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Digital and physical models for the validation of sustainable design strategies

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ABSTRACT

Contemporary architecture is generally characterised by shapes whose complexity, according to a multidisciplinary design approach, is related to the fulfilment of several requirements, such as structural and thermal efficiencies, exploitation of renewable energy sources, and reduction of construction and maintenance costs.
In this framework, the paper introduces and discusses the use of physical and numerical models for the validation of a sustainable tower design; the modelling of the building was developed at different levels, making use of computer numerical control (CNC) techniques. Rapid prototyping (RP) was used in the early design stages for the verification of the architectural concept, while more detailed experimental tests were carried out in a wind tunnel facility, with a rigid model. The case study had as its goal the integration of two conflicting needs: a clever exploitation of wind energy and the limitation of wind speeds in the living spaces of the tower. This process of graphical modelling, physical modelling, and experimental performance testing allowed researchers to overcome the limitations of the currently available analytical models, showing new fields of application of rapid prototyping and how technical drawing can help sustainable design.

1. Introduction

The project was inspired by the general idea that globalisation's impact on the built environment is manifested in the explosive growth of cities around the world. In this regard, through the 2010/31/EU Directive [1], the Countries of the European Community are committed to reducing current levels of emissions and energy consumption by 20% and increasing the use of renewable energy in new building construction by 20%, by the year 2020.

In this sense, the concept of the project was developed by applying active and passive bioclimatic strategies, in compliance with the new European Standards. This includes everything from optimum shape selection, architectural language, and technology choices, to the structural design. The objectives were to maximise the energy gains by using renewable resources and reducing fuel consumption and emissions into the atmosphere.

The detailed design of renewable energy-based buildings took advantage of physical modelling that, if properly developed, might be a powerful tool to integrate and correct traditional analytical approaches. In the contemporary age, in which generative tools and computer modelling afford opportunities to create complex shapes, the aid of physical modelling represents one of the ways through which designers can materialise their mental concepts [2]. Regarding the geometry, it is important to underline that the skyscraper, by its nature, has always been intended as a static building, lacking in dynamism. In recent design approaches, however, more attention has turned to the movement of volumes, using different manipulation strategies such as rotations, translations, or twisting, made possible by recent digital modelling software, which are strongly related to rapid prototyping techniques [3–7].

As a design representational medium, the advantage of the model-making process is that it can lead to new forms beyond the original concept. In fact, theoretical models are separately applicable to a single performance, and while they are technically valid in some respects, they were woefully inadequate for the purposes of this paper. This evidence resulted in the need to identify a method that would allow for the control of their effective integration. The coexistence of opposing performance knots created a need to test the building as a system, including the relations with the environment. For these reasons, it was decided to exploit traditional wind tunnel tests, in order to check with a holistic approach the structural loadings, renewable energy production, and the wind comfort at different levels. The model-making process was also useful for the communication between designers and technical staff in order to describe the complexity of the architectural concepts and to

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develop the construction of the final model [8]. The models generally serve as intermediaries between design and construction. This technique is hundreds of years old; many great architects, like Michelangelo [9] and Palladio [10], have already used physical models to explain construction techniques, building structures, and inner space ambience to clients and workers.

2. Theoretical framework

The creative and artistic process is characterised by different kinds of representation: architects, for example, explore many design possibilities through design sketching, hard-line drawings, and physical models, manufacturing artefacts for the exploration of diverse ideas [11]. Currently, the development of advance technologies, such as generative modelling tools with parametric transformations and CAD scripting, provides an opportunity for architects to control the building's development at the first stages of the design process by calculating the optimised shape and the best organisation of the inner space in order to reduce the total amount of energy demand and to achieve the standards of energy efficiency. However, nowadays, it is a common practice for designers to use the CAD–CAM technologies only in the concluding stages of the design process.

This paper presents the key aspects of the methodological framework to build physical models at various scales using different materials and techniques as part of the entire creative design process from the beginning to the end. RP is used as a design methodology in support of a paperless design and construction process.

RP is one half of a bigger field identified as digital fabrication (DF), a field that spans the application of RP for design and CAD–CAM for construction [12]. RP has been used mainly by product and industrial designers to demonstrate design concepts to clients through physical models. There are three principal types of RP techniques. First, 2D cutting devices such as vinyl and laser cutters are most frequently used by designers and architects to produce models of various scales and materials. Second, subtractive devices in the form of milling machines for desktop design carve from foam or other softer materials. Finally, additive manufacturing devices build solid models from loose powders or liquefied plastics. All three manufacturing types are generically known as CNC devices, and they are intended to translate from RP devices to real-world construction.

One of the main features of digital fabrication is the high quality of its output. It is possible to reach high levels of accuracy with both 3D models and laser cutting technologies, especially for complex designs. The creative process for producing variations of a single model or different models at various stages of design is supported by the RP technique. The potential applications of the RP modelling technique not only are useful in the design and construction process, but they also have certain didactic advantages that support the acquisition of knowledge and design procedural structures [13], such as those presented in this paper.

This paper describes three areas of research and design practice using RP. The first is the exploitation of RP in the early stage of design and the creation of designs as 3D shapes putting attention on the verification of architectural concepts and spaces. The second area is an emerging interest in the functional building model as a prototype for structure validation through test campaigns in wind tunnels. The action of the incident wind on a structure and its response to this environmental action are difficult to assess, but are of fundamental importance in the design of buildings and other civil facilities. The pattern of flow around a building and the corresponding pressure field is a very complex phenomenon; despite the available computing potential, both analytical and numerical approaches may lead to unsatisfactory approximations, in particular if applied to complex building shapes. This is because refined numerical models cannot disregard a proper calibration procedure based on experimental data and should be hence validated with regard to direct measurements [14].

The third and final area of research is the production of a 1/250 scale model, completely produced by RP technique, for the validation of building functionality and architectural concept as well for the aesthetic and communication skills of the model presented in the Culture Nature exhibition, a collateral event of the 12th International Architecture Exhibition Biennale of Venice (Fig. 1b).

The work presented here attempts to synthesize the conceptual stage materialisation through RP and construction information modelling. We demonstrate that the process of design is situated between conceptual design and building product modelling as a construction information model.

3. Design concept of the sustainable tower

The project area is located between the historical city of Roman origin, characterised by orthogonal street distribution, and the rest of the city of Turin, successively developed with a freer grid. This area was part of a wider refurbishment programme proposed to compensate for the almost total absence of green parks in the urban area, by creating an urban boulevard with trees and connecting the two parts of the city originally divided by the railway (Fig. 2).

The proposed skyscraper and the nearby railway station of Porta Susa constitute a place in the middle of change. This concept is embodied by the lines that move from the beginning of the lot (from the side toward the old passenger building of Porta Susa) enhancing their dynamism to totally break the historical rigid scheme. Everything flows in a vortex of sinuous lines, culminating in the tower that is the epicentre of the whole movement that continues up to its top, finally vanishing in the air. It is a building born from the earth and returned to it through a natural cycle: this was the generating concept of the project.

To minimize the environmental impact on the existing context, more attention was paid to the shape and orientation of the building, service location, finishing materials able to guarantee protection from solar radiation, integration of energy plants at different building levels, and natural ventilation.

The peculiarities of the project that made it necessary to conduct an experimental check and process various physical models were many and closely integrated. With reference to the envelope, the building façades were oriented according to different functional purposes: for the residences, a maximum south/southeast exposure facing the urban park, with the integration of a greenhouse system able to collect free energy contributions during colder seasons; for the hotel rooms, characterised by a lower residence time, a northeast fenestration with an urban skyline view was chosen; and finally, for the common spaces, an east–west orientation was designed in order to guarantee panoramic views of the city, the Alps, and the Mole Antonelliana.

The spatial solution included two buildings: the first, with an elliptic shape, for hotels and offices, and the second, curved and parallel to the perimeter, for residences. The two substructures were spaced so as to generate a central common area – aligned in an east/west direction – properly shaped in order to accelerate the incoming wind flow, improving natural ventilation and wind energy capture. The air passing through the inner living spaces contributes to the energy efficiency by producing natural air conditioning, which maintains the health of public spaces and is able to generate a level of environmental comfort consistent with the needs of the inhabitants. This, together with a maximisation of south exposure, was one of the energetic strategies considered in the development of the project, in order to achieve the integration of all renewable energy sources (Fig. 3).

The project provides a vertical succession of villages, each of which is characterised by the presence of a covered public square equipped with shops and hotel lobbies, overlooked by five more storeys of residences, hotels, and offices. The plan grows vertically with a complex volume, surrounded by an external diagrid structure modelled with a waisted silhouette which recalls the typical shape of a female bust and offers, at the same time, larger commercial areas at the base and the top of