AUGMENTED PARAMETRICS

A novel framework for numerical optimisations in a parametric design workflow

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Abstract. Current parametric design software lacks the capacity to integrate simulation and optimisation when they would be most relevant: at the early stages of the design process. This paper presents a novel framework to address this issue: A parametric program that supports performance-based modelling by integrating detailed physical simulation modules that also take construction issues into account, while at the same time providing easy access to high-level optimisation approaches. Providing bidirectional parametric modelling capabilities, we refer to the system under development as augmented parametrics. It is being developed as part of a research project sponsored by the Austrian Science Foundation.

Keywords. Parametric design; generative design; optimization; building performance simulation.

1. Introduction

As parametric software has been tailored to architects an ever-growing number of practices have embraced the possibilities of parametric design. While traditional CAD was little more than a substitute for the old drafting board, parametric design has caused a paradigm shift. Rather than describing a design as a fixed geometry, parametric models allow architects to control design methodology: they enable designers to model complex relationships between input parameters and emerging structures, formulate interdependencies between building parts and include project specific constraints.
While parametric design is becoming increasingly common, mathematical optimisation is already a mature field successfully applied in mechanics and engineering. Several robust numerical methodologies have been developed and are ready to be employed to inform design decisions in architectural practice. Given the growing challenges for architects, such as to reduce the energy consumption or to design structurally feasible complex geometry, it is just a logical step to pair parametric models as numerically driven, dynamic design representations with the capabilities of optimisation methods.

Many computer aided design and building information modelling programs today come with the ability to analyse a design for various building performance characteristics such as energy demand, carbon footprint, structural efficiency or building cost. These analyses can be performed at any time, so architects are well informed about the impacts of their design decisions. But these analysis processes are based on one single static representation of the design, the momentary "snapshot" of the project, and the results of these simulations do not directly feed back into the evolution of the design. Architects are therefore only able to modify their design iteratively, based on current analysis results, their experience and knowledge on the impact of design changes, and are forced to repeat the modification / analysis cycle until a design criterion is met. Especially for geometrically complicated buildings where it is difficult to guess how a performance characteristic can be improved, this is a very tedious procedure.

However, for parametrically formulated designs this procedure can be automated, and more than that, parametric models allow the precise optimisation of designs according to given constraints. Performatively characteristics of buildings are usually determined by a variety of different interdependent design decisions, often times conflicting and sometimes even contradictory. Gain for one design criterion mostly means loss for some other criteria. Therefore finding optimal configurations is in most cases non-trivial and nearly impossible to do "manually".

Usually such optimisations involve the application of multiple specialized software tools, requiring the user to switch back and forth between different programs in a process that is tedious to set up and absolutely requires expert knowledge. In our publicly funded research project we are developing a novel building performance analysis and optimisation framework to be used by architects in a coherent parametric design workflow. We are aiming to develop a flexible system that can quickly be set up, comprised of tools that can be employed throughout the design process, from conceptual stage to building detailing to fabrication.
2. Cognition in design

In their article Design Machines, Stiny and March (1981) present an abstract framework for the development of an autonomous system for creating designs. From their theory we can interpret that the missing part in contemporary CAD software is the cognitive link that bridges the gap between what is possible and what is actual. Cognition or knowing can here be defined in terms of the ability to respond to environmental events, and the stimulus is the part of the environment that is absorbed by the structure of the model. It is the selector of the best design solutions, describing how and when the language and the context correspond to each other.

Contemporary parametric modellers have their system parts connected with networks of constraints that are structured as a hierarchical dependency tree. As an improvement over traditional parametric design, several researchers such as Mahdavi (1997) and Kilian (2006) have discussed and explored the possibility of bidirectional parametric design. The key benefit of bidirectional models is the ability to swap the role of driver and driven during the design process (Kilian, 2006).

Optimisation systems with feedback loops have been studied for decades using a variety of different approaches. For example, Svetel (1993) developed an application called Parallel Distributed Processing Analogical Architectural Modeler that utilises an artificial neural network to design prefabricated single-family houses based on a list of catalogued components. Following a different approach, Schoenhauer (1996) uses several genetic algorithms for generating topology in 2D and 3D space to optimise structural problems of continuous shapes. However, none of these optimisation methods have been fully integrated into the standard BIM packages yet.

3. Augmented Parametrics

We refer to our developed system as Augmented Parametrics: a parametric program that supports performance-based modelling by integrating detailed physical simulation modules that also take construction issues into account, while at the same time providing easy access to high-level optimisation approaches.

The purpose of the presented project is to explore the fundamental premises of a new building design approach capable of dealing with more complex design tasks. In short, we expand traditional parametric systems by combining them with multiple concurrent simulation modules that are linked to optimisation algorithms in a bidirectional way.
The research is structured around three main parts: first, a data package that collects the information required for the analysis of a design from a parametric model. Second, an analysis package composed of several computationally efficient building performance simulation components that can be combined in a modular fashion. While our primary focus is the optimisation of thermal building performance, we are also developing analysis components for daylight analysis, building cost control and structural efficiency. The third part is the Cognitive System Control (CSC), which contains the optimisation and reconciliation engine – the algorithmic way in which the system "plays" with any given set of parameters in order to arrive at recommendations for improving a design. The CSC also contains an interaction model by which the user can steer and control the optimisation process in a transparent fashion.

4. System components

4.1. PARAMETRIC MODEL

As the platform for our tools we chose Grasshopper for Rhinoceros 3d, as this parametric modeller enjoys considerable popularity among architects today and its modular nature perfectly fits our component-based approach.

We put strong emphasis on the flexibility of the system. While the project is structured around our own analysis components, the framework is an absolutely open system and we make no assumptions neither on the structure of the parametric model nor the nature of the optimisation. Anything can become a design constraint, a design criterion to be optimised or a parameter for the optimiser to work with. This allows designers to easily incorporate their own metrics.
4.2. ANALYSIS

Although parametric modellers allow the testing of countless variations, all of these configurations also have to be evaluated and compared to each other. This takes time. While simple optimisation problems might only require a few hundred iterations, more involved problems might need hundreds of thousands of iterations. Many building simulation packages, especially for energy demand analysis and structural simulation, require a considerable amount of computation time, which basically prohibits their application in a framework that combines simulation and optimisation of various criteria in an iterative process. Since the majority of architects have limited computational power at their disposal, and optimisations that take days or even weeks to compute are of little use in a fast-paced office reality, the development of custom, highly efficient analysis modules necessarily became a core part of our research.

4.2.1. Energy demand analysis

Given the rising global energy demand and diminishing energy resources, sustainability and energy conservation is becoming an increasingly important topic in the building industry. However, optimizing the energy demand is no simple task.

Building energy analysis engines that rely on dynamic multi-zone thermal simulations such as Energy Plus ("Energy Plus", 2013) are able to produce very accurate results but are computationally extremely expensive because, in order to be precise, the interaction between thermal zones and the environment must be calculated for each hour of a reference year - sometimes even sub-hourly time steps are used. That way a single simulation will typically take at least a few minutes, which makes an optimisation process that might require hundreds of thousands of iterations a very time consuming task.

After comparing a number of simulation models, we implemented a model that treats the whole building as a single thermal zone and uses monthly energy balances in lieu of dynamic simulation with short time steps. We further increased the computational efficiency by separating the analysis in a "static" and a "dynamic" part. The static calculations thereby rely only on parameters that are known to stay constant during the whole optimization process, such as climate data or target room temperature, and thus can be precalculated once the optimisation process is started. An in-depth discussion of our approach is beyond the scope of this paper, but for the purpose of this system overview it should be noted that we have solved the performance issue, while still getting reasonably reliable results.
4.2.3. Light analysis

Two different approaches for daylight analysis were investigated. In the initial approach we calculated the daylight factor using an analysis grid. The mathematical approach is based on the split flux method, where the daylight factor is calculated separately for each point on the grid, similar to the calculations in Autodesk’s Ecotect software. This method allowed for real time calculations, however its precision significantly fluctuated, as is documented elsewhere (Ibarra and Reinhart, 2009). Therefore, a second light analysis tool has been developed.

It is based on improved global line radiosity, which enables a precision of light analysis comparable to professional software such as Radiance, but with massively faster response. Besides speed this tool has the advantage of being able to use unlimited numbers of light sources without affecting computation times, as well as outputting the overshadowing data required for energy demand analysis.

4.2.3. Economic analysis

Economic sustainability is essential in any project. As economic demands on building design are often contradictory to other design criteria, finding an optimum that would be an acceptable compromise for all contradictory demands is typically very difficult. The ability to impact the cost of the building is highest during early phases of the design process. Making design changes is also less expensive during the initial design stages. It is therefore crucial to make economic calculations already when defining the first concepts and form of the building and that economic analysis is an integral component of the project development.

The common practice is that a preliminary cost of the building is calculated with an average price per cubic meter while the final budget is executed as a detailed itemized sheet. The volume based method is rather imprecise and does not take into consideration many aspects such as the ratio of windows to wall areas where typically the windows are much more expensive. Therefore the options could only be compared on a volumetric level with this method. Itemized calculation provides reliable results but it requires a very detailed project, making this method a tedious and demanding process. The algorithm for economic calculations we are using in this project oscillates between both methods in order to ensure enhanced reliability in comparison to the volume based approach and relative simplicity in comparison to itemized calculations. The algorithm does not only include the construc-
tion costs calculation, as is usual with tools for budget and calculation creation, but we are also trying to cover more economically driven aspects of the design process and thus tackle the issue in a more complex approach.

4.2.4. Structural design module

The structural design module consists of a finite element code using a linear triangle layered shell description with an orthotropic material law for solving the problem. The computation of the mesh is done via a standard Delaunay algorithm for the triangulation of the single surface element providing a fast reliable mesh for the finite element calculation. To be able to reanalyse only parts of the structure and not needing to set up the full stiffness matrix for every iteration step we are using constraint equations. This allows us to retrieve the link forces between the elements directly once the stiffness matrix is solved (Bathe, 1982). These link forces are used to perform the element checks. Stress calculations are therefore not required. The advantage of this approach is that single elements can be changed easily without the need of rebuilding the whole stiffness matrix resulting in a further speed gain. A draw-back of this technique is that the size of the stiffness matrix increases significantly, but with modern multiprocessor machines solving large linear equation systems is no longer a problem.

4.3. COGNITIVE SYSTEM CONTROL

The Cognitive System Control (CSC) is the brain of the framework. It helps to find optimal solutions to the criteria given by the designer. It offers multiple state-of-the-art solvers for global and local non-linear constrained and evolutionary optimisations. The solvers work with design variables, which are numerical parameters that influence the parametric design and thus the design criteria that is optimised. During the optimisation process the solver tests different combinations of values for the design variable to eventually find the best feasible configuration in the search space.

The second part of the CSC is the graphical output. During the optimisation process the optimiser goes through a large number of iterations. The possibility of storing and later accessing these iterations is important; the designer gets not only the best solution found, but also the others that are geometrically better, but perhaps with marginally worse performance. For navigating through the variations we implemented a "radar chart", we refer to it as Interactive Graph Interface.
5. Example: Ve Struhach Apartment Building

To showcase the application of our framework we adapted a design proposal for an apartment building in Prague by Echorost Architects. We rebuilt the design as a parametric model to demonstrate the application of our tools in an early design phase as well as the capabilities and limitations of building optimisations in general.

![Figure 2: Optimising for minimum energy demand (right) and maximum profit (left)](image)

5.1. DESIGN CONSTRAINTS AND PARAMETRIC MODEL

The building site is a narrow lot situated on Ve Struhach street. According to Czech codes, the maximum building volume is restricted so that the new building will not overshadow an existing housing block on the on the north-west side of the lot, which implicates a stepped elevation of new building.

In our parametric model we define lengths and widths of each of the 5 storeys as independent parameters free for optimisation, with the constraint that no floor plan can exceed the geometry of the floor below, and that all geometries lie inside the maximum building envelope. We define a window for every wall element, which is parameterised as a ratio between opaque wall area and glazed area. Lastly, we define the wall and roof insulation thicknesses as optimisation parameters. The floor height is fixed at 3m.

After programming the geometry, build-up for the exterior walls, the roof and terrace areas and parameters for the windows are defined. The physical, ecological and economical properties of materials are selected from our database. Information is associated with parametrically generated geometries using a Grasshopper component that generates a custom class of objects, building elements, which combine all data necessary for the analyses. The building elements are fed into our energy demand and economic analysis components, which calculate the design evaluation criteria (the objective function results) used for our optimisations. After configuring the simulation
settings, all there’s left to do is to choose an optimisation algorithm, hit the start button and let the computer compute.

5.2. ENERGY DEMAND OPTIMISATION

We optimise for minimum energy demand with a constraint that the building be profitable: total building costs must be less or equal to the revenue of apartment sales. We assume an apartment price of 2500 € per m² plus 1000 € per m² terrace. Terrace areas exceeding 35 m² are not considered. Instead of implementing a hard constraint for the economic condition, we punish non-profitable configurations by adding the deficit to the objective function result, which in our experience helps to make the optimisation converge faster.

Since our parametric model is rather constrained, the most decisive factor for the building geometry is the ratio of total floor area to exterior wall and roof areas. We optimise for minimum energy demand, measured in kWh per m² floor area per year, so the optimiser will aim for a configuration where a large floor area is enclosed by a building envelope that is as compact as possible, always under the condition that the emerging design is profitable and does not exceed the maximum building volume. Things get a bit more complicated when it comes to window sizes. Here, the optimiser must find the best possible balance between beneficial solar gains in winter and disadvantageous insulation in summer, while also considering the differing heat loss properties of windows and walls. The optimiser will greedily open the walls facing south almost entirely here, while basically neglecting the rest of the facade. This could be remedied by adding a daylight simulation at a later stage when a concept for the inner organisation of the building has evolved.

The optimised wall and roof insulation thicknesses are of little surprise: we get the largest possible values that we defined in the parametric model as 25 cm for walls and 40 cm for roof areas.

5.3. PROFIT OPTIMISATION

Next we optimise the model for maximum profit. To spice things up we investigate the total building costs (construction and maintenance including energy costs) over a period of 30 years vs. sales revenues. Additionally we limit the annual heat demand to be less or equal to 15 kWh per m², implemented as a soft constraint like the profit condition in the previous example.

For the building geometry the result is pretty clear: the sales revenues outweigh increased construction and maintenance costs, which results in increased net floor areas compared to the previous example. The optimisation of wall and roof insulation thicknesses is more interesting. Here, the best possible balance between construction costs and energy costs over the period
of 30 years must be found. Additionally, more insulation means increased wall thickness, which in turn decreases the net floor area that can be rent.

Although we’re optimising for maximum profit, the window areas on the south-west and south-east facades are larger in this example, even though we set the window price to 750 € per m² and the wall areas with 18 cm of insulation come at a cheap 302 € per m². This is due to the constraint that the annual heat demand must not exceed 15 kWh per m². In this example it makes economically more sense to enlarge the windows and benefit from solar gains in order to meet the 15 kWh condition than to increase the insulation thickness, which will moderately raise the wall build-up cost but additionally decrease the net floor area and thus sales revenues.

6. Conclusions

We have presented the framework and components of the system for augmented parametrics that we are currently developing. This system is designed to include highly efficient simulation and optimisation modules while providing bi-directional control of parameters - a feature essential for tackling complex optimisation tasks at an early design stage and currently missing in commercial BIM or parametric design software. It is an ambitious undertaking, the system is still at prototype stage, but the first results are encouraging. Our next steps will be to consolidate the modular system and run tests to compare the results of our fast simulations with real-world data.

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References