Performance driven design and simulation interfaces: A multi-objective parametric optimization process

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Performance Driven Design and Simulation Interfaces: A Multi-Objective Parametric Optimization Process

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Keywords: Multi-Objective Optimization, Environmentally Driven Façade, Parametric Modeling, Integrated Design Strategy, Simulation Interfacing Tool, Performance Driven Design.

Abstract

Despite the continuous development and integration of simulation interfacing tools in current architectural research, the availability and operability of off-the-shelf tools has still not met the timeframes and performance requirements of current architectural practice. The complexity and demanding performance goals of contemporary large-scale projects often require innovative approaches, as well as the development of novel simulation interfacing tools to meet these requirements.

This paper reports on a multi-objective optimization process, aiming at reducing incident solar radiations whilst optimizing daylight penetration, for the façade of a large-scale office building. This was achieved through the combined use of a parametric model and a genetic algorithm, along with an integrated data set of pre-computed results. To minimize the resources demand of analyzing the plethora of potential configurations of the façade, a number of strategically defined modular cases were modeled and simulated using bespoke interfacing tools to produce a database of results. This database was then linked to a parametric model, providing real time feedback and allowing for an exhaustive search of design configurations. To further explore potential optimal solutions, a multi-objective optimization process using a genetic algorithm, also linked to the results database, was implemented. The overall optimization process provided invaluable insight to the design problem at hand.

1. INTRODUCTION

1.1. Context

Architectural research has long been witnessing a continuous shift towards the development and integration of simulation tools, which aim to facilitate the feedback loop between design intentions and performance (Malkawi 2004). Recent developments range from whole-building energy simulation platforms (Rysanek and Choudhary 2012) and energy simulation tools for double-skin façades (Kim and Park 2011), to integration methods of daylight simulations in the architectural design process (Kim & Chung 2011) and fluid dynamics simulations for open joint natural ventilated façades (Sanjuan 2011) amongst many others. Apart from the continuous development of more effective and robust simulation models, current architectural research has also been engaged with the development of new interfacing tools, which aim to integrate the available simulation tools seamlessly into the architectural design process, as well as facilitate their utilization by non technical users. Recent examples include the linking of CAD packages to simulation engines, such as the DIVA plug-in that links the Rhinoceros software to the Radiance advanced raytracing software (Lagios et al 2010) or the development of design tools that integrate solar radiation, energy and windflow analysis modules, such as project Vasari by Autodesk Labs.

Despite this continuous effort towards the integration of simulation tools -which provide valuable performance feedback to the designer at all stages- the need to tackle the challenges of interoperability, ease of use, and resource requirements (all of which have been pointed out numerous times in the past e.g. Huang et al 2008, Lam et al 2004, Malkawi 2004), still remain. Moreover, with the advent of optimization computing paradigms in architecture, the need for integrated and efficient performance feedback tools has become even more evident. Optimization techniques have become common ground in architectural research (Malkawi 2004) and are also widely applied in current practice. This trend for performance-driven solutions to architectural problems often dictates the emergence of ad-hoc development of demand-oriented tools (e.g. Mark 2010) or, possibly, the use of novel and less resource demanding simulation approaches (e.g. Chronis et al 2010). However in many cases the complexity of current architectural projects has been proven to be beyond the capacity of even the most capable systems (Hanna et al 2010). The amount of different – and often conflicting – parameters one needs to take into account requires not only novel and more efficient tools, but also innovative approaches towards performative solutions. These should combine the current computing capabilities with the ingenuity that lies in the designer's overview of an architectural problem.

In this paper we report on an innovative approach towards a multi-objective optimization process, aiming at reducing façade incident solar radiation whilst optimizing daylight levels, for a large-scale office building. The scope of this process was twofold, aiming on one hand to provide valuable real time feedback to the design team through the use of a parametric model, and on the other to generate optimized solutions through the use of a genetic algorithm. Both of these procedures were linked to a data set of pre-computed results for a number of specifically designed modular cases.

1.2. Diverse Problem Definition

The project to which the above process was applied was developed in the Middle East, and was an ideal candidate for deploying the aforementioned optimization techniques. This new development incorporates the urban planning and architectural design of three office parks, and its office accommodation was perceived as directly reflecting the needs imposed by its surrounding environment. The project was developed as a pioneering example of sustainable, energy-efficient design, responding to the culture and climate of Middle East. Under this spectrum, sustainability has been a central theme and driver for developing the scheme. The goal was to establish flexible, efficient, humane and sustaining environments: buildings with low energy consumption, high-performance cladding, solar shading and efficient insulation to achieve maximum comfort for those that use them.

Defining an exterior and interior (courtyard) envelope that responds to the sustainability goals set by the programme demanded a multilayered approach. Initially the basic shape of the individual buildings needed to be defined so, as to minimize the solar gains and maximize the self overshadowing capacity. Secondly a façade system had to be developed in such a way as to respect the structural grid of each building and allow for modularity and architectural variety. Thirdly an integrated process had to be set in place, by which multiple analysis iterations for the various configurations of the façade could be produced, analyzed and graded in terms of effectiveness, feasibility and sustainability. All of these within very frequent design cycles. Additionally, all of the above needed to be seamlessly integrated within a parametric model that allowed for quick design iterations, analysis and evaluation. The model form produced had also to be driven by specified parameters and constraints -representing the environmental, structural and buildability inputs- as well as promoting user interaction with the general form, in order to reflect interventions shaped by architectural and aesthetical criteria.

2. BACKGROUND

2.1. Initial Form Configuration

As a preliminary response to both the required spatial and environmental considerations, the initial form-finding was defined in conjunction to the input provided by the assigned environmental consultants. Therefore, the general shape started as an extruded box, on which different façade inclinations were tested against their total annual radiation score and self-shading capacity. This investigation resulted in a generic shape resembling an upside-down, four sided cone – a form that ensured lower radiation scores on the façade due to the ability of the higher floors to provide overshadowing to the lower ones. The addition of a considerably overhang roof also assured protection for the higher levels of each building. The optimal inclination for this configuration was set to 23 degrees.

In parallel, each floor was defined based on the base structural grid, measured from the centre of the building outwards. This grid was perceived as a sequence of bays that could be set back or protrude from the main form, in pursuit to the optimal environmentally driven response.

2.2. Environmental Parameters and Multiple Configurations

In addition to the development of the generic building form based on the above considerations, there was also a second set of defined sustainability criteria, which were namely the incident annual direct and diffuse solar radiation as well as each façade's potential daylight capacity. Under that spectrum, for each bay, a number of flexible parameters were defined to permit for an optimal solution. These were namely the glazing to wall ratio as well as the Solar Heat Gain Coefficient (G value) for the glazing itself.

This, consequently, added an extra degree of complexity due to the numerous parameters and potential differentiated forms that had to be iteratively designed, analyzed and evaluated. Each of the four façades of every building had hundreds of bays that could have thousands of different configurations of inward/outward offsets relative to each other, with each bay having 10 different glaze-to-solid ratios (from 10% to 100%) as well as various potential glass G-values. This resulted in tenths of millions of different configurations to process, an impossible feat for the given timeframe if using traditional design techniques.

2.3. Shaping a Parametric Environmental Response

An answer to the above requirements was the development of a) an integral parametric model and b) the specification of individual "test cases". The former incorporated an array of bespoke scripts and permitted the management of the model both based on specified constraints as well as direct form manipulations from the designers. The latter minimized the millions of potential configurations into a smaller selection pool, by specifying smart assumptions about the offset and glazing ratio as different test cases.

Based on these different cases, a set of models were developed and simulated and their solar radiation, daylight and vertical sky component results, were pre-computed and registered in tailored Excel spreadsheets. This method ensured direct feedback for any single manipulation of the parametric model as well as facilitation of the optimization process of the façade.

A very important aspect of this integral model was the possibility it gave to the designer to individually manipulate the model and get a direct feedback in relation to how well the drawn configuration performed. Every change in the offsets of singular bays, their glass ratio and G value could directly inform the designer of how good or poorly the new model performed relatively to any other given solution and allowed for educated decisions to be made during the form finding process.

2.4. Optimization Strategy

The final stage of this environmentally driven façade investigation included a multi objective optimization process, using a genetic algorithm, which generated a series of optimized façade configurations. Through several iterations of optimization runs and the manipulation of the weighting of conflicting parameters, that were made possible in the timeframe by feeding into the optimization process the pre-computed data set of results, a range of solutions to the given problem were produced.

The generated configurations were not considered as mere optimal solutions to the given problem, but rather formed part of the guidance of an overall informed architectural solution. The designer intervention was again a key aspect in shaping a solution that satisfies not only these specific performance criteria, but also a range of other architectural parameters, including but not limited to structural, aesthetic and other sustainability parameters of the problem.

3. METHODOLOGY

As already mentioned, for the optimization of the buildings' façade several steps had to be made. These were:

- The design and specification of key 'test cases' for analysis
- Precomputing of incident solar radiation and daylight results for the specified cases
- Development of a results database which allows interpolation lookup in between the specified cases.
- Development of a parametric model that links the precomputed results database and provides real-time feedback to the designer
- A multi-objective optimization process through the use of a genetic algorithm.

A detailed description of these steps follows.

3.1. Design of test cases

One of the most significant steps towards the minimization of the option pool, and therefore the complexity of the searchable solution space was the definition of key points in the movement range of the façade bays and the design of appropriate 'test cases'. The test cases were designed with the aim to minimize the required analysis runs but also cover all possible options.

For this reason, the effect of the protrusion or setback of the neighboring and top bays on the incident solar radiation and daylight performance of each bay was studied, and a set of test cases with a combination of neighboring and top protrusions and set backs were modeled. To cover all possible configurations of the façade the cases were designed in such a way that their combinations could be used to predict the performance of any possible bay option. For example, instead of allowing every bay to have innumerable potential offsets, a set of four points in the movement range was defined. This resulted in a total of 27 bay cases that needed to be simulated, produced by the combination of the effect of the three movement steps, for each neighboring bay (excluding one inward step which has no effect). For convenience, these were modeled as 9 different three-storey models, each of which represented three different cases per each orientation (Figure 1). By combining the effect of the protrusion of each neighbor the result for every possible configuration along those predefined steps is easily achievable. Furthermore, the interpolation of results between those steps, again for every neighboring bay, allows for every possible configuration to be assessed (Figure 2).

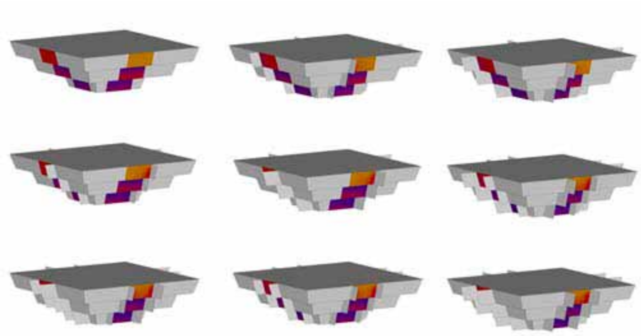

Figure 1. Solar radiation results for a number of test cases.

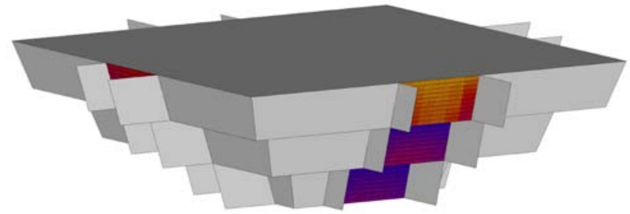

Figure 2. Solar radiation results for one test case.

3.2. Results database

For this defined set of test cases a series of simulations were run to precompute the incident solar radiation and daylight performance of each case. The incident solar radiation was calculated using a bespoke script that links the Radiance simulation engine to a standard CAD package. The results were given as annual solar radiation per panel, on a pre-defined grid of panels and for each test case. For the daylight performance the simulation was run using the Autodesk Ecotect software and the results were calculated on a grid of panels on the floor plane. For each test case, daylight results were computed for a series of different glazing ratios and for two specific time sessions, at 09:00 in the morning and 15:00 in the afternoon.

The combined set of results were then imported in a spreadsheet which was structured as a look-up table to facilitate both the quick look up of different façade configurations as well as the interpolation of results for non calculated options. A representation of the façade panels and their solar radiation results was also incorporated in the spreadsheet along with a number of changeable parameters, such as the solar heat gain coefficient and light transmissivity, providing the ability to explore the performance of different glass configurations (Figure 3). An indication of the percentage of performance improvement over the ASHRAE base case was also included both for the solar gains on the glazing as well as the solar gains passing through it. Finally a representation of the daylight results was incorporated as well providing visual and textual feedback on the daylight performance of each option (Figure 4).

The development of this pre-computed results database was a quite significant step not only because it provided the means to the real time feedback of the developed parametric model and allowed for a set of optimization iterations of the

GA, but most importantly because it provided a first level of understanding of the complexity of the problem.

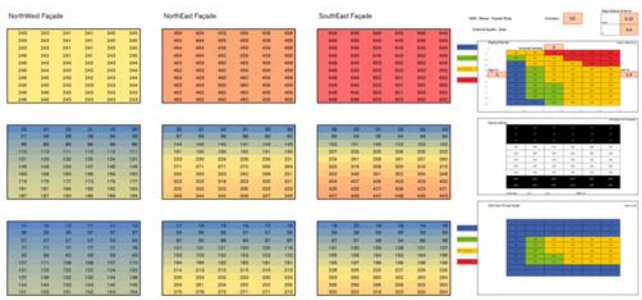

Figure 3. Solar radiation results database.

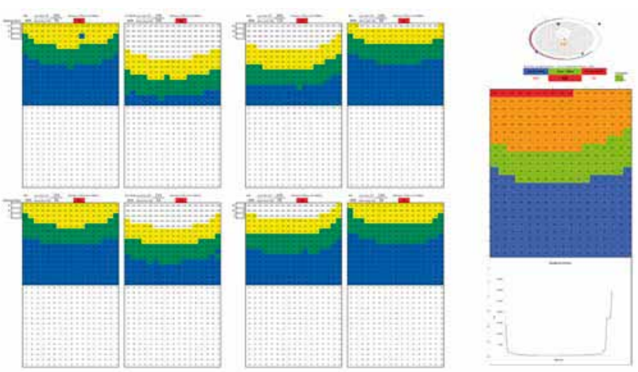

Figure 4. Daylight results database.

3.3. Parametric model

As already discussed, the development of a parametric model, which would be linked to the data set of results, aimed to provide valuable feedback to the design team for the assessment of performance of a given façade configuration and allowed for the exploration of many different design options. The parametric model, which was created using Bentley Generative Components (GC) was linked both to the pre-computed results database, as well as a color-coded set out spreadsheet, which allowed the user to have an overview of the complex set of parameters that define a configuration. The geometry of each building was generated using a series of GC scripts, according to the set out file which defined both the offset from the structural grid as well the glazing ratio of each bay. The resulting configuration was then used to query the database for solar radiation and daylight results for each bay and according to the offsets of its neighbors but also its specific glazing ratio. These results were then applied back to the parametric model giving both visual feedback as well as indicators of performance improvements of the specific configuration (Figure 5).

Through the manipulation of this informed parametric model the design team managed to explore a vast amount of different configurations without the intensive resource requirements of iterative simulation runs. Moreover the emergence of performative patterns on the façade highlighted the important aspects of the design parameters on the performance impact of the buildings and provided a deeper understanding of the problem at hand. Nevertheless a further investigation on optimal solutions, with the aid of computational methods was considered an important further step.

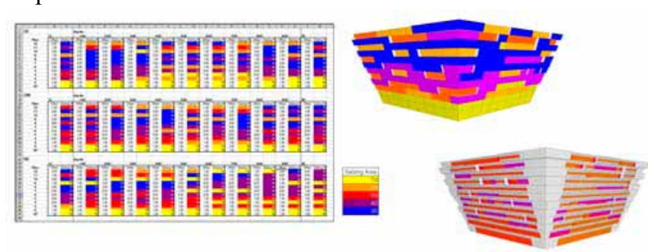

Figure 5. Set out file, generated geometry and results on the parametric model.

3.4. GA optimization

For the GA optimization process a bespoke application was developed in the Processing programming language which was also linked to the pre-computed results database. The choice of a custom written application was not only dictated by the specific needs of this problem but it was also proven invaluable in manipulating the optimization framework to accommodate the architectural constraints of the problem. The optimization framework was developed in accordance to the problem's needs, allowing the configuration of offsets and glazing ratios for each bay of the façade. These parameters were encoded in the genes of the GA enabling it to search through all of their possible configurations. A configuration of all the offsets and glazing ratios for every side of the façade was set out for each of the studied buildings. Also a look up table for the pre-computed results was developed, allowing the quick evaluation of each generation. In detail the algorithm was set out as follows:

- A random generation of configurations is initially generated
- For each member of the population the solar radiation and daylight performance is evaluated as follows:

- For each bay of the façade the relevant pre - computed cases are looked upon and the interpolated result is registered to the fitness function
- The member is evaluated and ranked, according to the different fitness functions used
- The algorithm continues to run until it converges

The optimization process was integrated seamlessly within the design process, including data exchange. The generated optimal solutions were properly exported as set out files for the developed parametric model facilitating the generation of 3d models and visualizations of the optimal solutions. The timeframe of an optimization run using the pre-computed results is not comparable with an equivalent optimization process that would require iterative simulation runs to assess the fitness of every member of the GA population. The time needed to calculate the performance of a building configuration was only a fraction of a second, making feasible the offspring of more than 150.000 generations in one optimization run (Figure 6).

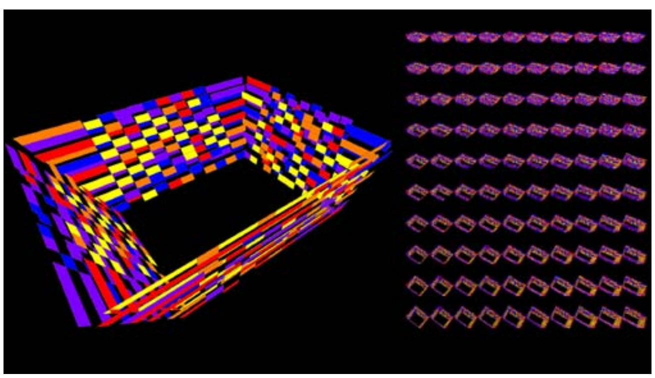

Figure 6. Optimization framework screenshot.

The first results of the optimization process showed clear trends towards offset and glazing patterns, however the conflicting objectives did not initially allow the scheme to converge to a single optimum solution. This led to a further experimentation with various different fitness functions which weighed the importance of the conflicting parameters. The fitness of each member of the GA population was assessed according to its performance in terms of minimizing solar gains and maximizing daylight, as well as its overall improvement ratio over the ASHRAE base case. These were calculated either per bay or per façade or as a combination of both, yielding different results in each case (Figure 7). To rule out solutions that would not be viable, such as minimal glazing ratios on the whole of the façade the optimization process was steered according to architectural constraints. Finally a two step optimization process was also implemented, allowing in a first step the optimization of the offsets of the bays and in a further one the optimization of the glazing ratios for the optimized massing. The final result clearly indicated a trend towards an egg-crate massing with minimal glazing ratio on protrusions and maximum ratio on the set-backs while also converging towards specific glazing ratios per orientation (Figure 8).

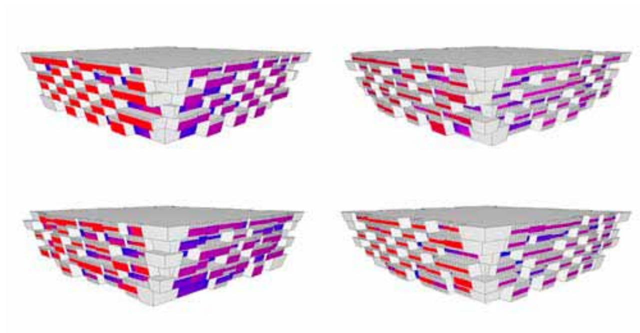

Figure 7. Trade-off between daylight and solar gain

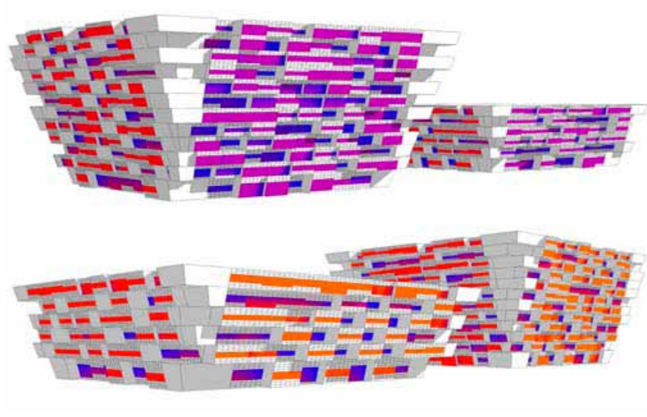

Figure 8. GA Optimization result – Incident solar radiation on the façade.

4. PERFORMANCE DRIVEN DESIGN

The above analytical approach was developed in such a way as to facilitate the development of a design that is shaped based on its performance. To achieve a seamless process two factors needed to be taken into consideration: a) the complex nature of the problem definition and b) how to translate this multi-objective task into an easy to use interface/decision making tool.

4.1. Harnessing Complexity – Integration in Design

Design is, by default, a multidisciplinary affair. Therefore any given consideration has to span through various fields in order for any sort of optimization to be achieved in the scheme as a total. This complexity is actually in the heart of any design development and the way one harnesses it - in order to from design processes and procedures - can define the success or not of the outcome. In this aspect, integrated design as a practice allows for the designer to fully understand the underlying complexity of any given task and the various disciplines through which an optimal outcome should span. That has as a result an underlying weaving of a plethora of factors, which could even contradict each other, but are essential for the project's successful adaptation to the multidisciplinary fitness criteria set.

The parametric approach, thus, is the first step of visually defining the above rules and considerations. This is achieved via a defined compilation of variables and constraints that can reconfigure the model relatively to the various environmental, structural and managerial considerations. In addition to that, the definition of "key cases" for the environmental analysis investigation is essential, as it helps translate innumerable multiple configurations into a more manageable set of options to test against, thus taking upon the task of understanding the complex nature of the problem and then simplifying it as to make it controllable.

4.2. Simulation Interfacing Tool

After defining the above process the subsequent step is developing a tool that can, in real-time, provide the user with the simulation results and the score of each configuration. That is essential in assisting the designer to form the design intentions at an early stage of the process, based on direct feedback provided by the various analyses. Therefore the performance of quick simulations and their ensuing results instantaneously feeding back in the model are of paramount importance. This cycle provides an easy and straightforward way of shaping the design, not based on assumptions, but on synchronized analytical processes that can evaluate the success or failure of each iteration. Therefore the seamless interface between the analyses and its application to the model, where the user is not concerned with interoperability issues but rather directly witnesses the results of his manipulations to the model, provides a very powerful tool for decision making with performance driven design intent.

5. CONCLUSION

The techniques explored for the façade optimization of this project represent an integrated approach to design, achieved through a set of parametric simulation interfacing tools. In order for the form of the building to provide a direct response to the needs imposed by its environment, a bespoke design system was developed which allowed not only the direct manipulation of the model (based on specific constraints and parameters) but also a real-time feedback in terms of it achieving the sustainability goals set.

Based on the multilayered diversity of the problem, the workflow was distributed in different stages. Initially the basic form was analyzed and chosen relative to each self-shading capabilities. Then a parametric model was introduced in order to facilitate quick model changes to match the design cycles. Subsequently "key cases" were defined, so that to minimize the pool of configuration that were to be pre-computed and analyzed relative to environmental fitness criteria. This defined a mechanism of direct feedback in terms of the trade-off achievement between optimum daylight and minimal solar gains: every time the model was changed the designer could directly see how much better or worse the new solution worked relatively to the specified environmental goals. Finally a custom multi-objective Genetic Algorithm was developed so that a global optimal solution could be specified. This optimal candidate was not the "answer" but rather the guide towards a set of potential manipulations that could be taken into consideration in addition to all the architectural, structural, aesthetical and space planning criteria.

Throughout the development of the project it was made evident that an integrated approach to design is greatly facilitated via a set simulation tools that can interface in a parametric manner throughout the design process and allow for direct feedback in every stage of the model manipulation. Thus the user is no longer "guessing" of the configurations that may provide optimal results, but rather makes educated choices based on the instantaneous response of the various diagnostic analyses performed (either those are environmental, structural, pedestrian or similar simulations). Although this approach was developed according to the needs of this specific project, it is expected to serve as a precedent for future relevant multi-objective optimization problems, as its efficiency, both in terms of resources, as well as in terms of integration in the design process, was considered significant. Such a strategy though requires a computational design approach that incorporates considerable custom programming in various languages of CAD or analysis packages, as well as the ability to interoperate between them. But in the same time those custom mechanisms empower the designer in meeting his goals and promoting innovative approaches to an integrated design processes driven by multidisciplinary concerns.

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