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Architectural design for optimised performance supported by aerospace Value Assessment methods

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Abstract. This paper focuses on novel interdisciplinary design methodologies between architecture and aerospace engineering in support of drastic required changes for the construction of genuinely resilient and sustainable buildings. Current design and construction methods are rarely truly interdisciplinary; driven by successive development stages as opposed to holistic system views capable of integrating valuable feedback loops into the design process and whole life cycle stages of a building. We address these deficiencies by integrating two methods that have been successfully tested independently. Firstly, the “Virtual Design Studio” (VDS) approach that focuses on holistic architectural design processes, initially funded by the US Department of Energy at Syracuse University and the New York State Center of Excellence for Energy and Environmental Systems. Secondly, the Value Assessment (VA) methodology supported by Visual Analytics in aerospace engineering design cycles, initially funded by the European Commission FP7 through the TOICA project and currently funded by Innovate UK through the APROCONE project, and developed by the Engineering Design Centre at the University of Cambridge.

1. Introduction

The purpose of the research is to demonstrate how aerospace and architectural design techniques can be merged into a novel, advanced, fully integrated and coordinated design approach that will benefit the construction industry of the future.

The objective to combine VDS with VA methodologies stems from the need to add critical evaluations to the design process from an engineering perspective—particularly in the area of efficiency, productivity, manufacturability, and whole life cycle analysis for projects focused on the integration of complex systems and manufacturing principles. This concept is aligned with major industry initiatives that are intended to mitigate acknowledged productivity gaps in the construction industry.

There is the need for change; according to recent UN Environment statistics, buildings and constructions account for 36% of all energy used worldwide, with a resulting share of 39% of energy-related global greenhouse gas emissions [1]. It is further predicted that, unless significant changes can be realised, emissions from the building sector could double by 2050.

Ambitious benchmarks have been established by various international agreements and concepts. The Paris Agreement (COP-21, December 2015) includes a 50% reduction of energy consumption through the implementation of highly energy efficient, near or net zero, and energy plus building standards, as well as an upgrade to the existing building stock by 2030. Furthermore, according to the



UN Climate Change division, new concepts of a circular economy can further contribute to the mitigation of the anticipated impact of climate change [2].

Given the complex challenges of such high demands, the aim of the project that is presented in this paper is to support productivity increase through the combination of architectural design methods with design engineering and optimisation principles. Recently, significant investments have been made into knowledge and technology transfer initiatives that are intended to boost the construction industry. As an example, ambitious goals have been set by the UK government in 2013 in its Construction 2025 agenda that demands 33% lower cost, 50% improvements in export, 50% faster delivery, and 50% lower emissions [3].

Although some emerging targets in the building sector have already been met in the aerospace industry, equally there are ambitious targets within the “ACARE FlightPath 2050” [4]. Hence, current design and product development practices applied in aerospace are not a panacea. When investigated targets are fulfilled then new challenges and weaknesses are exposed. One of the main remaining and shared challenges between building and aerospace industries is the effective communication between diverse stakeholders and various design and manufacturing entities. Value Assessment methods ([5], [6]) directly address this issue. The combination with visual analytics has proven very beneficial in other aspects of the design process, including the ability to trace decisions made against requirements and to identify the causality of changing requirements or targets. With the application of the Value Assessment approach to the design of buildings and its combination with an existing architecture design approach, VDS, we expect to be able to identify new ways to define and quantify non-standard decision-making criteria. We anticipate being able to address questions such as ‘What is the response of the building behaviour to climate change?’, ‘How can we implement vibration considerations in wind powered buildings, impact to wildlife, noise pollution, and how can we identify their margins?’, ‘How can we perform lifecycle analysis of the building?’, ‘What is the impact of alternative material properties and their relationship with for instance operational aspects (like thermal mass)?’, ‘How do we design smart buildings?’. These design questions are difficult to be addressed on their own, but we aim to even expose their trade-offs and facilitate a holistic decision-making environment. The impact to the design and product development process will span from the building industry back to the aerospace industry and potentially to others, such as automotive, telecommunications, IT, and infrastructure to name a few.

2. Methodology

In the following section we present the high-level background of the two methodologies that we consider in this work.

2.1. “Virtual Design Studio” (VDS): facilitating interdisciplinary building design processes

The “Virtual Design Studio” (VDS) is a software platform currently under development in support of an integrated, coordinated and optimised design of buildings and their energy and environmental systems. It assists collaborating architects, engineers and project management team members throughout from the early phases to the detailed building design development, supported by an integrated Computer Simulation Environment for Performance Based Design of very low energy and high IEQ (Indoor Environmental Quality) buildings (Figure 1). The VDS platform also helps to facilitate the workflow and the processing of information in combination with appropriate, task based performance simulation tools in an interdisciplinary setting. The project was initially funded by the US Department of Energy under Award Number: DE-EE0003844, with \$702k over three years (Syracuse Center of Excellence in Environmental and Energy Systems, and Syracuse University) in collaboration with Prof. Jianshun (Jensen) Zhang.

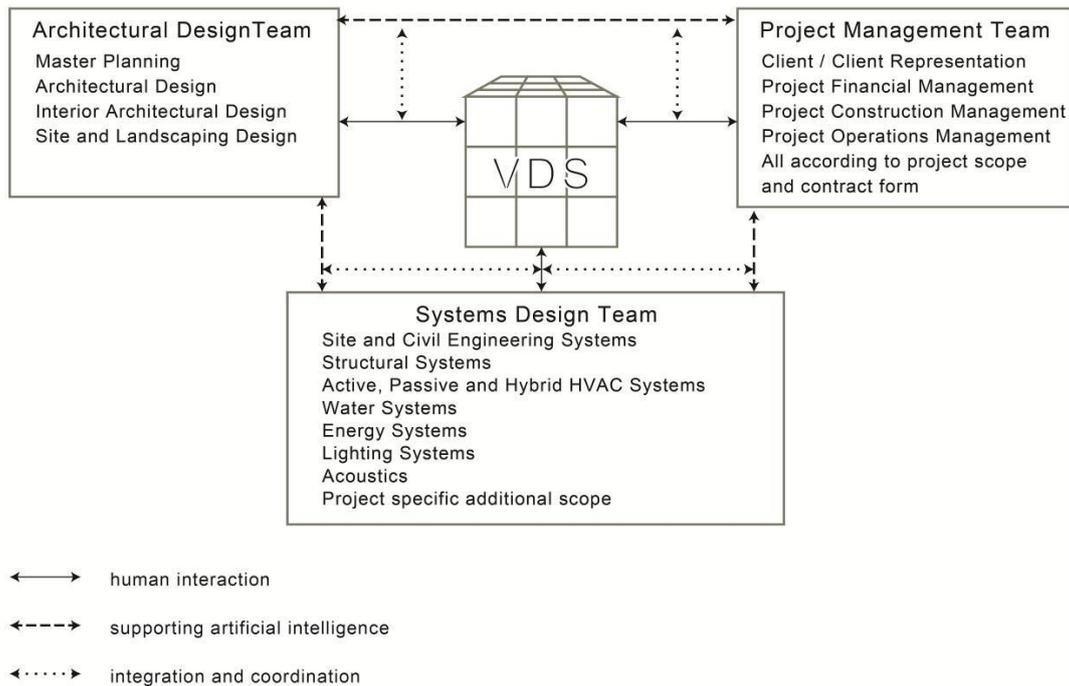


Figure 1. Coordination of Human Interaction and VDS supporting Artificial Intelligence.

2.1.1. VDS Platform Organisation. The VDS platform is designed to mirror and simplify professional project stages as defined in the legislative requirements of various recognised national architects' chambers. Design criteria include: planning parameters, project types, possible contractual configurations, and project specific team constellations. These parameters can be specified through an initial customised project setup in the program scope. In general, the building design process can be categorised into four overarching stages: 1) pre-design, 2) pre-construction, design and systems coordination, 3) construction and systems implementation, and 4) occupation, operation and maintenance. Typical working stages can be simplified and further translated into performance evaluation stages that can now be seen as universal steps for a performance evaluation and the implementation in buildings.

In the area of optimised building performance, VDS allows for the evaluation of various metrics and assessments as part of a simplified overview of a building's performance criteria. These metrics have been derived from recommendations and value systems from various international agencies and programs [7]. Table 1 shows the five performance assessment stages considered by VDS and their relationship with those included in the various performance ratings systems reviewed according to VDS's "ADDAM" design stage structure. All aspects should be considered throughout the service life of the building from design to construction, to operation.

2.1.2. VDS development goals and intentions – resulting methodology. The VDS provides a hybrid tool made of components from architectural design practice and engineering simulation techniques that promote energy-efficiency and indoor environmental quality throughout all design phases through quantitative and qualitative analysis of respective performance assessment stages. VDS gives guidance from early to advanced design stages and can also assist performance evaluations during building construction, occupancy and operation. VDS also helps the architects and engineers to conduct a synchronised performance-based design via a methodology that fosters continual feedback loops between key stakeholders.

2.2. Value Assessment methodology in Aerospace Engineering

In modern engineering, the application of computational design techniques is common practice at all phases of the overall design process of a product. Most often, these design systems are configured to identify the appropriate values of settings, or design parameters, that improve the performance of the product. However, very often, there are important aspects that can characterize the product in a qualitative way, for example, the comfort or the experience of the passengers in an aircraft. These 'metrics' can express the value of the product which is equally important as the technical performance. The development teams wish to include such metrics in their design process in order to develop a successful product as perceived by stakeholders such as the end customer. Evidently, there is a trade-off to be made between quantitative performance characteristics and other – less quantifiable value assessment criteria.

Table 1. Professional project working stages simplified to the VDS ADDAM design stages [7].

Simplified Professional Working Stages	Performance Assessment Stages
Pre-Design	Assess project and formulate strategic brief
Pre-Design	
Design Development and Coordination	Define performance scope and goals
Preliminary Design and Concept Development	Design to meet/verify performance scope & goals
Schematic Design, Final Design, Detail Development	Apply and revisit scope and goals
Post-Construction/Operation Assessment Building Systems monitoring and supply of data base	Monitor performance/post construction verification

The success of any product is eventually determined by how well the product is able to satisfy its stakeholder's needs and expectations – what value they deliver. In doing the engineering and optimisation of such products in product development contexts, such knowledge is by definition limited. Instead, the engineering teams relate to requirements, load specifications and constraints that has been derived and defined through the requirements establishment process.

Earlier work [5] has shown how information critical for value assessment can be organised via a Value Driven Design process (Figure 2). Once organised, and made explicit, it was shown how such information can be used to include value dimensions into the computational engineering design process. They related Value Drivers to design parameters, and Value Dimensions to objective functions for simultaneous improvement. The industrial context of that work was the development of aircraft, and aircraft systems.

In order to support the VA methodology a number of computational models are necessary to be deployed in the process. These can be pre-embodiment descriptions and representations of the product architecture, but also detailed geometrical CAD models, as well as low—and high—fidelity simulation and analysis tools. In [8], Raudberget *et al.* have presented such an example and they used the DSM [9] modelling approach and the CPM [10] method to evaluate certain characteristics of the behaviour of the different architectures of the product.

2.3. Combining VDS and Value Driven Design

Current design methods rely on either numerical or simulation-based assumptions that depend on the degree of geometrical resolution, defined spatial or material properties, and systems characteristics. The new method intends to enable more efficient and effective design collaboration and coordination and allows for quantitative and qualitative assessment of the integration of different building technologies and their resultant performance prediction. This new collaborative working platform goes beyond the streamlining of the conventional design process and allows for the visualisation of completely different system interdependencies and relationships that architects rarely take into account. When applied to the early conceptual design stages, our methodology paves the way for the testing of unique architectural decisions based on these newfound and complex technology and performance criteria.

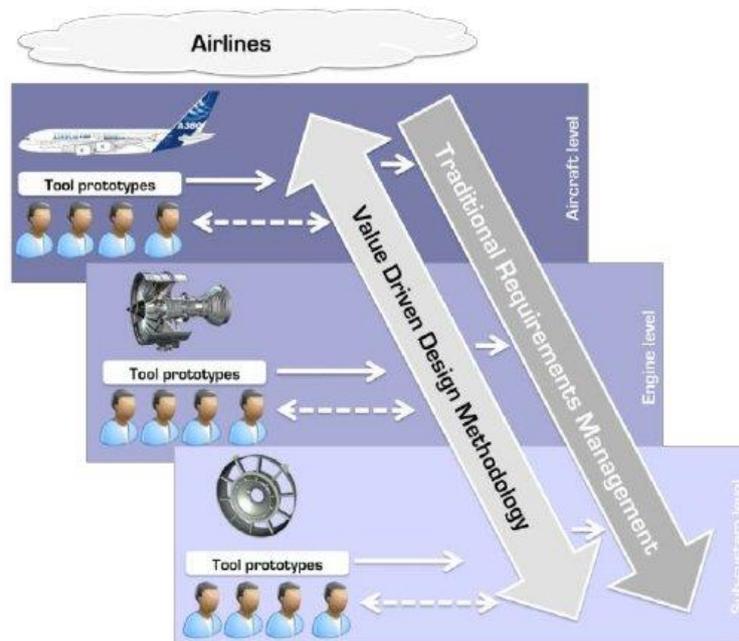


Figure 2. A multi systems level approach of Value Driven Design [6].

It is important to not see any of the mentioned factors in isolation; almost all aspects of the design are closely related and will impact each other and the resulting system efficiencies (Figure 3). For example, the building location, its massing and its orientation determine a variety of efficiencies related to regional and local climate conditions such as thermal performance, daylight utilisation, noise isolation, heat island effect, and visual qualities. The programmatic zoning and interior organisation of a building impact system loads and external envelope characteristics. Alternative approaches for the use and combination of active, passive and hybrid HVAC systems, as well as energy and water conserving strategies are to be considered. Façade typologies and the quantity and quality of openings will determine thermal properties, impact energy and HVAC system efficiencies as well as the occupant's wellbeing, productivity, and human comfort. Among many others, a life cycle assessment, the choice of materials and the use of renewable energy sources also impact viable financial models. This new design optimisation system has the capacity to accurately evaluate the impact of all of these design decisions and resultant efficiencies.

Compared to traditional architectural or engineering based properties for evaluation, the proposed method allows for a higher degree of abstraction for the investigation of relationship based performance aspects and system interdependencies. It is the intention to thus better understand system relationships between the wide range of criteria that are part of the planning and coordination process. Compared to a conventional delivery 'package' like organisation or a set of distinct (and isolated)

design criteria, the proposed interrogation includes the impact of the quality of one design aspect on others.

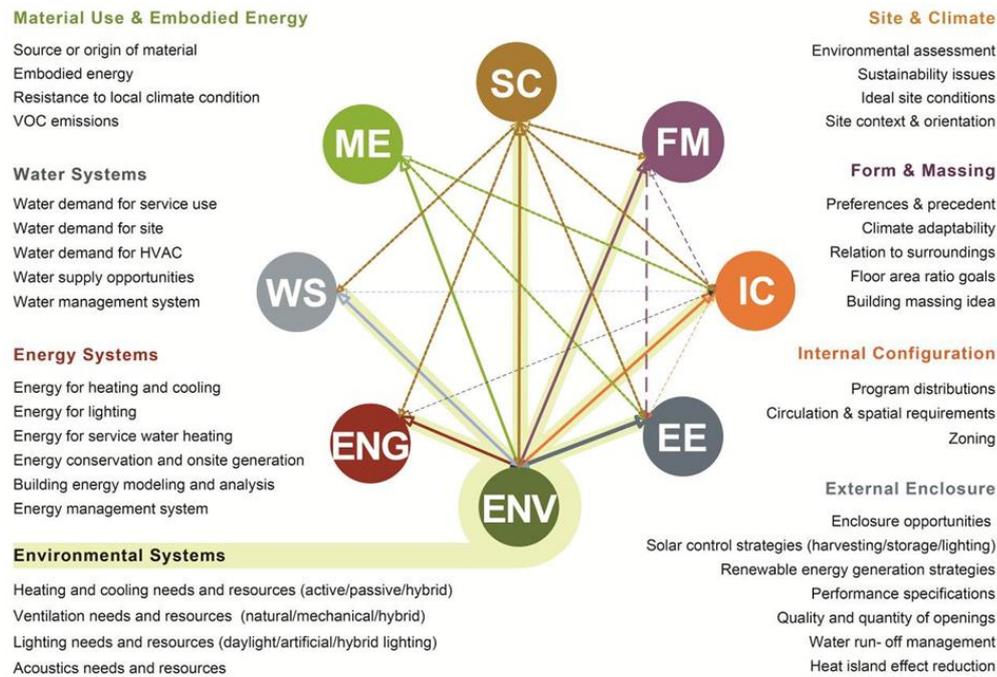


Figure 3. Interrelationships of design factors during the Assessment Stage in VDS.

In order to practically link the two design approaches, we will use a model representation of the building based on the Design Structure Matrix (DSM) approach [9]. This matrix-based model is an intuitive way to represent complex systems, processes, and organisations. In addition, the model can be a high-level abstraction but also a very detailed description, or even a combination of different levels or types of description of a system. This will enable the application of the Change Propagation Method (CPM) [10] that allows identifying the weak spots in a system, or its most influential elements. We can also experiment with different types of technologies, or even new technological solutions, and assess their impact at an abstract level. This can be at the preliminary stage of the design and architecture of a building, or at the pre-embodiment stage of an aerospace product development. Furthermore, the two methodologies share the important characteristic that the human designer interacts with the software platforms which support their decision-making process and allow them more time for creative thinking. The vision for the integration of the two methods and the application on the case study described in the following section is represented in Figure 4.

3. Case Study and Challenges

As part of the VDS ADDAM structure and evaluations system, an appropriate climatic and site-specific design response is critical. While not restricted to Mediterranean regions, our proposed collaborative working model provides a flexible tool for the planning and design of buildings that help achieve ambitious “Construction 2025” targets. In particular, the model aims to address building performance in energy consumption, human comfort, societal impact, full coordination from system to component levels, material efficiencies, life cycle, as well as the development time from inception to completion.

To exemplify the potential of such a highly integrated process and testing setup, we have chosen to use the prototypical energy plus building concept of the Turbine-House [11], as shown in Figure 5, which incorporates patented wind turbine principles, PV and PV thermal installations, and geothermal solutions into its design. The Turbine-House form is generated and characterized through the

implementation of various active, passive, and hybrid operational optimisation approaches, allowing for off-the-grid operation that has the capacity to support various neighbourhood and site installations.

As a test site, we have chosen Rhodes, Greece, where we defined typical Mediterranean climate conditions as the frame work for its design performance evaluation.

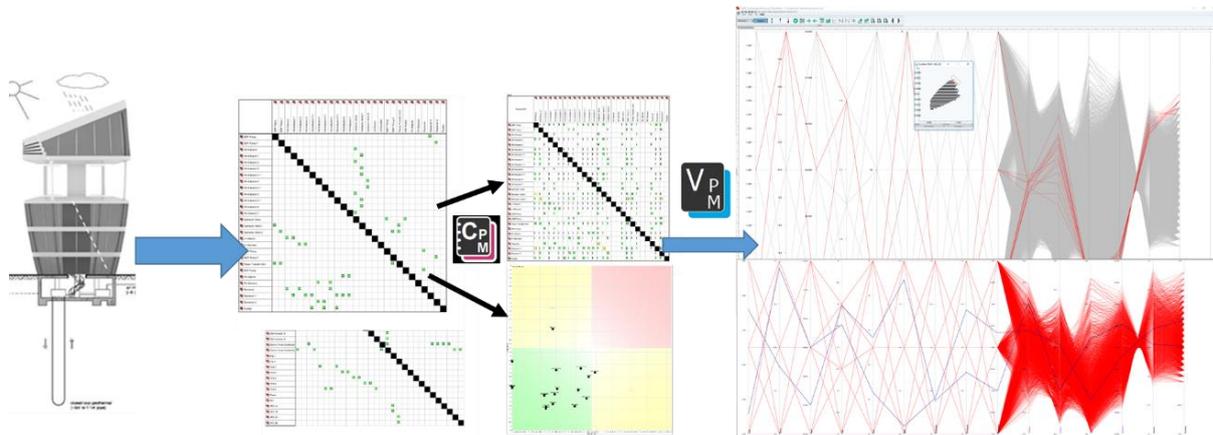


Figure 4. The vision of the integrated software platform.

The overall form incorporates an optimised operation of a Vertical Axis Wind Turbine (VAWT) developed for product and building applications [11]. The patented and efficient design form can increase wind energy harvesting from VAWT capacity up to 250%, can reduce system start-up requirements, and can allow for efficient operation at lower wind speeds. Numerous 2D and 3D Computational Fluid Dynamics studies have been used to facilitate the design and geometry optimization process which has the capacity to generate surplus energy from a VAWT during operational peak times. The building is an experimental prototype that can be further optimised for a particular site, program and climate, while providing flexible open spaces with optimal lighting conditions and fantastic views to the exterior.

The VAWT of the Turbine-House not only allows for advanced energy generation, but also dictates the overall building orientation, massing, programmatic as well as environmental zoning strategies (Figure 6). The turbine is located at the top of the building for maximum exposure. The sleek compact circular form provides good surface to volume ratio for maximum solar and heating efficiency. Through an overhang design, the curved façade allows for solar shading during the summer months and maximization of solar gains in the winter. The circular and non-directional arrangement of the building geometry allows for equal pressure distribution at the envelope and thus provides consistency for enhanced natural ventilation modes. Other considerations are the sloped roof area that allows for rain water collection, the installation of photovoltaic panels and solar thermal heat exchangers, and various other energy strategies such as earth ducting, geothermal heating and cooling loops.

Figure 6 also illustrates the overall kWh/year that the house will be able to generate based on climate averages, and energy calculations based on low-energy standards, for an area such as Rhodes, Greece. The site was chosen to illustrate the capacity of the house to function in an environment with a typical Mediterranean climate of average wind and ample sunlight.

These calculations and studies were done independent of the Value Assessment Methodology as outlined in section 2.2. However, they serve as the base for areas where advanced aerospace engineering assessment tools can extend simulation capabilities and have novel future impact on performance. Potential considerations include energy as well as manufacturing and construction methods, the impact of the choice of materials, and the implementation of new technologies. Aspects like human comfort can be considered to greater degrees for various occupational needs and standards. Sections 4 and 5 outline the practical next steps for applying Value Assessment Methodologies to

architectural design processes in combination with the VDS structure. As a next step, a comparison of 'before and after results' will test the process and demonstrate the added value.

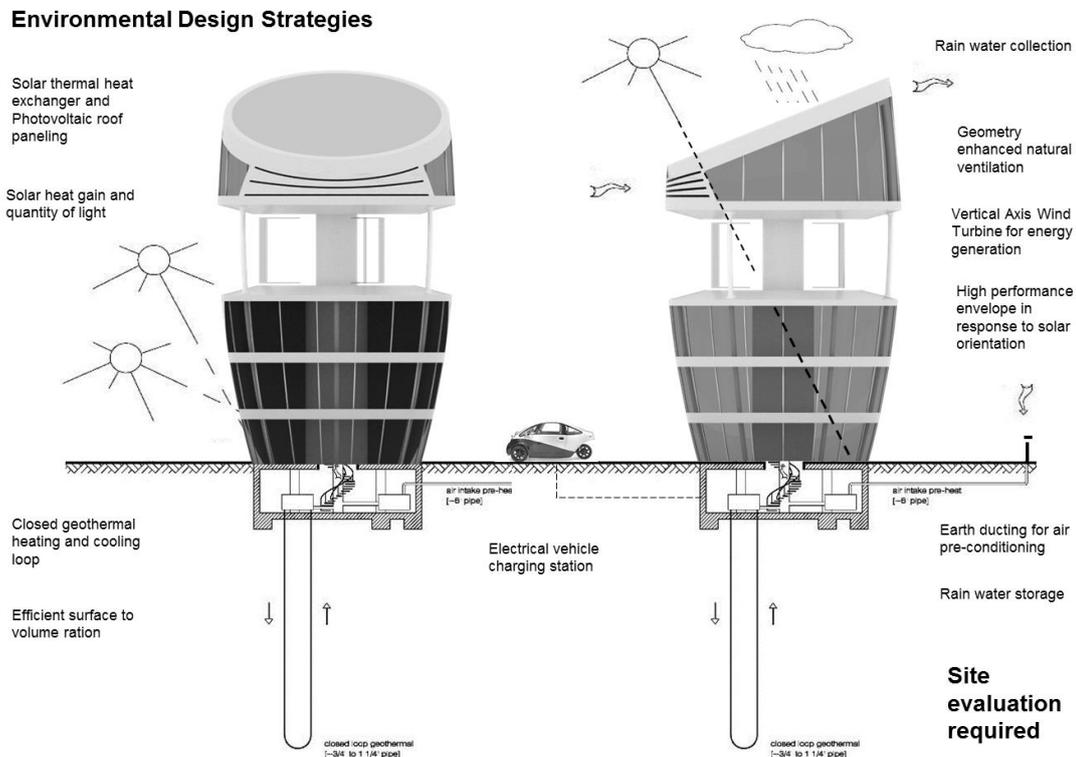


Figure 5. Structural and hybrid environmental design strategies for the Turbine-House.

4. Potential for Next Generation Buildings Using the Turbine-House as a Case Study

We have identified several opportunities for improvements to a design process that leads to an optimised building performance. These include:

- Combining aerospace modelling techniques with ADDAM criteria and Value Creation Strategies.
- Identifying additional design criteria or sub-categories for design considerations of site and climate response, form and massing, external enclosure including the roof, internal configurations, environmental systems, energy and water, and material use.
- Creating an advanced 'deep dive' comparison and parallel evaluation of design options for a synthesis of the above criteria (e.g. climate and material use, carbon and comfort).
- Using Value Assessment Methodology to enable new data-driven, interactive use of visualisation methods for modelling and scientific analysis.

In the case of the Turbine House, much like tested methods in the evaluation of aerospace technologies, Value Assessment Methodology can be used to analyse the performance of the turbine in the context of the solar array as well as other embedded energy-saving as well as predict potential system incompatibilities and potential losses at the pre-embodiment stage where geometry and dimensions have not been defined yet (as an example). This would maximise initial design productivity and essentially monitor systemic functionality while providing designers with data-rich opportunities for process optimisation at the early stages of the development but also to more targeted studies at the later stages of the design process. Currently, there are no such tested methodologies that have the capacity to offer architects visual predictive models that have a direct impact on the overall design of the energy systems as they relate to the form and architectural considerations of a given project.

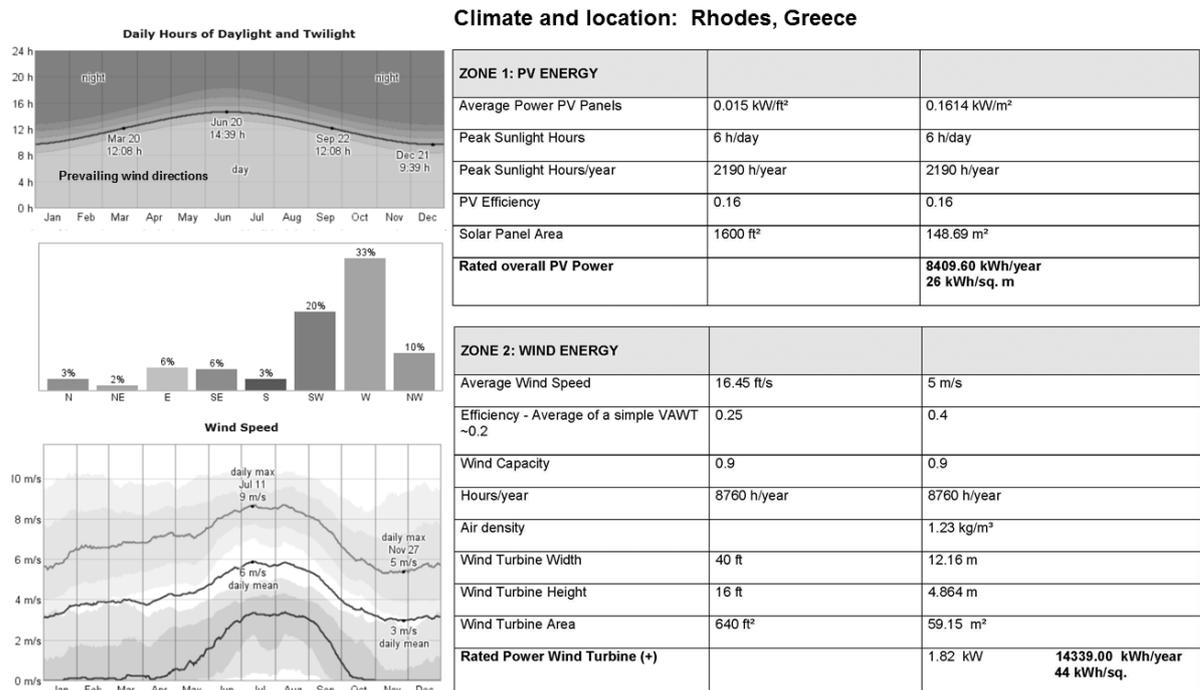


Figure 6. Turbine-House energy calculations for Rhodes, Greece

5. Conclusions and Future Work

Instead of focusing on one particular design issue or disciplinary view, the Value Assessment method supported by Visual Analytics tools allows to detect multiple dimensions in a 2D matrix where constituents can be compared and evaluated through the visual establishment of relationships currently not observed in the VDS design matrix or conventional design practice. Furthermore, the merging of the two approaches allows for a direct knowledge and technology transfer from aerospace and manufacturing sectors to architectural design. This will further enable architects and systems designers to go beyond current predictive planning processes, be very clear what criteria and interdependencies to look for, and apply a more integrated and coordinated approach. Added capabilities include:

- The ability to view the effect of key environmental components to the building function and form.
- Quantitatively and qualitatively investigate the integration of novel, unusual and/or untested components in the overall construct, and envelope and environmental control systems integration.
- The ability to evaluate the knock-on effects of specific component-oriented decisions to the overall performance and behaviour of the building (and risk assessment of the potential for failure).
- To interrogate and implement aerospace akin Modern Methods of Construction (MMC), Design for Manufacture and Assembly (DfMA), and other forms of efficient prefabrication.
- Capture lessons learnt from project executions to process typological and technological advancement, and their potential impact on current industry standards.

The architectural design and engineering of innovative buildings, such as the wind powered Turbine -House, can solve current problems and bring building technology closer to meeting expected next generation standards. However, this comes with the price of new types of challenges that have never been considered before in the architectural design industry in terms of shifting conceptual, contractual and performance based considerations. At the same time, new business and procurement models are posed that foster innovation and shape the future of the building industry. With the

proposed method we believe that we address exactly this point. Apart from defining technical requirements for innovative buildings, we can develop the capability to understand whole life cycle assessment methods of a building in parallel to, for instance, societal impact. In this frame work, a range of diverse criteria that have different value systems can be compared according to a shared 'currency'. This way of working has the potential to tackle greater complexity while overcoming disciplinary hurdles.

With respect to Mediterranean climates (Rhodes, Greece for example), the combined approach can further benefit the investigation of the relationship between climate mitigating design decisions (orientation, prominent local materials, massing, and passive systems integration) and their respective architectural and formal impact. In the case of the Turbine-House, the combined method has the potential to effectively predict possible system configurations and potential areas for the further assessment of other technology integration. Perhaps, in the near future smart buildings can play a key role to the development of smart energy infrastructure and the evolution of the energy market.

In essence, new forms of knowledge and technology transfer from more advanced design fields can help the building industry move forward, and tackle the pressing challenges we are facing. As an example of new design capabilities, small and mid-scale integration models in the built environment require added design and predictive planning capabilities that this new approach is intended to assist.

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