Further structural verification indicated that the node with the optimal shape reduced the weight from 20 kg to 5 kg, while still ensuring sufficient structural capacity needed for the design.

Topology optimisation is not only for the design of small components, but also bears the potential to be implemented for larger scale structures in the built environment. During the steel roof design of the National Maritime Museum of China, Arup implemented this method to solve the design challenge of optimising the diagrid truss layout under the demanding seismic actions (Fig. 11 and 12). The design of the steel roof consists of single curved trusses with diagonal circular hollow section members as the lateral load path. Starting from the original design with diagonal members distributed everywhere over the entire roof, an iterative algorithm was developed to optimise the material distribution of the diagrid topology while meeting the requirements of the serviceability limit state. Through the optimisation carried out, the design team managed to reduce the total steel tonnage by 20% and managed to deliver the schematic structural design in just 6 weeks despite all the design complexities within this project.

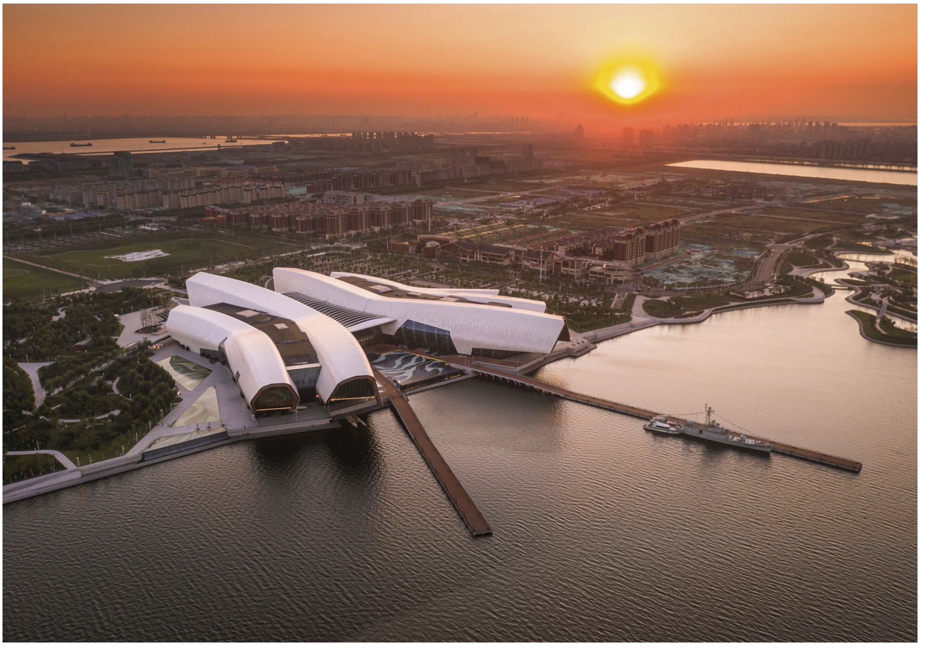

Figure 11. National Maritime Museum of China (©Cox Architects)

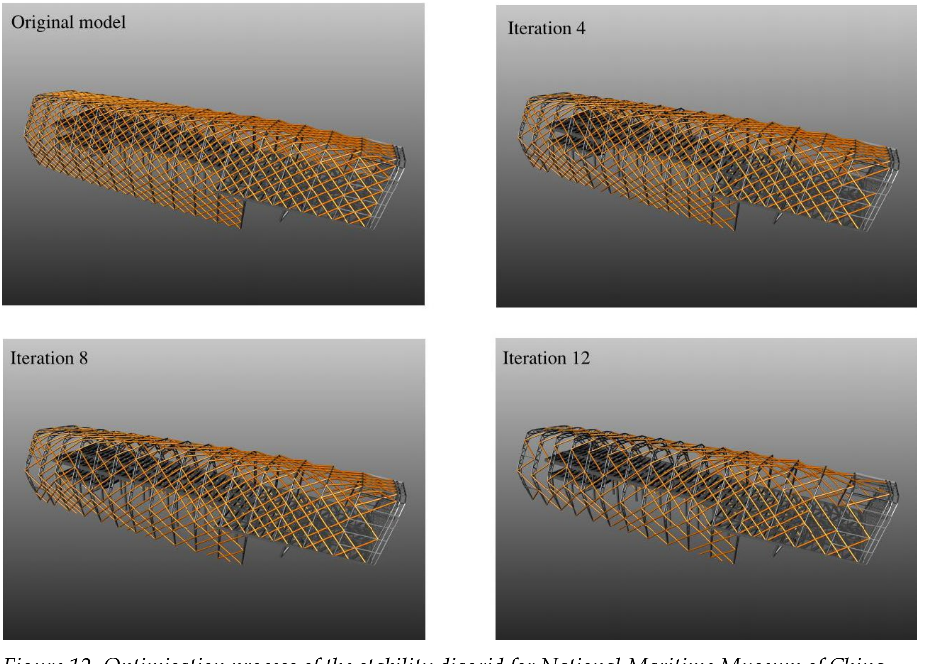

Figure 12. Optimisation process of the stability diagrid for National Maritime Museum of China (©Arup)

As shown in the examples above, topology optimisation has great potential when used to find the optimum shape and size for structures under complex constraints, which leads to weight reduction and shape efficiency, and helps to dramatically minimise the environmental impact of structural designs.

2.4 ***Automation***

Automation can be described as a process where the human intervention is reduced [IBM, 2021]. In design terminology, automation enables the designer to re-use engineering knowledge and intent [Autodesk, 2021]. Automation can increase the quality of project deliverables by improving consistency, reducing errors, and providing automatic checking. Besides, automation can reduce time spent on repetitive tasks and therefore free up more time on the more challenging and interesting areas of projects. By using automated processes, the designer is also able to explore a wider range of potential solutions and optimise outcomes of our clients.

For decades structural engineers have been using computers to automate the analysis of a structure. Automation for structural engineers can be used on various aspects, from model generation and design checks to automatically creating design reports. Over the past years Arup has designed many steel platforms for a specific client. The client requested steel tonnages in the concept stage of the design, but also wanted the structure to be as efficient and flexible as possible. By automating the workflow from setting up the structural model to reporting and communicating the outputs to the client, the design efficiency was greatly improved by eliminating the repetitive process and ensuring high quality of the design. Figure 13 shows the interface of the automation workflow that integrated analysis, data processing and design communication.

Engineers also have complex workflows which need to cater to each project's unique set of requirements. There are opportunities for unitising workflows where all projects can benefit from the same process. The figure below proposes an automated structural design workflow, where the project starts from the Digital Design Brief, a centralised location where all the project parameters are stored. From that brief the whole process is started. The 3D model is generated as the single source of truth. This information can be transferred with Speckle [Speckle, 2021] to automatically obtain structural analysis models. These are linked to result databases and Eurocode Design Check libraries to check the structural elements. This can all be pushed into the report platform to complete the workflow.

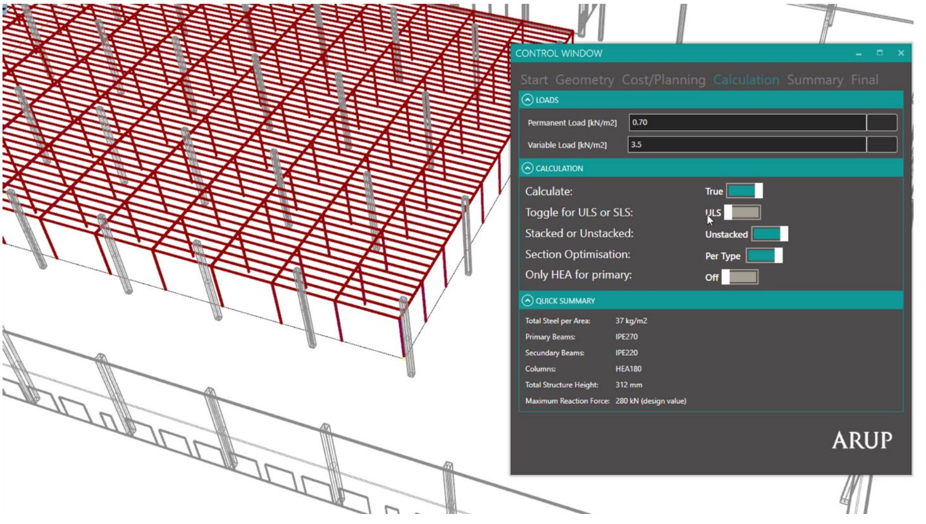

Figure 13. Automated steel platform design (©Arup)

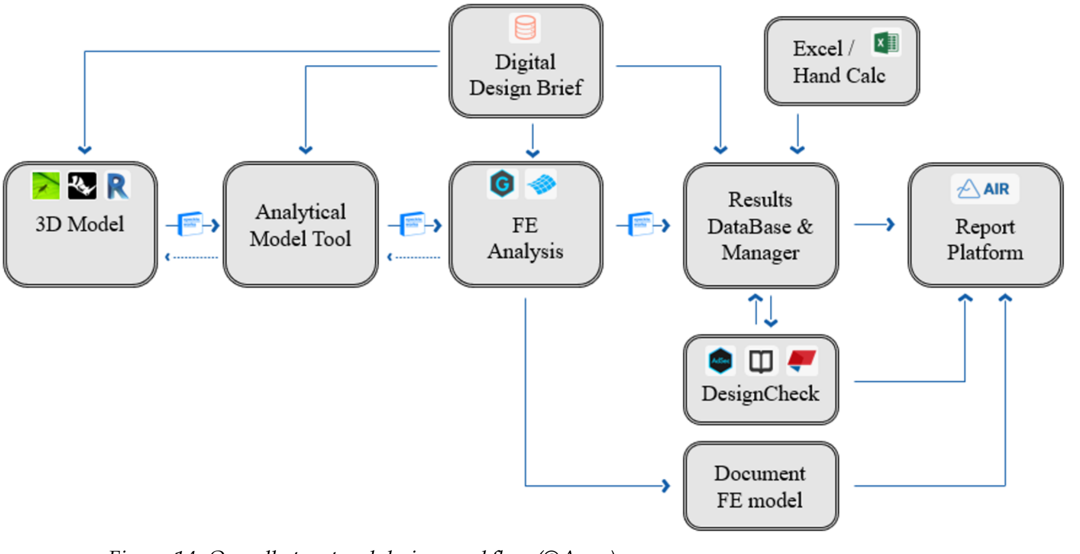

Figure 14. Overall structural design workflow (©Arup)

Automation and improved use of data becomes valuable when designers address them as core aspects of their workflows. As shown, it can save time and improve the quality of our industry, reduce failure cost of projects, and catalyse innovation. By this it can significantly contribute to a net zero industry.

2.5 ***Digital Fabrication***

With the rapid development of disruptive digital technologies and emerging production methods recently, architectural, and structural designers are constantly informed by new opportunities to rethink the design process and to calibrate among shape, material, performance, and production. Digital fabrication, as a way of using digital data to control a fabrication process, has spurred a design innovation between design and making [Iwamoto, 2009]. With the process of additive or subtractive manufacturing, digital fabrication enables the freedom and possibility of fabrication for components with highly complex shapes and various functional requirements. These technologies enable the creation of parts with high-level efficiency and allows for new opportunities for waste reduction and material reuse in a circular context.

The term Additive Manufacturing (AM) refers to a whole set of different production techniques and the process of joining materials layer upon layer from 3D model data [ASTM, 2009]. Over the past years, Arup has extensively investigated various AM techniques, including, among others, Robotic Wire Arc Additive Manufacturing (WAAM) and Selective Laser Sintering (SLS) for metals.

Arup's collaboration with MX3D for the design of MX3D bridge started in 2015. Being the world's first 3D-printed steel bridge, the graceful bridge spanning 12.5m was produced using WAAM in stainless steel. Although the technique of using the electric arc as a heat source to weld objects has been available for a long time, the freedom allowed by this technique could bear huge design potentials and opportunities when used for the built environment. With the idea of making a robust design and simplifying the number of structural members and connections, a structural scheme with an organic bone structure was developed with a generative form-following-force process. Under a set of loading and support conditions, the information of distribution and orientation of the principal stress trajectories generated were generatively linked to the overall shape of the bridge (Fig. 15). This allowed the engineer to identify the efficient load path and to steer the design development from a straight U-shape bridge at the beginning to the final S-shape bridge as shown in the figure below. With this information, the topology of the main load bearing structure of the bridge, including six longitudinal beams and seven transverse beams under the deck, as well as two web structures, was defined responding to the flow of the forces.

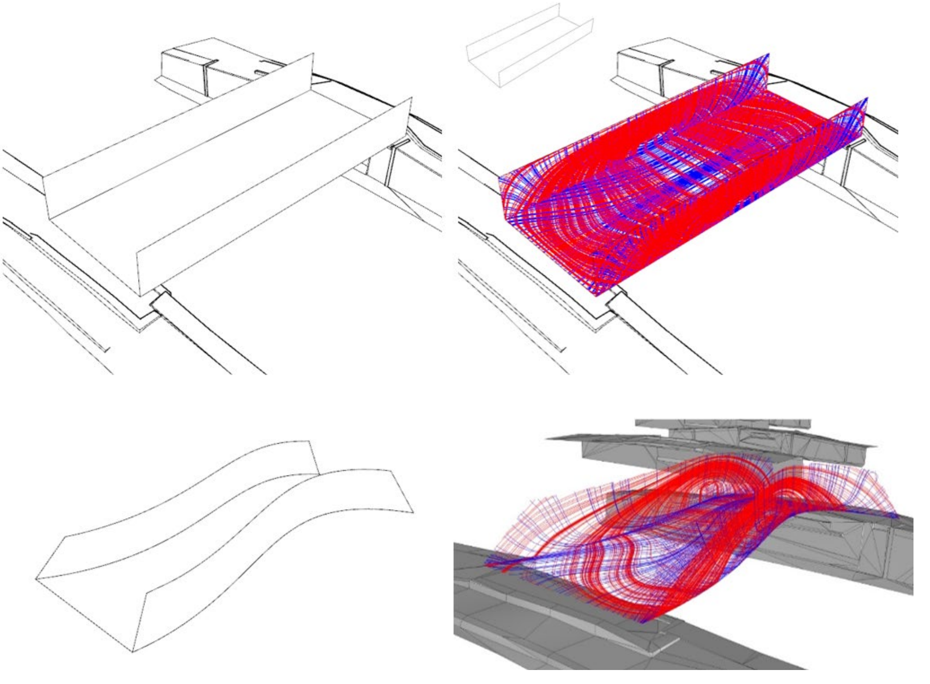

Figure 15. Structural form-finding with the stress lines of MX3D bridge (©Arup)

With the challenges brought by this new printed material, Arup also helped to define a thorough testing programme to outline all missing information one would need for the purpose of the structural assessments, including testing carried out at three levels from material test, element test, to full-scale final test to verify the stiffness and strength. In July 2021, the bridge was installed at the Oudezijds Achterburgwal canal in the centre of Amsterdam and was opened to the public (Fig. 16).

Rather than adding in layers with WAAM, subtractive manufacturing involves removing sections of a material by machine such as computer numerical control machine (CNC) in three dimensions. The cuts are smoother compared to additive manufacturing and the process is usually more cost-effective with the use of the traditional sheet or block materials.

Figure 16. MX3D bridge at its final position (©Theavandenheuvel)

For the recent Theater Zuidplein project at the South neighbourhood of Rotterdam, Arup and the architect StudioRAP designed the enveloping acoustic wall, which features 6000 bespoke robotic-fabricated panels, resulting in a wrap-around atmosphere for the main hall of the theatre (Fig. 17).

The geometrical complexity of the design called for a holistic solution integrating shape, acoustic, structural, and fabrication logics. This was approached with a total digital workflow by all the stakeholders through the entire design from sketch to the final digital fabrication and installation.

The optimisation of the acoustic wall was steered by an algorithm-driven sound shaping process. With the setup of the design parameters and acoustic requirements related to sound reflection and diffusion, the global shape of the wall, as well as the tessellation pattern and placement of all the 6000 panels at different angles, were optimised through iterating thousands of different options automatically.

A structural parametric model was integrated as part of the total digital process, allowing the engineers to quickly assess the global structural performance, and to define the structural rules parametrically for further detailing the unique panels and their connections. Following that, the 3D tessellation of the design was then translated into the 2D nested pattern with a file-to-factory workflow optimised for CNC cutting, creating all the pieces differently while reducing the waste. Scoring cuts were also made, with which the single panel could be folded precisely along the three edges. After that, multiple folded panels were assembled into one larger unit to gain overall structural stiffness.

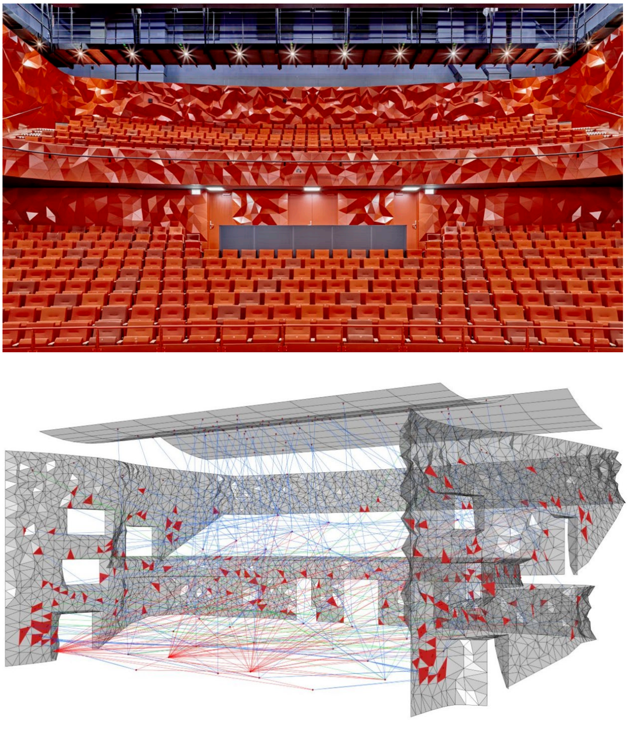

Figure 17. Parametric design and optimisation of Theater Zuidplein Rotterdam (Left: (© Pim Top; right: © Arup)

In the end, one single digital workflow was made and used by all the stakeholders. Thanks to this, the team could make the 6000 unique panels, and 2800 structural connectors, within time and budget, but also stayed flexible in terms of changing the design at a very late design stage (Fig. 18).

Embracing robotic construction techniques opens a whole new dialogue in terms of reducing material waste and what the built environment can look like in the future. In this way circular design could be realised through design and fabrication facilitated by parametric design, optimisation, and digital fabrication to maximise the material efficiency and to reduce the waste, while still ensuring the design criteria in a multidisciplinary context.

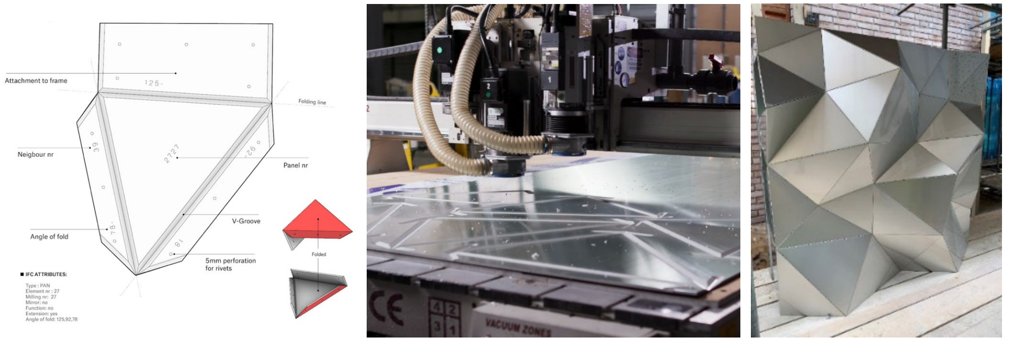

Figure 18. Digital fabrication with CNC and the mock-up (Left and middle: © StudioRAP & Aldowa; right: © Arup)

2.6 ***Digital for Materials Integration***

The convergence of digital and materialisation is becoming easier with the emergent technologies and computational methods these days, integrating the virtual process of design and analysis with the physical realisation of a concept. Digital provides a powerful agency for both informing the design process through specific material characteristics, and in turn informing the organisation of material across multiple scales [Menges, 2012]. This facilitates a material-driven design process which promotes the material efficiency and allows for easier deployment of irregular materials.

For the Flemish-Dutch wall pavilion of Frankfurter Buchmesse 2016, the architects from Civic & Matters (The Cloud Collective) were interested to use the reusable semi-transparent polycarbonate panels to build a wall pavilion, inspired by perceptions of the similar landscapes of the Low Countries. As the polycarbonate material chosen has unique layered patterns and varied densities, the material characteristics played an essential role during the design and engineering process (Fig. 19).

The Arup team helped to develop the design principle by stacking the polycarbonate panels as ‘bricks’ and connecting them with prestressed cables. Because each wall has been designed as a free-standing structure gaining its stability by its own material distribution and hook-shaped geometry, a digital workflow was developed to bring the design parameters together with the structural stability evaluation. The stacking pattern and the panel dimensions are specially optimised to be adaptive to the shape of each wall. With this digital workflow, the design team could determine the optimal result in view of the various design parameters for the walls and the material system, such as shapes, thickness, height, angles, openings, material density and pattern of the panel layers (Fig. 20).

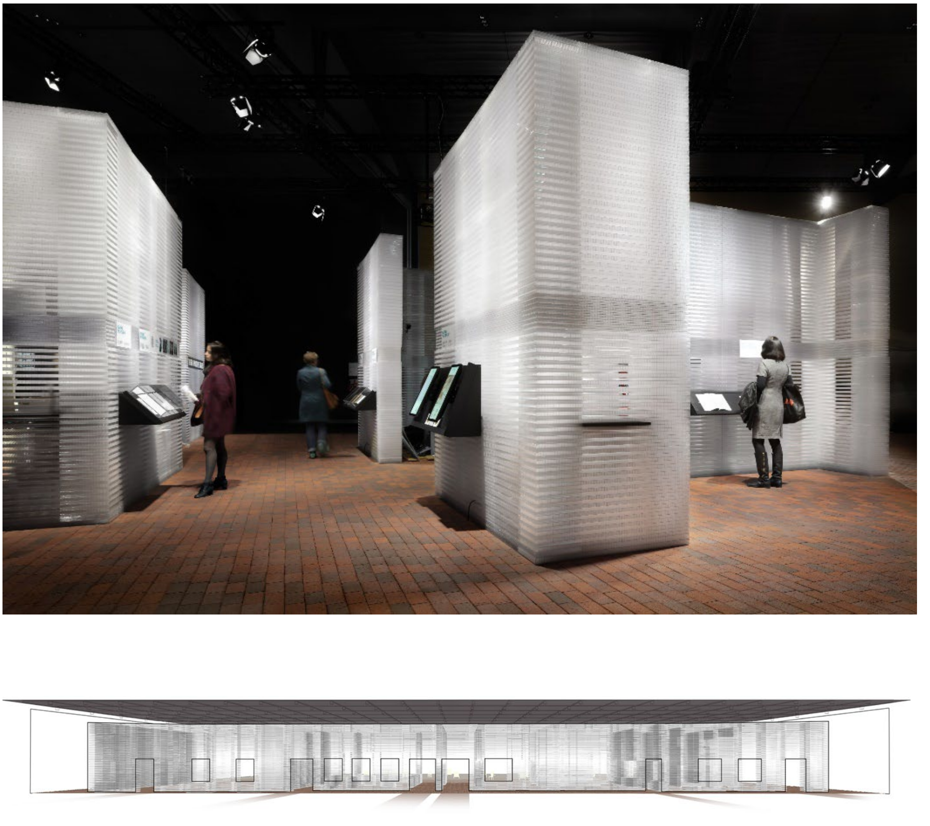

Figure 19. Frankfurter Buchmesse Pavilion (©Civic Architects, The Cloud Collective)

DoubleFace 2.0, another wall design project led by TU Delft with several companies including Arup as the design partners, a digital workflow informed by an innovative material system for a multi-functional solar wall was investigated. As an adjustable and translucent Trombe wall, the system used Phase Change Material (PCM) for heat storage, and aerogel as an insulator, encapsulated in an optimised hollow wall produced by robotic

FDM printing. The PCM stored in the system could store and re-radiate solar heat for heating in winter, and capture internal heat for cooling in summer, allowing for passive indoor climate control [Tenpierik et al., 2018].

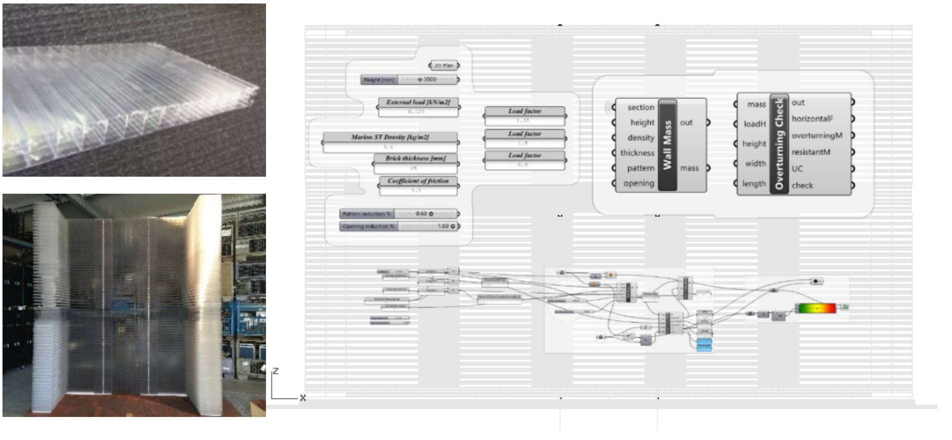

Figure 20. Mock-up and digital design process of Frankfurter Buchmesse Pavilion (©Arup)

The overall geometry of the wall, as a container of the PCM, is produced with the material PETG by a 6-axis robot with stereo-lithography in a wall thickness of approximately 3-6 mm, providing the overall stability of the wall (Fig. 21). One layer of aerogel is also

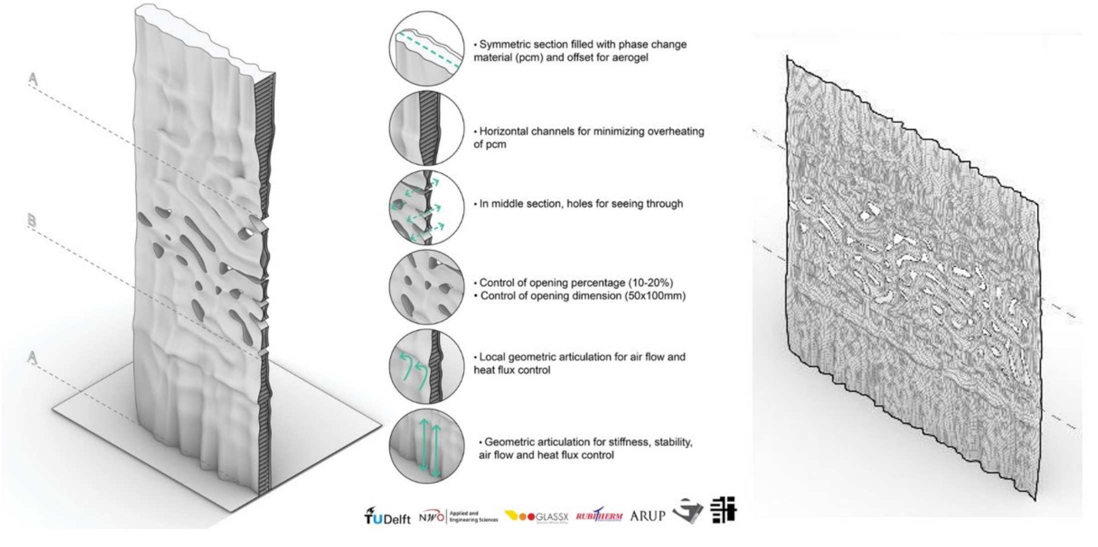

Figure 21. DoubleFace 2.0 Solar Wall 3D diagram (©TU Delft)

applied at one side as insulation layer, with the PCM on the opposite side to protect it from heat source as a composite layer-system.

For the design of the DoubleFace 2.0 wall structure, a digital framework was developed by the teams, including the thermal and robotic printing parameters developed at TU Delft, and a structural module developed by Arup which can perform the strength and overturning stability check parametrically. This digital process is meant to facilitate the engineers to gain insights on the relations among geometrical parameters, material distribution and the resultant structural performance oscillations and to integrate the engineering performances within the design process (Fig. 22).

Figure 22. DoubleFace 2.0 Solar Wall full-scale mock-up (©TU Delft)

Materialisation through advanced digital design and fabrication technology opens up new opportunity to integrate material characteristics in a materially efficient manner and allows for easier implementing of irregular material in the built environment. This helps to release the potentials of material at various scales and leads to a sustainable bottom-up design approach.

2.7 **Data-driven Design**

Data-driven design or engineering can be described as informative design backed up by data or where data plays a significant role in the design process. It strongly links to previous paragraphs such as parametric design and automation. In both those digital technologies data is key in the process or workflow. In design work it is also essential to share data and collaboratively explore ways to sustainable design. By collecting and storing data in databases, design decisions can be made based on new ways of visualising alternatives.

The built environment holds the key to drastically shift from a 'take, make, use, dispose' linear model of production and consumption to a circular economy, to keep materials, components, products, and assets at their highest utility and value at all times [Pajula et al., 2017]. The overall goal is to minimise resource use, eliminate waste and reduce pollution by designing and producing more durably, and thinking about repairing, refurbishing, disassembling, and reusing materials. Arup has set up an assessment tool based on a database of calculations of complete build-ups of elements to assess the circularity on an integral scale. The goal is to explore and inform clients to come up with the most efficient and suitable options fitting the project needs.

Circular decisions are extremely impactful on costs and risk of a project. Existing environmental impact calculations require an extensive bill of materials or a detailed BIM-model. Generally, circular decisions are not about replacing one material by one that is more circular. It implies changing whole element build ups and transitioning from traditional methods into new circular building methods.

This requires the need for a quick assessment tool on building element level, which is the Circularity Builder that connects multidisciplinary properties to building elements. The Circularity Builder is a digital circularity assessment tool on element-, building- and portfolio level. In Figure 23 the Circularity Builder is shown, in which design teams can make holistic decisions for element build ups in a building design.

The users of the tool can interact by filtering structural span and loads for example. In the back end of the tool, that information is linked to calculation packages that are stored in an Arup library called DesignCheck. The alternatives that are generated are stored in a database and even on a project level the overall score can then be calculated (Fig. 23, 24).

The Circularity Builder enables designers to make informed decisions by comparing, filtering, and choosing element build-ups based on quantitative circularity scores.

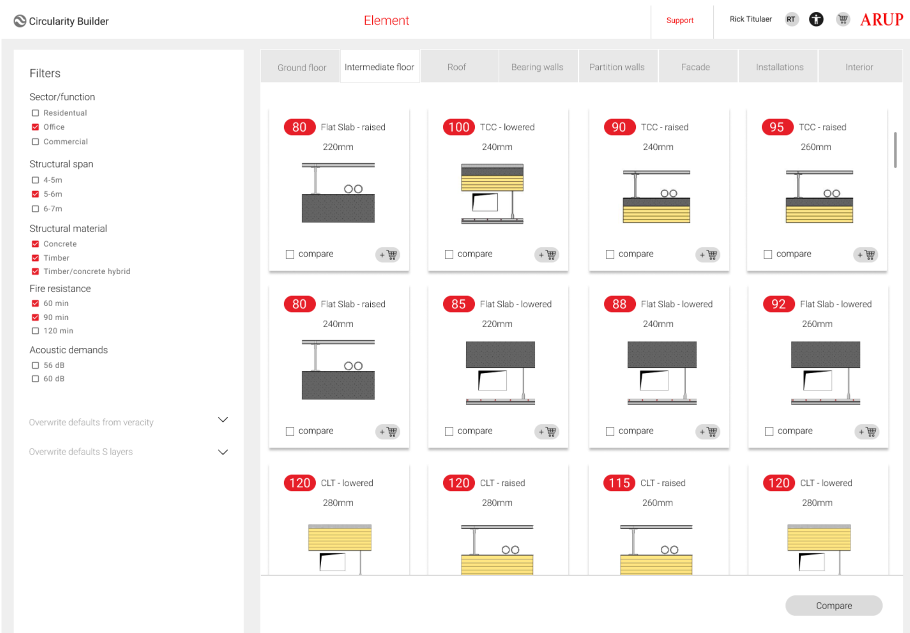

Figure 23. Circularity Builder (© Arup)

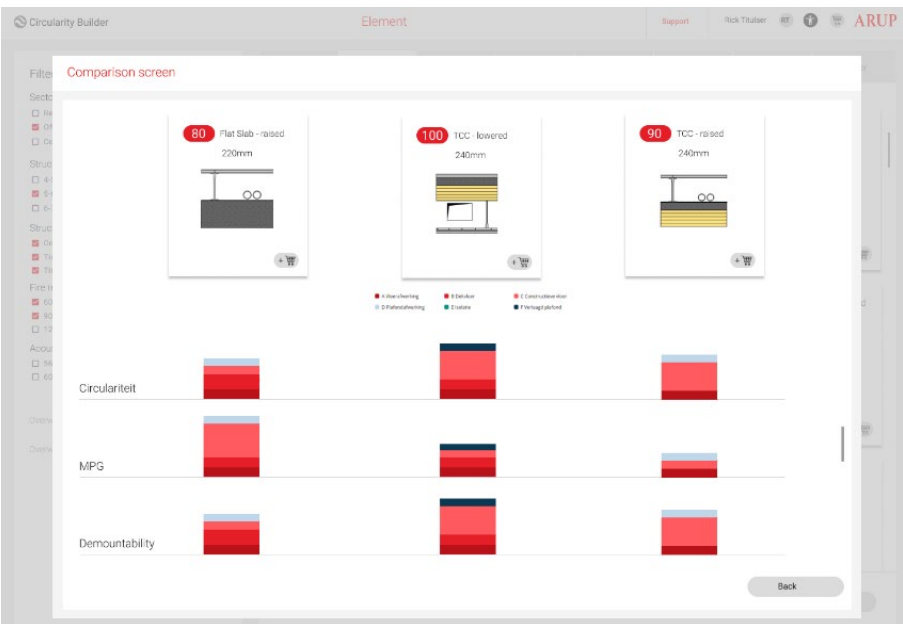

Figure 24. Comparing element build-ups (© Arup)

3 Looking forward

The development of digital technologies and their application as presented in this paper demonstrate the value and are paving the way for the future built environment. These technologies allow engineers to explore the design space, push the boundaries and find the most optimal holistic solution in a rapidly changing environment.
However, there are also challenges ahead.

In parametric design, the engineer needs to transfer from a traditional mind-set of analysing a few iterations or alternatives into learning how to programmatically define the logic of the design and understanding the relations between various parameters. By connecting input and output together using an algorithm, the engineers of the future can explore unlimited possibilities. On the other hand, they must be careful. The number of design variables exponentially increases the design space. And the larger the design space under consideration, the harder it will be to assess and to find the most suitable design. Parametric computational design needs to be seen as a means to an end instead of a goal in itself to designing for a net zero built environment.

Automation promises an exciting way forward, but admittedly, there are challenges along the way. Engineers have to operate a catalogue of bespoke design and analysis applications that need to exchange information across one another and coordinate information across multiple disciplines and parties. The key is data transfer and storage. Future engineers and designers will need to capture and store data to stay in the game. Machine learning and artificial intelligence can only be used when there is a large enough data set. The challenge lies in storing the data in a consistent way so that it can be used in the future for data analysis.

While most of the available digital technologies focus on optimisation problem solving, the challenges for the structural engineers remain at the intersection of optimisation problem formulation and including other relevant design criteria.

In all these technologies described above, structural engineers hold the key to a sustainable future by exploring new ways of thinking, embracing new construction methods, and designing beyond their traditional expertise. Digital technologies offer exciting potential and new operative mediums to contribute to the integrated design process and to rethink the design considering the complete building life cycle to gain a holistic view of the environmental impact of a structural system. Some materials might have larger footprints from raw material to production, however, could be reused or recycled at their end of life. It is important to get the whole supply chain together to identify overlapping obstacles, remove the barriers, and show the opportunities.

4 Conclusions

This paper provides an overview of various digital technologies by looking at some of the recent key developments. The digital technologies show huge potentials and value to be used by structural engineers to meet the design aims through all design stages and to shift our understanding of the engineering process. It demonstrates the new opportunities for the building industry to achieve a net zero built environment.

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Chronological project credits

Camp Adventure Tower

Client: *Camp Adventure Developments*

Architect: *EFFEKT*

Structural engineer: *Arup*

Contractor: *Levi Jensen*

Elements

Client: *Kondor Wessels Vastgoed*

Architect: *Koschuch*

Structural engineer: *Arup*

Key consultants: *Boom Landscape, Buildung, HVTC*

AM metal node

Structural engineer: *Arup*

National Maritime Museum of China.

Client: *Chinese Government and Tianjin Municipality*

Architect: *Cox Architects*

Structural engineer schematic design: *Arup*

Key consultants: *Tianjin Architecture and Design Institute*

MX3D bridge

Client: *City of Amsterdam*

Architect: *Joris Laarman Lab*

Structural engineer: *Arup*

Robotic Fabrication: *MX3D*

Key consultants: *Autodesk, ArcelorMittal, Force Technology, Imperial College London, Air Liquide, ABB Robotics, Heijmans, Lenovo, The Alan Turing Institute and Lloyds Register Foundation*

Theatre Zuidplein Main Hall

Client: *City of Rottterdam*

Architect: StudioRAP

Acoustic and Structural engineer: *Arup*

Contractor: *BAM – Ballast Nedam*

Fabricator: *Aldowa*

Frankfurter Buchmesse Pavilion

Client: *Frankfurter Buchmesse*

Architect: *Civic Architects, The Cloud Collective*

Structural engineer: *Arup*

Contractor: *Uniplan*

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