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What is the legacy of Structural Design Expertise? The Parametric Design Approach to High-Rise Buildings

Denis ZASTAVNI*, Mark P. SARKISIAN [a], Jean-Philippe JASIENSKI [b], Luca SGAMBI [b]

*SST/LAB – Louvain research institute for Landscape, Architecture, Built environment [LAB]
UCLouvain – Faculty of Architecture, Architectural engineering and Urbanism [LOCI]
Place du Levant 1 (L5.05.02) - B 1348 Louvain-la-Neuve (Belgium)
denis.zastavni@uclouvain.be

[a] SKIDMORE, OWINGS & MERRILL, One Maritime Plaza, San Francisco, CA 94111 (USA)

[b] SST/LAB and Faculty of Architecture, Architectural engineering and Urbanism [LOCI], UCLouvain

Abstract

Some structures from the past such as large bridges constructed during the industrial revolution demonstrated rare qualities of efficiency and aesthetic character. These bridges were designed based on the fundamentals of engineering, where mistakes or inefficiency was irrelevant in the structural design. Today, high-rise buildings have similar structural challenges and potential opportunities of expression. Some of these buildings are among the most complex in the field of structural engineering and required fully integrated design approaches.

Particularly with a height of 500m or more, designers face challenges in developing the most efficient solutions for these complex structures. For the student or junior engineer, a design exercise has been created and experimented considering full sets of sequential operations to complete the design. After reviewing the development of engineering sciences and engineering education, the paper presents a design exercise based on parametric design, interactive numerical analysis, comparative design and environmental assessment to provide architecture-engineering students with a complete design expertise, with the main benefits that can be gained.

Keywords: Structural Design, Research by Design, Parametric Design, Environmental Assessment, Structural Dimensioning, Integrated Design

1. Introduction

Transmit knowledge and know-how for structural design will remain in any circumstance a complex exercise. On the one hand, a real skill on structural design presupposes a long and careful training involving the candidate to solving on several design exercise. On the other hand, structural design is frequently confused with structural analysis and skills on design convey far more aptitudes than structural analysis only as drawing skills, mastering approaches of geometries, analysing construction methods and so on.

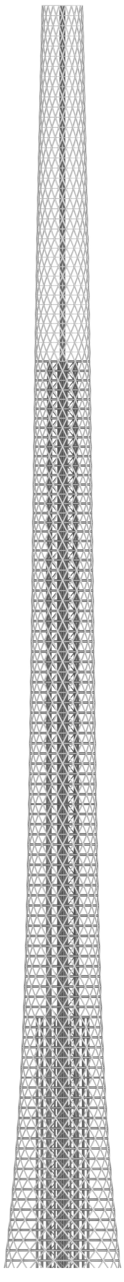

Figure 1: design by Bongen + Georges for LICAR-2711, 2020

This paper will question several of these constitutive elements and feedback some approach recently developed to transmit this skill of structural design.

First this paper will present some time benchmarks in the development of engineering school.
It will stance the difference between the academic view of the topic of structures, the code view and the designers' view. Famous example of academic brilliant discoverers in Mechanical Sciences who designed structures that failed or represented a problem are not exceptional. For instance, Henri Navier who formulated the general theory of elasticity in a mathematically usable form [6] in 1821 or Ernst Suter, who developed in 1916 [15] the technique of the fixed point to analyse statically undetermined structures as continuous girder or frames, both designed structures that presented issues [16]. This paper will the present in detail the successive steps that are followed to train students to structural design and avoid main obstacles to this.

Finally, it will make parallels with the approach of 'research by design' methods that echoes a series of methodological approaches that are used for the presented teaching experiment, and show multiple convergences.

2. The architect, the engineer and the designer

The profession of engineer appeared with the development of the so-called Applied Sciences, where mathematics, physics and chemistry were applied to the study and resolution of concrete problems which are today the domain of the engineer. These problems include those of the stability of buildings and engineering structures, using, among other things, the new materials of the 19th century, such as cast iron, steel and, later, reinforced concrete. The use of these materials led to a completely new way of looking at structures for the time, in terms of beams, frameworks or even more complex systems. Architects, who were more inclined to academicism, followed different paths from those of engineers who, for construction, invested in the Mechanical Sciences and the Resistance of Materials as a unique and primary truth.

A fact that led to the development of the profession of the engineer is the use of iron and cast iron in construction. Up to that time, construction was made of stone, clay bricks and timber and it was the prerogative of the architect to design the building and its structural system. Etymologically, the architect – *αρκη* expressing the extreme degree, "the one who comes before" and *τεκτων*, worker [1, s.v. *archi-* et *architectecte*] – is the "first worker ", the builder par excellence, who masters all the means of the Art of building. The distinction between architect and engineer would therefore be artificial, the result of a difficulty in mastering, without specialisation, all aspects of the Art of building.

This need for specialisation emerges with the increasing complexity of the types of constraints to be integrated in the course of an architectural project or a work of art. It also arises, probably, from the difficulty of reconciling, in the same person, high-level technical approaches with more informal qualities, sometimes associated with the architect's "artist" status; architecture being considered as the major discipline of the Plastic Arts (Arts of space).

3. Historical references in the training of engineers.

From antiquity to the Renaissance, the mathematical sciences, the mother of physics and applied sciences, took a rather different form from what we consider mathematics today [13]. The development of algebra dates from the Renaissance, and analysis is even later. Before that, mathematics was essentially a science of geometry, which also solved most of the arithmetical problems that the numbering of the time made complex. The mathematics is the science of order and quantity, which becomes measurement as soon as it is applied to concrete objects [1, s.v. mathématique]. And measurement has a lot to do with construction and architecture. So much so that the description of a building such as Solomon's temple in the Bible is made only with the help of numbers. These bases can explain the development of proportion rules in architecture and further development of Graphic statics.

Mechanics only appeared in the 17th century. But Archimedes (~287 - ~212) is generally credited as the founder of the mechanical sciences, knowing the law of the lever (sufficient to determine the reactions of a simple beam). After him, Leonardo da Vinci (1452-1519) knew the equation of static moments. The notion of moment in mechanics is however stated by Pierre Varignon [3], who also establishes the law of composition of forces, obtained however graphically. Galileo Galilei [4], also known as Galileo, was one of the first to try to use mathematics to solve the concrete problem of the resistance of a problem of the resistance of a beam. He is in this respect the father of the Resistance of Materials. The Theory of Elasticity, which considers the properties of proportionality between force and deformation (Hooke's law [5]) shared by many materials, is the heart of Structural Mechanics. With it, it becomes possible to calculate the deformations of structures, but above all to solve - at least in theory - most of the problems of structural design. One of them is that of statically indeterminate structures, also called hyperstatic. The concept of hyperstaticity emerges in the work of Henri Navier [6], precisely the one by whom the Theory of Elasticity was established as a science of structural design, the one by whom the Theory of Elasticity was established as a science of structural calculation.

Some architects [7, 8, 9] worked on giving a rational, scientific background to the analysis of structures. It is known that in the Middle Age a certain knowledge in between proportion rules and geometrical methods were used to give their form and shape to structures were kept secret in masons' corporation. Heyman [10] showed the nature of certain of these rules at the occasion of the expertise on the cathedral of Milan. Some of these rules of proportions took the form of architectural styles (Doric, Ionic, Corinthian, Classic, etc.) that, once respected, guarantees a certain form of rational dimensioning, and hence of safety for buildings.

Renaissance times brought some rules to be revealed and in the same time some scientific works started to develop a science of the dimensioning [11], as in the work of Galileo [4], for instance. It was the role of the architect to master the building process and hence the structural safety. Even in the late 19th century, architect's plans integrated dimensioning elements that were not reviewed by engineers. Nowadays' architects' plans are accompanied by engineer's plans to describe in detail the structural components, the first becoming relieved of the responsibility of the structure, and the latest becoming responsible for the stability of buildings.

Engineering schools appeared in France in 1716, when Jean-Rodolphe Perronet founded the École Nationale des Ponts et Chaussées. Prior to this, engineering was the preserve of the military elites, who necessarily belonged to the nobility [2], or was the domain of empiricism and the undisclosed knowledge of the construction guilds.

The founders of these schools were scientists who developed a rational approach (a science) to the study of structures. From the eighteenth century onwards, the main contributions were made in France, Italy and England by Pierre Simon Girard, Jacob Bernoulli, Leonhard Euler, Henri Navier, James Clerk Maxwell, Alberto Castigliano and Enrico Betti [12]. All of them contributed to the progress of mechanics, and in particular the discipline of Static. Engineers attending the Polytechnic Schools were thus trained in the analysis of structures based on mathematical analysis and the Resistance of Materials. Thus the 19th century became the century of engineers, who designed and calculated structures of never-before-seen shapes and sizes, using iron and cast iron.

This context, and the training courses associated with it, have created the conditions for the transmission of knowledge useful to the practice of architects and engineers alike. However, many design courses in the schools of the two professions turn out to be courses in the application of this knowledge - or even the application of calculation codes - for all purposes of structural analysis. However, the exercise of structural design is much more extensive and difficult than the subject of structural analysis alone.

4. Structural analysis – design by analysis

The most basic aspect of the construction engineer's work is to ensure the stability of the form presented to him, while at the same time defining the amount of material to be used to achieve this. The method he follows is therefore analytical: by calculation, he determines the forces in the zones of concentration of material that the designer of the form has defined for him. From these forces, he calculates the dimensions to be used and the assembly methods. For an engineer working in the contemporary context, with extremely powerful calculation means at his disposal, the analytical difficulty is most often evaded.

In this approach, the central role is played by the calculation, whether for structural analysis or the calculation of cross-sections. Consequently, it is in the construction of the necessary model, and the ensuing calculations, that the engineer will spend most of the study time. The zero degree of this activity is to use elements pre-calculated in an abacus or by a pre-manufacturer, to graft them onto the work being designed. Without going to this extreme, it can be seen that the engineer is often reduced to a passive attitude in the work of "designing" a structure. His job is to solve the problem of the resistance of a spatial arrangement imposed by others or by a partially arbitrary choice. The results of the structural analysis and dimensioning can lead to problems of compatibility with the planned forms. This is where the work of refining the proposed solution must begin. The distribution of the material in the structural work changes its behaviour, and the work must again be modelled in an updated manner. This model is then the subject of a new analysis, and so on.

It is therefore the forces obtained by the analysis that define the amount of material needed to resist them. Since the formal result of this work is not known a priori, the process is essentially guided by calculation, with the analyst serving the process. He is thus subject to the vagaries of the detail of his models and his method of calculation. The question of the structural model's nature, and its relevance, must be regularly asked. The trap of the young engineer is to build the universal model that will accurately reflect the structural behaviour of the structure, its "digital twin". The more complex and accurate the model, the less practical it is for effective structural analysis... and the less useful it is for structural design. Ultimately, it is useful for validating a structure whose design is finalised. In Germany, this is the prerogative of the "*statiker*", the verifier, who is not the engineer. A poorly designed model will lead the design process to an inappropriate set of structural stiffness which may lead away from the initial model. The design of the structural model to analyse the structure is therefore a matter of knowledge, sensitivity and experience that requires specific learning.

For the analyst, the importance of the accuracy of the model and the numerical result is therefore essential, since it is on them that the 'structural truth' of the object being analysed rests. The analyst cannot understand, therefore, in view of the importance to him of the accuracy of the mathematical result, that a designer uses a simplified method for the calculation of the structure. The analytical approach is suitable both for a certain form of "design" and for the verification of structures. It is in this latter mould that the standardisation of structural design is formed. When the engineer is the designer, his role is naturally more active. In this case, the engineer himself proposes the structural scheme that initiates the cycle of successive analyses and dimensioning.

5. Structural design

Structural design is a complex process that extends from the first sketches of a structure to the validated drawing of its form and details. This design work becomes even more complicated when it is integrated into a building, with the specific constraints that this entails. It then becomes, ideally, an integral part of the architectural work on the structure.

Designing structures for an engineer is a complex exercise with approaches that may considerably vary [13]. The minimal requirement for the engineer is to create a structural design that meets the requirements of code. This approach presupposes that the structural behaviour is well understood and that the engineer inherits sound design objectives. The most comprehensive design includes defining inherent structural characteristics and external loading, developing sound geometric placement of structural elements, designing in accordance the structural behaviour considering the structural system definition, executing the full structural analysis, assessing the environmental performance of the structure, optimizing the structural system, detailing the structure and potentially defining aesthetics characteristics.

Architects have a special training in architectural design which involves the exercise of design itself. The architectural project, carried out in design workshops, which has been designed to train students architects in architectural design, involves a variety of skills including drawing skills, formal, functional and programmatic analyses, thermal and daylight analyses, architectural detailing, some simple structural dimensioning and graphic communication. It is an extremely demanding creative exercise that goes through an iterative series of graphic attempts that are supposed to be informed by all the above-mentioned dimensions. Many architects, however, sacrifice the structural dimension of their project by hiding behind the competence of the engineer who will be responsible for the stability of their projects. Engineers, because of their extensive scientific and mathematical training, have gradually neglected the ability to draw and the mastery of the geometry of their project, in favour of an almost exclusively analytical approach.

The challenge of training in structural design is therefore to reconcile these formal and artistic skills with physical and mathematical ones.

6. An integrated training to structural design - Parametric structural design

It is known that some structures from the past such as large bridges constructed during the industrial revolution demonstrated rare qualities of efficiency and aesthetic character. These bridges were designed based on the fundamentals of engineering, where mistakes or inefficiency was irrelevant in the structural design. Today, high-rise buildings have similar structural challenges and potential opportunities of expression. Some of these buildings are among the most complex in the field of structural engineering and required fully integrated design approaches and with a height of 500m or more, designers face challenges in developing the most efficient solutions for these complex structures.

In September 2019 the project of an advanced teaching on structures with a focus on the design of high-rise buildings was born. Mark Sarkisian (Skidmore Owings & Merrill, San Francisco) had shown in his book Designing Tall Buildings, subtitled Structure as Architecture [14], the close links between architecture and structural engineering for high-rise buildings... The conditions of 2020 did not allow Mark Sarkisian to join on site a team with the project of developing such an exercise for civil engineers-architects as trained in Louvain-la-Neuve, Belgium. But the infrastructure deployed by UCLouvain to teach at a distance, combined with the willingness of the incumbents to invest in parametric structural design, would open the door to cutting-edge, innovative teaching:

Teams of two students develop the structural design of a 500 m high building and its variants, calculate them through parametric definitions, programmed in an online environment shared with the whole class, allowing collaborative and interactive work on a platform; and, during the evaluation sessions, Mark Sarkisian is welcomed, directly from the USA, for specialized feedback. Under this format, the 'Architectural Research Seminar: Structures in 2019-2020' and 'Architectural Structures 3: Advanced Issues in 2020-2021' taught architectural engineering students structural design, structural modelling, advanced calculus, applied carbon footprinting and optimisation.

The tallest tower building in Europe (Russia excepted) is 300 m high (The Shard in London and Varso in Poland), and in Belgium is 150 m high (Tour du Midi in Brussels). So, when the students were asked to design a 500 m tower, the demand exceed all they knew in terms of practice and knowledge. 500 m is a scale that is only found in Asia and the USA... and which currently forms the top-10 tallest buildings in the world. At this scale of building, mistakes are not forgiven and, as with the great metal bridges of the 19th century, the structural reasoning must be flawless.

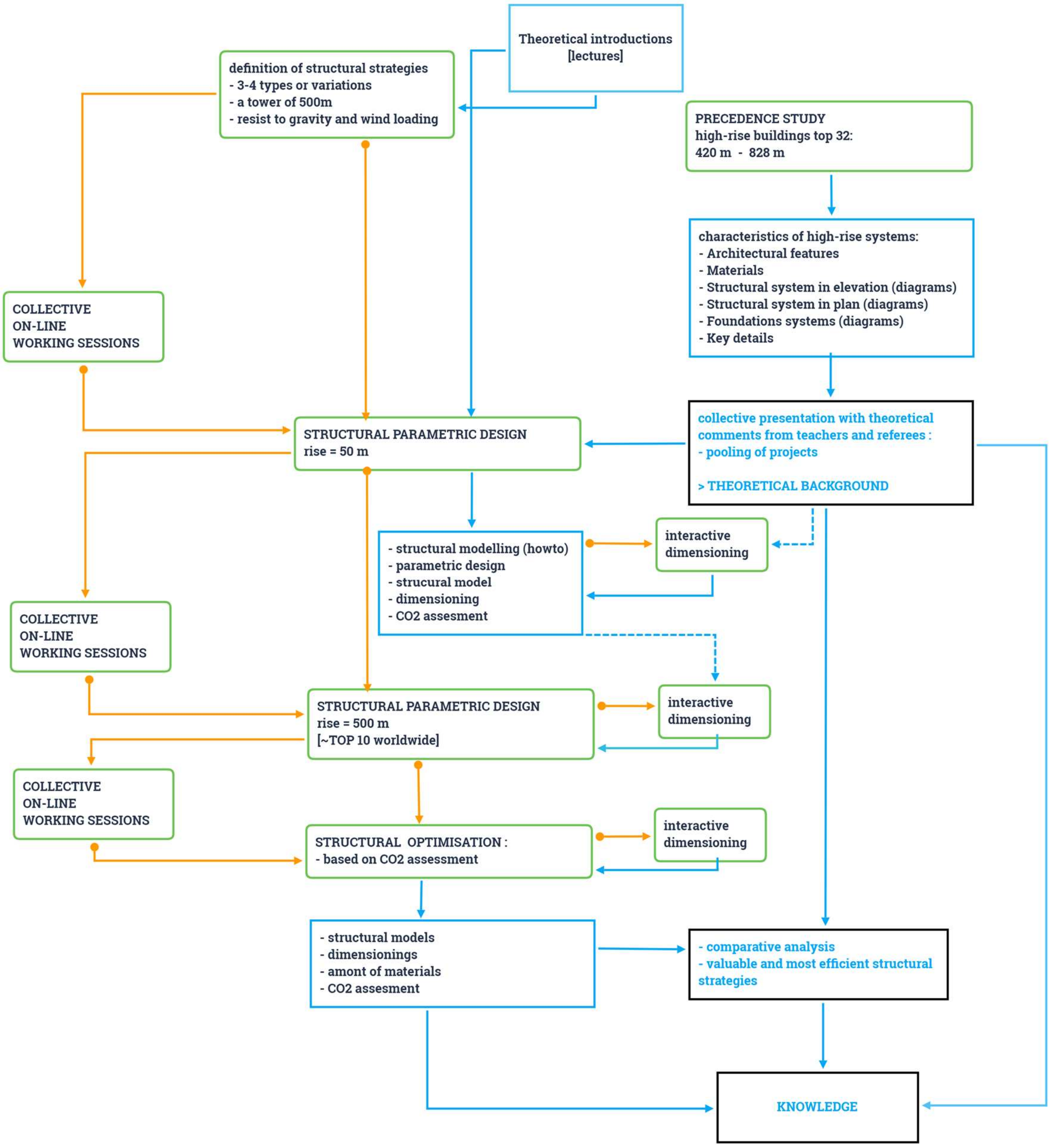

Figure 2: Mindmap presenting the main steps of the design exercise of a 500m high building [credits D.Zastavni]

As we have seen above, designing structures revealed complex and demanding. The complete design necessitates several steps to discover the problem, represent and analyse it, design and assess solutions. Students have to prepare precedence studies on buildings of the top 32 tallest buildings in the world / taller than 425 m and summarize with text and graphics with a presentation board format. These analyses are expected to summarise a description of superstructure and foundations from the points of view of architecture, structural system in elevation, structural system in plan, foundations, structural system diagrams, drawings for superstructure and foundations and key details.

With the help of lectures and sharing precedence studies in the class, students first assemble the elementary knowledge required along with parametric definitions for a building of a smaller scale 50m in height. Initial design approaches include powerful approaches such as graphic statics. Strategies for structural modelling are developed for the structural components of the project. Indeed, students must also discover and understand the type of structural model that should be used to adequately model the problems encountered while managing the size of such a structure and the number of elements it contains. An interactive FEM model as karamba3D enables students to quickly assimilate the order of magnitude of structural members sizes suited to this scale of structure, which may usually require years of practice. The students then consider the building at 500m height, adapting the design approach learned at the lower heights. Design are modelled using parametrical design so that they can continuously be adapted according to the result of their analysis. The structural analysis of these buildings can be complex, on the one hand due to the type of loading depending on the shape of the design, especially with wind forces, in addition to vertical loads, and on the other hand due to the size of the numerical model which complexity increases quickly as calculation time for large structures.

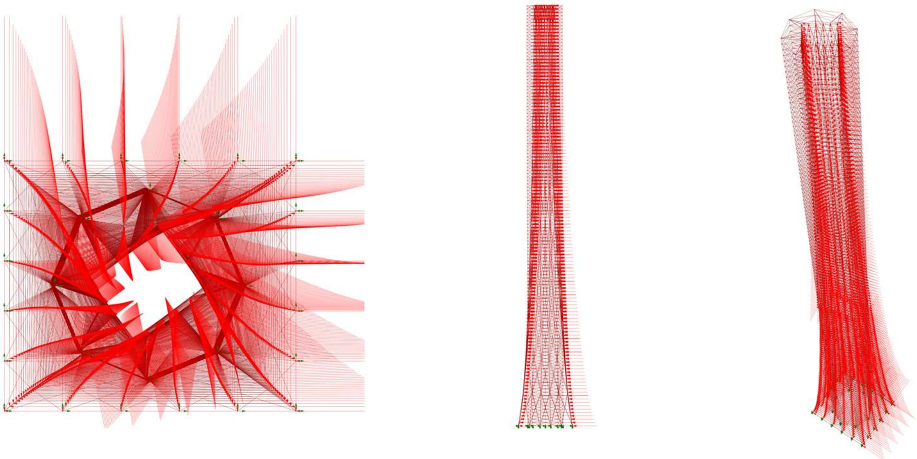

Figure 3: Wind forces on a 500m high building [credits Denis Zastavni, 2020]

Analyses and dimensioning are collectively reviewed and the structural material and CO2 balance are assessed considering the efficiency of the design. This assessment guides continuously the design and homogenise the quantity of structural material used in the project. The student works, presented successively in spring 2020 and autumn 2020, were ranked on the basis of their structural efficiency, measured by the structure's carbon footprint. The slenderness, combination of structural systems, staggered height, cross-sections and materials used are then taught to the students by the projects with the best structural approaches.
Once completely assessed and designed, these trial structures are discussed in a large group to gauge the relevance of each strategies developed by the students enabling learning from that collective experience and allows them to put their own work and approaches into perspective.

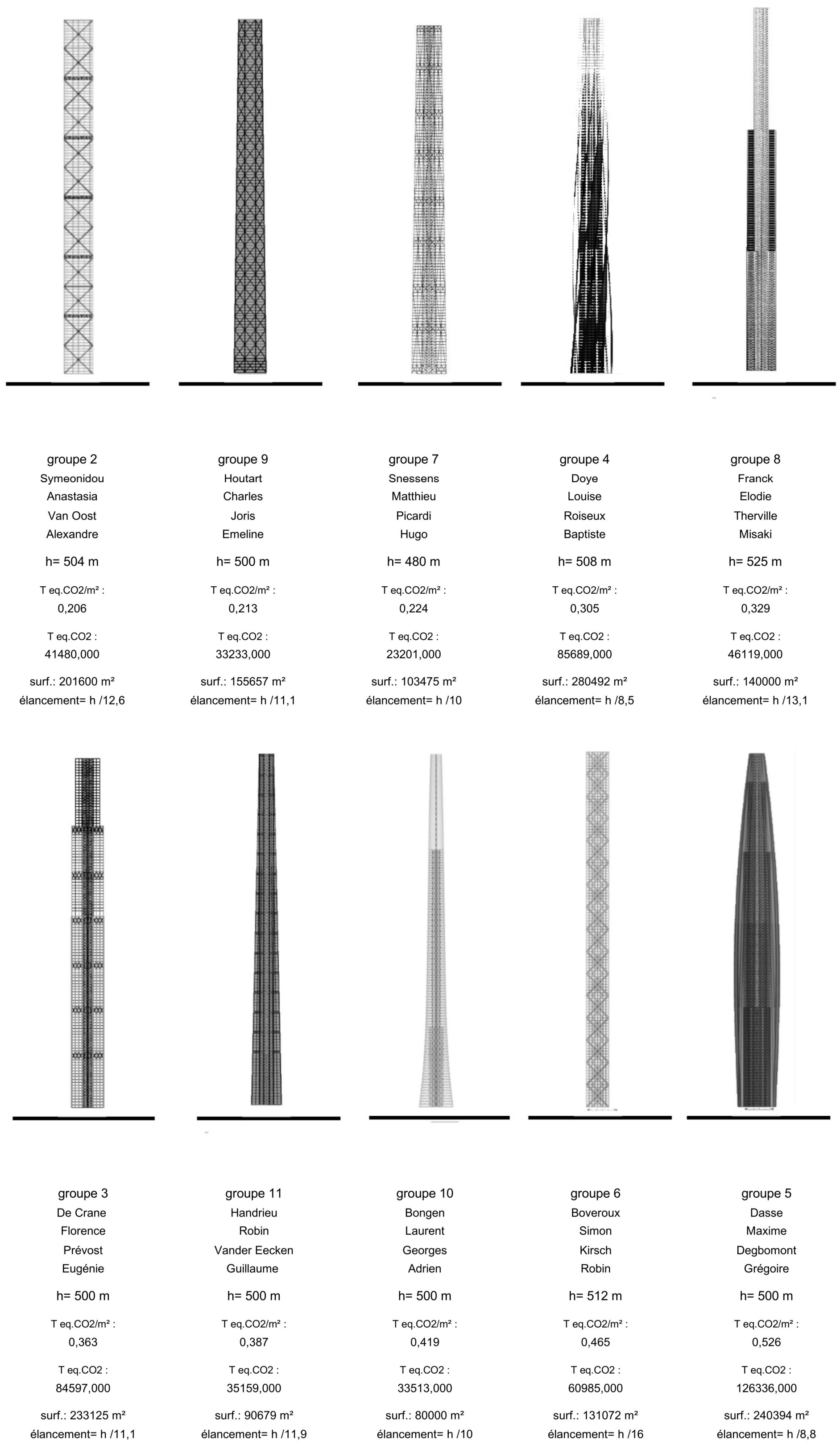

Figure 4: Designs ranked according their green assessment [credits LOCI LICAR 2402 – LICAR 2711, 2020]

7. Research by design

Research by design emerges in the last decade with the aim of taking advantage of designing skills of researcher to reach meta-level in heuristic processes and to explore the field of possible solution of complex problems. Researches in architecture – due to the specific profile of their researchers - frequently resorts to this approach which makes it possible to tackle multifactorial problems of great complexity as encountered in the practice of major architectural and urban planning projects. What emerges from discussions with people involved in this type of research is its great multiplicity.
It is at the same time 'research on design', hypothesis formalisation, laboratory, heuristic process, analytical process or result in itself. The following figure, elaborated as a provisional synthesis from focus group analyses between 2019 and 2021 at UCLouvain, graphically summarises most of these dimensions.

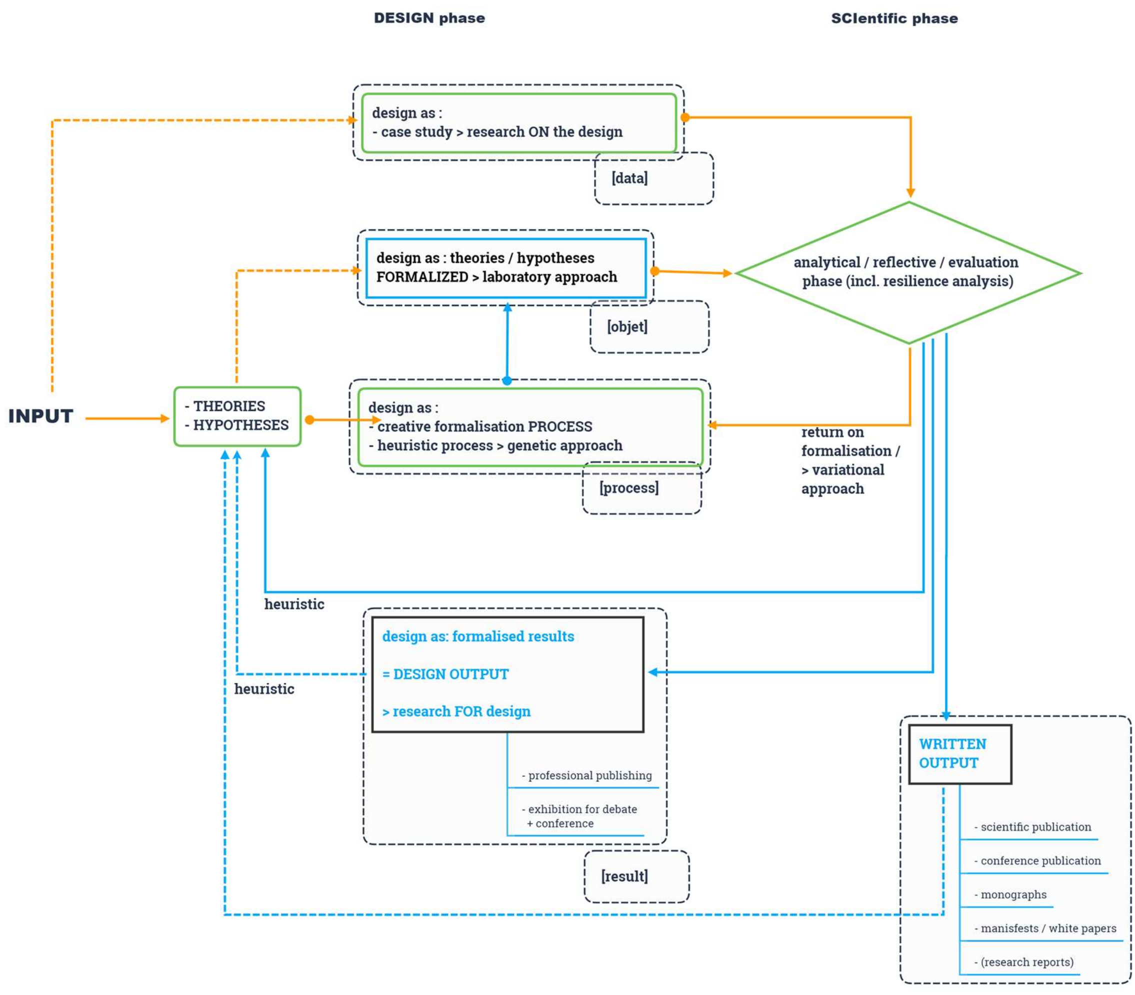

Figure 5: Research by design main significances [credits Denis Zastavni and Commission RPP, 2021]

What is striking is the number of connections that can be made between "research by design" and a process that combines some research for knowledge and knowledge transfer. The figure below shows how the majority of the elements characterising "research by design" can be associated with the methodological steps and main deliverables of this parametric design exercise for a 500m high tower. This observation shows in another way the universality of the approach that has been developed in this exercise.

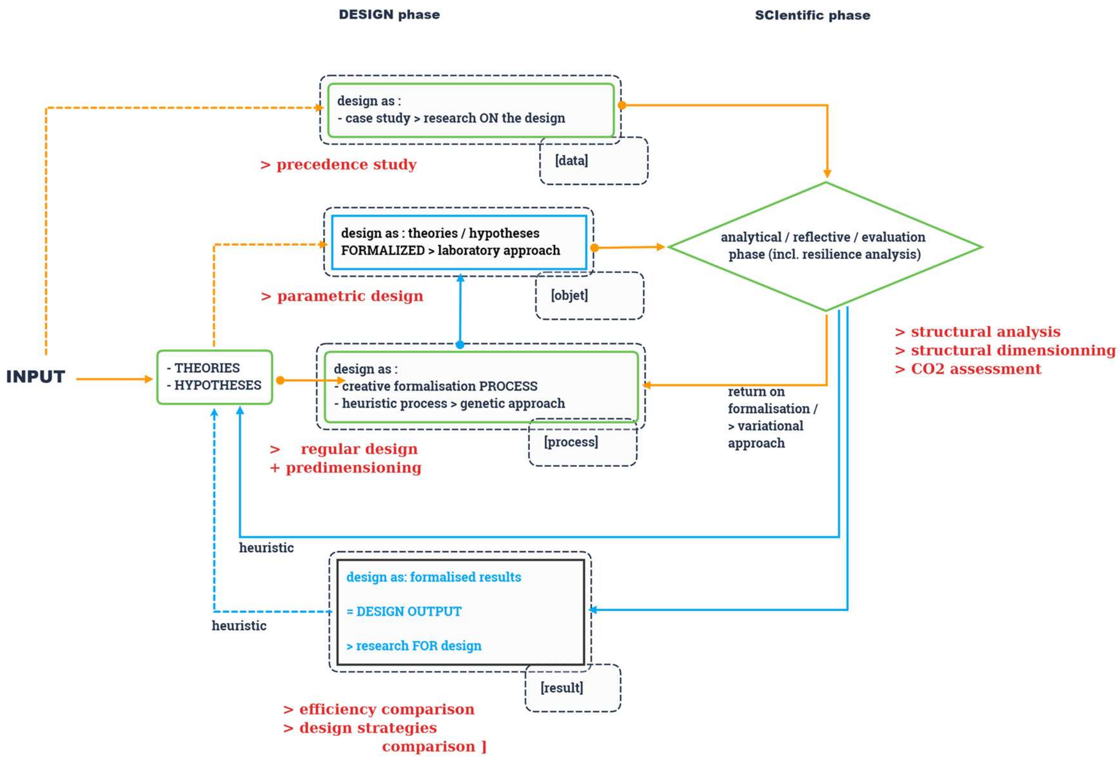

Figure 6: links between Research by design and high-rise design exercise [credits Denis Zastavni, 2022]

Conclusions

This technological approach used for a design exercise intended to students both trained to architecture and civil engineering as shown above revealed a process that avoids most of the
typical design obstacles encountered in design that is well beyond the minimum requirements of building codes. This approach revealed to be a success and was very appreciated by students. The analysis also shows that it has close links with research by design approache.

Considering the complexity of transmitting Structural Design Expertise, a Parametric Design Approach to High-Rise Buildings revealed sound and efficient. It requires however a very good basis in architectural design, parametric modelling and structural calculations, which may have to be reserved for engineers-architects at the end of their studies, or for high level international workshops.

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