Surfaces Plot

A data visualization system to support design space exploration

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The notion of design spaces (DS) can be understood as the potential of a parametric model, it is basically the number of possible combinations for its input parameters. When combining tools that produce these alternatives automatically with different simulation softwares, the concept of parametric analysis (PA) emerges. This implies a simultaneous evaluation of the alternatives as they are constructed by the parametric model, producing large amounts of information. This article describes a sectional approach to the management of this information and a visualization technique to represent it looking for correlations between the input parameters and their performance. Correlations that are fundamental to making decisions with confidence when design problems challenge traditional methods of decision-making based on heuristics and design expertise.

Keywords: *Design Space , Performance-Based Design, Parametric Analysis, Generative Design, Data Visualization*

INTRODUCTION

A design process considers all the necessary steps for the development and materialization of the built environment. It is an iterative non-linear process of decision-making from early to late stages (Maher & Poon, 1996). As constructions become more complex, demands for performance increase and regulatory requirements become more rigorous, we found design problems that challenge traditional methods of decision-making based on heuristics and design expertise. (Lawson & Dorst, 2009).

The traditional approach to design is a heuristic method based on the intuition and ability of the architect to understand and solve a design problem. This usually limits the possibility of spending time evaluating multiple design alternatives in the early stages of the process, when dominant decisions are made. (Lawson, 2006)

Even with the proliferation of parametric modeling tools, methods to automate the generation of design alternatives or performance analysis software in terms of energy use, natural lighting, carbon emissions and others, designers have limitations to handle the amount of data involved with this kind of multi criteria design problems.

We can understand these scenarios as the set of design parameters, each with a range of possible options and a design space (DS) as the cross product of all the parameter ranges of the design problem (Zdrahal and Motta, 1995). Basically the universe of possible solutions to a design problem derived from the construction of our objectives, the importance we assign to the different parameters involved and their performance with respect to them.

The notion of performance as such derives from the argument that we can critically measure the relevance of a design solution with respect to the requirements it seeks to meet, through an evaluation that considers form, function, and the conditions under which both come together in a specific context. (Kalay 1999). When this evaluation of performance considers multiple disciplines, the design space becomes multi-criteria and multiple trade-off emerge among conflicting objectives. For example, the best solution for natural lighting usually compromises the energy efficiency. (Haymaker et al., 2018).

This leads to all kind of cross compensations while making decisions. These trade-offs incrementally grow while we extend the number of requirements to satisfy. It is commonly recommended to explore these alternatives in terms of experencial, ecological and economic aspects. (Hueting, 1990) Parametric analysis (PA) tools can consider these aspects, at the same time that they provide us with valid information regarding each variation of the parametric model that produces the alternatives. It runs simulations after every parametric change and quantifies their impact producing a large amount of data.

There are multiple ways to manage this information, some methodologies involve search algorithms or prediction strategies. This research focuses on those that involve information visualization systems. Data visualization (DV) is one of the most demanded data analysis techniques to date, since it is easy to detect patterns in data structures through a graphic or image. It is a process of searching, interpreting, and comparing data, especially useful when we seek to understand large amounts of multivariable data.

In recent years, the appearance of these visualization techniques integrated into design workflows has increased.The broader question of this study is how to used that to explore these multidimensional spaces derived from parametric analysis to better support decision-making.

DESIGN SPACE EXPLORATION

The visualization of information is a transversal discipline that focuses on organizing data in a synthetic way in a graphic environment that facilitates its interpretation. We could define it as the representation of data destined to assist our visual perception of computer patterns. Normally there are two types of representations, static, such as a diagram or traditional drawing, or dynamics, which allow the interaction of the designer as a method of exploration.

Interactive visualization allows the possibility of controlling the amount of information displayed. Commonly, the information produced by a parametric analysis is so much that there is no way to present it simultaneously, without a synthesis strategy. These techniques allow to visualize more deeply extensive databases. Using filters, we can explore data that does not appear in a first view, revealing new patterns and relationships.

Project Discover is a clear example of application for a static representation. This is a workflow developed by Autodesk for the generative design applied in architecture. It involves the integration of a geometric system based on rules, a series of measurable objectives and a system to automatically generate, evaluate and evolve a large number of design options.The result of this evolution is represented by a graph that shows the decitions taken by the algorithm as it produced the different generations involved with the process. (Figure 1).

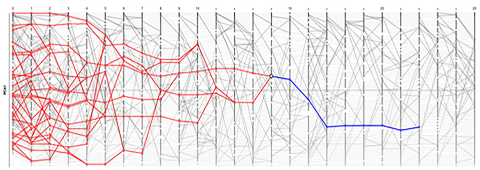


Figure 1
Static representation for the Moga algorithm, Project Discover

On the other hand, a series of emerging methodologies integrate the use of a dynamic representation, such as a parallel coordinates plot (PCP) a visualization technique for multivariable data sets. This represent the dimensions of the design space as parallel vertical axis and the alternatives as polylines across all of them according to how they perform on each dimension.

Design Explorer (DE) is an open source data visualization tool developed by Core Studio, the computational research group of the engineering firm Thornton Tomasetti (Design Explorer, 2016). DE visualizes and filters groups of iterations to explore large design spaces. The tool has a web interface that imports and plots data sets of inputs and outputs of different design alternatives, and an open source plugin to export this information from parametric modeling tools. The visualization of the information is mainly based on a PCP. One of the fundamental characteristics of the PCP is the normalization of values. The bottom of the axis represents the lowest value, while the top the highest one. The scale of several columns is completely independent. DE also connects each profile of the chart with an image and a model of every alternative for interactive visualization.

Fractal Project (FP) is a tool developed by Autodesk to visualize design options from parametric models (Project Fractal, 2017). Unlike DE that requires data tables produced by external applications, Fractal allows generating, managing and visualizing information directly from the parametric model. Its web-based infrastructure facilitates the generation of thousands of alternatives in reduced computational time, and the management of large amount of data.

Even though the integration with analysis engines is limited, this tool allows exploration of design options in early design stages. For performance analysis, the selection of alternatives must be imported to Revit for assigning material properties before being evaluated in Insught 360. The selection itself is before the performance analysis, and it is not driven by objective data at least in the first iteration. On the contrary, the selection is based on subjective qualitative analysis as a way to narrow down the design space early on.

Design Space Construction (DSC), is a methodology developed by Perkins + Will Process Lab research group (Haymaker et al., 2018). Is a process of gathering and structuring information to support decision-making. DSC includes the organization of the participants involved in the decision-making process, their roles and objectives, the automation of the generation of alternatives and integrated parametric analysis to evaluate the performance of every alternative. Evaluation of the overall value according to preferences and data visualization interface to support the interpretation of the data (Inselberg & Dimmesdale, 1990)

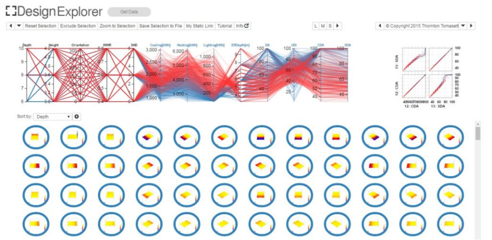


Figure 2
Design explorer interface. Thornton Tomasetti

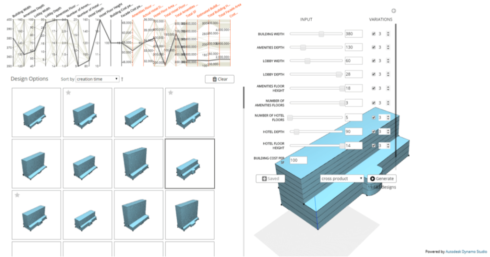


Figure 3
Fractal interface. Autodesk

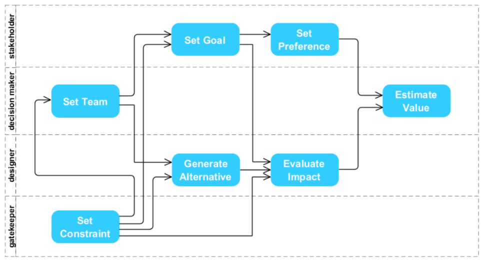
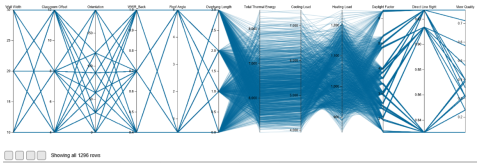


Figure 4
Design space construction workflow.

In addition to the full integration of performance analysis into parametric scanning, the main difference with other workflows to explore design spaces is the value function concept. The DSC approach defines the degree of influence of each aspect related to the design problem, since different stakeholders may have different priorities.

The use of a value function seeks to represent these preferences in terms of the weight of each factor in decision making. The assignment of different percentages of influence to the performance indicators can lead to the selection of different alternatives. Therefore, the problem of decision making becomes a problem of variable distribution of the weight of the indicators.



Wall Width...	Classroom...	Orientation...	WWR_Bac...	Roof Angle...	Overhang...	Total Ther...	Cooling Lo...	Heating Lo...	Daylight F...	Direct Line...	View Quali...
20	12	0	0.4	0.5	0	5669.711	4754.81	914.9004	2.0769	0.9138	0.2381
30	12	0	0.4	0.5	0	6032.005	5139.962	892.043	2.6429	0.9273	0.3572
10	12	30	0.4	0.5	0	5364.661	4412.092	952.5689	1.5089	0.8303	0.2379
20	12	30	0.4	0.5	0	5690.839	4764.699	926.1399	2.0756	0.9138	0.4761
30	12	30	0.4	0.5	0	6060.743	5151.233	909.5095	2.6389	0.9273	0.7143
10	12	60	0.4	0.5	0	5318.57	4361.604	956.9656	1.5045	0.8303	0.3903
20	12	60	0.4	0.5	0	5670.636	4733.928	936.7074	2.0794	0.9138	0.5809
30	12	60	0.4	0.5	0	6064.774	5137.436	927.3381	2.6386	0.9273	0.7715
10	12	90	0.4	0.5	0	5328.535	4378.067	950.4679	1.5072	0.8303	0.31

Figure 5
Design space construction interface.

The potential of these tools lies in their ability to manage the large amount of information produced by the parametric analysis of different aspects. Their common goal is to provide an integrated environment to support the decision-making process. They allow to explore large spaces for the design of possible solutions in an acceptable time and to support the iterative generation-evaluation process. Although the methodology of each research group has singularities, they share the use of a form of graphic representation for the understanding of the information.

However, each approach has limitations to visualize the performance detail of each zone or section of a building, since the indicators represent the overall score of the design criteria. The use of this technique hides the details of how each area performs independently, and becomes difficult to read when the number of indicators grows excessively. If we think of a house with two rooms as an example, with a general value indicator of 50%, we can ask if the specific value of each section is relevant.

In detail, this 50% can be given by a room valued close to 0% and the other close to 100%, which averages 50% overall. Or failing that, for both rooms valued close to 50%. This level of detail that is lost with traditional assessments can be decisive with respect to the decisions made during the design.

Problems that are repeated in all the methods that base the selection process on the representation of the information. The specific objective of this study was to extend the resolution of these techniques to visualize similar performance indicators in different areas of the same building. For this purpose, the proposed method produces a discrete representation by area and interpolates through all of them to characterize each alternative according to the singularities of each zone instead of the average performance of the building.

SURFACES PLOT

Given that the objective of this study is the exploration technique by sections for design spaces, the emphasis of the methodology lies in the management of the information. Parametric analysis tools already developed by other research groups are used for the construction and evaluation of alternatives.

This workflow considers three main stages. The production and adaptation of the information to a data structure useful for the method. The normalization of information and the introduction of priorities by sections. Finally, the visualization of information using the surface plot (SP) technique.

DATA MANAGEMENT

The role of graphics applied by other research groups is the representation through a unique profile of the general behavior of a design alternative. Relating its input parameters with each performance evaluation and its respective value indicator. The "surfaces plot" method proposes the construction of an information matrix for each alternative. Basically a table that presents: on the one hand the different evaluations of performance considered, and on the other, each one of the zones.

To describe a single design alternative at the same time this table is quite clear. Separating the general analyzes of a complete project to a presentation by zones allows to study the behavior of each part of the project from its singularities.

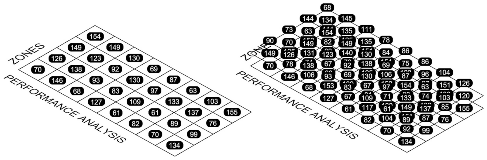


Figure 6
Data tables ordered by zones.

A zone oriented to the north, evaluated with respect to its natural lighting, could have ranges of values and a performance completely different to an area oriented in the opposite direction.

The use of general analyzes hides the detail of these singularities. This can cause a design alternative with: a poor area and an outstanding area; Be valued with the same percentage, as a design alternative with all its similar areas.

When we superimpose the tables that represent the behavior by zones of several alternatives at the same time. The amount of information begins to impede the reading. Image 6 presents only three overlapping tables, for a multivariate design problem, thousands are usually considered.

VALUE FUNCTION

As we mentioned earlier, the problem of decision making becomes a problem of variable distribution of the weight of the indicators. In a representation matrix like the one proposed in the previous step, a single column of information is independent. The analyzes have their own scale and commonly different units of measurement.

The normalization of these values allows the comparison between columns, understanding that the pinnacle of each column of data will be the best result achieved in this aspect by any of the alternatives of the design space. On the contrary, the base of each column will represent the worst result achieved. The rest of the alternatives are between these two points. But of course this normalization does not represent a value as such. Even with the amount of information involved it is difficult to select possible solutions based solely on the best or worst results. The value indicator is presented through a matrix of priorities, which charts the preferences of those involved in the design. Also determining what is understood as “the best combination of parameters” to achieve the design objectives.

The search for this best combination is guided by the same concept of performance. We will understand as the best combination of parameters, the set of input variables that produce the best valued model in relation to our priorities. Even different stakeholders can establish different matrices of priorities, getting completely different results. Varying the percentages of value for each section would permute the parts of the entire project obtaining unique results for each party involved.

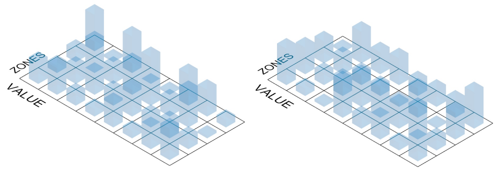


Figure 7
Two different value matrices.

The overall performance of each selected part translates into the overall performance of the building. The exploration can be done by changing the specific value indicators of each section to improve the overall result. It can be given in some aspects of the design to benefit others.

VISUALIZATION

After normalizing the information and assigning a value table for each aspect of the design problem, we can graph the surface that represents the specific value of each performance evaluation. With respect to the rest of the design space produced. This also selects the best alternatives for each section, based on the delivered value indicators, feeding the parametric model for the production of a complete proposal. Or several proposals, as the case may be.

Each section is represented by a unique profile that relates each aspect evaluated in the parametric analysis. It is easy to visualize the profiles that represent a single complete alternative, but when including the rest of the design space filtering the information is fundamental. (figure 8)

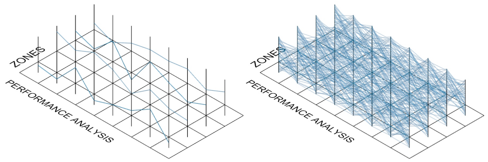


Figure 8
Representation of some discrete profiles.

The surface that forms under each unique profile, describes the behavior of a section in all aspects evaluated. On the contrary, the surface that is formed by the cross product of these profiles, describes the behavior of all the sections in a single aspect. Different filters to explore the information obtained from the analyzes. (Figure 9)

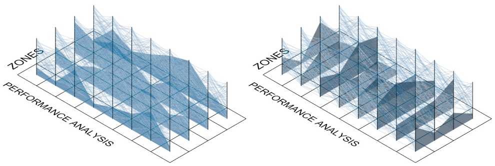


Figure 9
Parallel surfaces representation.

Finally, the interpolation of each discrete profile on a single surface provides a new reading of the information. The maxima and minima of this surface represent the singularities of the information.

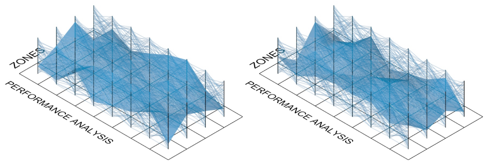


Figure 10
Surfaces Plot Interface.

The question of finding the weak and strong points of a possible solution becomes a problem of graphic interpretation. When modifying the value indicators this surface responds by altering the general result. The performance of the general proposal has a value given by the sum of the individual results for each section. In addition, each section can be improved in isolation.

TEST CASE

The proof-of-concept was carried out using a building with variable section as test case, originally proposed during a workshop given for the dissemination of the DSC methodology and developed in depth during a professional practice with the perkins and will process lab group. This was structured in four stages: generation of a population of alternatives, the corresponding performance analysis, and the visualization of the results, and the comparison between PCP and SP visualization methods.

For this case of specific study, the concept of performance is considered under the compensation of two parameters, thermal performance and percentage of protected spaces. Understanding that only these two aspects can not be considered as performance as a whole, if not only as a problem of compensations between two isolated aspects, sufficiently varied as for the proof of concept.

ALTERNATIVE GENERATION

The case study was based on the design for a kindergarten. The proposal for a variable section building is based on the idea that each section of the project could respond differently according to the program it hosts. It was expected that this would be the main factor behind a better thermal performance for the building. In contrast, the building was oriented against the wind, so reducing its section impaired its ventilation and reduced the protected spaces of this for children. Encouraging compensation

The parametric model to generate alternatives has two fundamental objectives: to minimize energy consumption and maximize outdoor spaces protected from direct wind. This is constructed from different control points for the interpolation of a curve as the main axis according to the context.

The proposed approach to improve energy efficiency is to lower the level of the building to reduce the heat losses through the walls. On the other hand, to protect the outdoor spaces from the wind a taller section is required. Therefore, lowering the level penalizes this second objective. The combination of both provides a design space of compensations useful for the demonstration of the visualization method. Each zone of the building independently varies parameters for width, height, length, percentage of the underground volume, and slope of the roof. The resulting catalog of all combinations of parameters is greater than ten thousand alternatives.

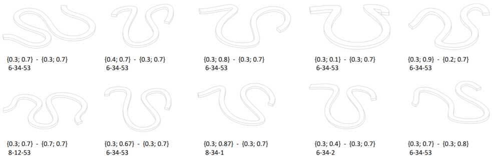


Figure 11
Sample of design space

PARAMETRIC ANALYSIS

The parametric analysis was carried out with tools introduced by the DSC framework. It relies on the integration of parametric modeling tools and analysis engines though plugins that exchange information between them after every parametric change (Roudsari, Pak, & Smith, 2013).

The energy simulation calculates the heating and cooling energy required to maintain the building at a comfortable temperature throughout the year in kWh/m2. For the wind protection study, a parametric analysis of the model was programmed, under an equation to calculate the wind shadow produced by its variable section. The metric is the percentage of the protected spaces produced by the building, with respect to the total area of open spaces.

The study of energy efficiency has improved the results when the building is underground, due to the lower heat losses. However, it compromises the protected areas against the wind. On the other hand, a higher building increases the exposed surfaces where heat losses occur. Producing a compensation space large enough for a detailed exploration.

EXPLORATION

The conflicting objectives create a compensation space to test the approach. Each zone of the building has different requirements, since not all the sections are close to the open spaces that we want to cover from the wind. The zones at the ends have a different influence with respect to the analysis of energy efficiency. The SP method produces a specific value indicator corresponding to the requirements of each section.

RESULTS

To verify the effectives of SP of finding higher overall scores by searching zone-by-zone rather than at the overall building level, the results of wind protection (%) and thermal performance (Kwh / m2) of four zones were compared against the other methodogies. The value indicator is set to 70% influence for energy efficiency and 30% for protection against wind. The following table shows the best results obtained by this indicator in PCP. The control parameters correspond to the main height (A), an exterior height (B), an interior height (C), the low level phase difference (D) and the phase difference between the two levels of each zone. The combination of the parameters describes a design space of 15,630 possible alternatives.

Table 1
Better results using PCP method

A	B	C	D	E	Energy	Wind	Value
5m	6m	4m	4.5m	3m	43 Kwh/m2	24%	76%

The result of the PCP is the selection of an alternative. On the contrary, SP selects an alternative for each zone. The result that allows comparing both approaches is given by the average value of the five selected sections.

Table 2
First result with the SP method.

A	B	C	D	E	Energy	Wind	Value
3m	6m	4m	3m	3m	31 Kwh/m2	10%	72%
4m	4m	3m	3m	3m	38 Kwh/m2	11%	73%
5m	6m	4m	4m	4m	43 Kwh/m2	24%	76%
7m	6m	5m	4m	3m	53 Kwh/m2	62%	83%
Average					43 Kwh/m2	26.7%	76%

While the average of the results for energy efficiency per section remains similar, the range for the percentage of protection against wind is lower in some sections. The same value function in different sections selects other combinations of parameters. The result for wind protection is 2,7 points higher. It is slightly better, but not conclusive yet.

We can also adjust the value function for each zone. The sections at the ends of the project, for example, has a very low wind protection range. If we reduce the influence of this indicator to only 10%, the losses will not be as great as in in the central sections. In this way, the sections at the ends have a value indicator that benefits the thermal performance and the central zones a value indicator that benefits the protection against the wind. The results obtained when calibrating the indicated area value per zone are significantly better.

A	B	C	D	E	Energy	Wind	Value
1m	4m	5m	2m	2m	22 Kwh/m2	04%	83%
3m	3m	2m	2m	3m	29 Kwh/m2	09%	87%
4m	4m	3m	3m	4m	36 Kwh/m2	21%	89%
6m	5m	5m	3m	4m	44 Kwh/m2	74%	84%
Average					32.7 Kwh/m2	27%	85.8%

Table 3
Better results using SP method

The best option regarding thermal performance achieves 22 kwh / m2 in zone one. However, In terms of wind protection, it gets the worst result with 4%. On the other hand, zone four achieves 74% in its best result. This difference is due to the value function that penalizes wind in favor of energy in zone one. For this reason, section one has a high value indicator for energy performance, which will result in savings for the total building.

This allows us to conclude that the problem with these design problems lies in the assignment of the value indicator. The general evaluation of the building improves from a selection of value based on the singularities of each section. We must assign values to each aspect of the design, but we do not always have confidence in the influence that these would have on the final result. SP tries to be a way to explore this influence.

From intuition to prediction

While there does not seem to be a real substitute for the experience when establishing priorities in the aspects involved with the design. These methods are an approach to a systematic process of calibration in this selection of value. The future challenge lies in the construction of the value table. If these simulation models produce enough information, historical patterns can be established in it. The construction of these priorities could be proposed by a predictive model and not by the designer's own experience.

Maybe it's just a matter of facing interaction interfaces against prediction models.

ACKNOWLEDGEMENTS

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