Solving the Black Box: Inverse Approach for Ideal Building Dynamic Behaviour Using Multi-Objective Optimization with EnergyPlus

Nelly Adriana Martinez

University College London, Bartlett School of Graduate Studies, Faculty of the Built Environment, London, UK, n.martinez.12@ucl.ac.uk

Abstract

The need for zero carbon buildings is changing the trial-and-error process that Architectural design has traditionally employed towards a system that allows wider analysis capacity at the conceptual stage. By visualizing design as a “Black Box” where the composition variable B can be cleared from knowing the stimuli S and the desired response R; optimal solutions arise to the surface. The Dutch FACET project which initiated to find the ideal dynamic properties of a building shell to get the desired indoor climate at variable outdoor conditions implemented this inverse approach and served as inspiration for this work which will build on their findings but implementing a two-step methodology. (1) Fabric properties where optimized using EnergyPlus+jEPlus+EA aiming to reduce heating & cooling energy and minimize thermal and visual discomfort. (2) Best solutions were used to create an ideal dynamic building using the best performance at each timestep and interchanging material properties accordingly. The results presented indicate that adaptive behaviour stands as a promising way to harmonize energy consumption and discomfort levels conflictive nature.

Keywords: Multi-objective optimization, Dynamic building, EnergyPlus, jEPlus+EA

1. Introduction

The ever changing conditions that a building is subject to, make reaching optimal performance along the entire time a difficult task to achieve. Weather and user patterns greatly fluctuate along time in contrast to the steady parameters that are perceived as comfortable for the people inside them. They are the bases that determine energy consumption for, whenever these are not meet, artificial systems enter to recreate a benevolent atmosphere. This contradictory paradigm along with the traditional way of conceiving buildings as static elements places their design out of context; not following the logic behind a dynamic environment.

The search for a built environment that reconciles energy efficiency, comfort and health has led to strategies that follow passive and nature design concepts, artificial systems efficiency or alternative energy sources. Although these paths have for sure signified a progress; current building stock performance shows that much is still left to do. Proposing buildings with the capacity to mutate offers the possibility to combine the best of these strategies and provide optimal performance under any circumstance.

Acting as the difference between the exterior and interior; adaptations of the building fabric have the greatest potential to transform conditions into acceptable ranges by changing its properties and by hence the way energy is balanced. Advances in
technology and material science have made this a possibility already achievable; a series of “smart windows” can vary opacity or infrared transmittance according to different conditions and Nanotechnology and Micro-engineering have found in the atomic level a way to manufacture materials that respond in ways that were not possible before.

Incorporation of adaptive behaviour is changing the Architectural method from solving a space to solving a process (Loonen 2010), where successful designs are determined by the analysis capacity at the conceptual stage when the world of possibilities is large. This work will explore the implications that adaptive behaviour in buildings carry to the design conception and emerging tools identified by previous research in the field (Wang et al. 2005), (Bakker et al. 2009), such as Multi-objective Optimization (MOO) and the Inverse Approach for their potential to balance the conflict between comfort and energy savings.

2. Building Adaptive Concepts
Multiple adjectives are commonly used in an attempt to describe a building’s non-static behaviour. Such buildings are commonly referred in literature as: active, dynamic, adaptive, kinetic, responsive, living, smart, interactive, high performance or advanced, to name some (Schnadelback 2010), (Loonen et al. 2013), (Velikov & Thün 2013). Since few years ago different initiatives have tried to cluster and define under one concept these buildings that accommodate to the ever changing external and internal conditions in a search for communication, energy efficiency, health and comfort.

Environmentally Responsive
The Energy Conservation in Buildings & Community Systems (ECBCS) programme, coordinated by the International Energy Agency (IEA) In 2004, unified the concept under Responsive Building Concepts (RBC) & Responsive Building Elements (RBE) which definition and design guidelines were published in Annex 44 (Aschehoug & Perino 2009), (Heiselberg 2012). In this case responsive referred to the ability for energy capture, energy transport and/or energy storage (Heiselberg 2009). Information from existing cases was collected in an aim to maximize their potential and a design approach which articulated responsive building elements, building services and renewable energy systems through an integrated design process where the different experts are involved from the conceptual stage was proposed. Its weakness is that they relied on the same method architecture had been conceived and focused only on commercial technologies.

Adaptive Architecture
This concept stills somewhat ambiguous but seems to have begun to form about a decade ago in an effort to describe these emerging examples. Its objectives are not only environmental but also societal and communicational. Even though many authors have discussed it; perhaps the best effort to give it a framework are those by (Lelieveld et al. 2007) who as part of her Ph.D. defined it as “Architecture from which specific components can be changed in response to external stimuli” and (Schnadelback 2010) who defined its drivers, what they react to, methods, elements and effects. Although his categorization has a humanistic approach where environmental goals belong to the social motivations together with lifestyle and fashion; it allows inclusion of internal and aesthetic adaptations regardless of whether or not they have a physical effect.
Climate Adaptive Building Shells (CABS)

Initiated in The Netherlands, hub for research in the field for several years, CABS started as a research project between the Organization for Applied Scientific Research (TNO), Energy Research Centre of the Netherlands (ECN) & University of Plymouth in 2008. It was defined and contextualize by (Loonen 2010) in his MSc Thesis as:

“A climate adaptive building shell has the ability to repeatedly and reversibly change its functions, features or behaviour over time in response to changing performance requirements and variable boundary conditions. By doing this, the building shell effectively seeks to improve overall building performance in terms of primary energy consumption while maintaining acceptable thermal and visual comfort conditions.”

It is until now the best one documented with a database of around 200 built, prototype and patented cases (Loonen n.d.). His categorization was found to be the most successful as it uses simulation tools logic, layering them according to the physical domain involved and presenting them as the result of a process. It will be the one on which sections 2.1 and 2.2 develop.

2.1. Adaptation Mechanisms

Adaptation in architecture has been found to be determined by either the material’s inherent ability to change (micro-scale) or a mechanism assembled to produce the transformation (macro-scale). At the micro-scale, physical properties of materials vary according to how they convert a certain energy input (potential, electrical, thermal, mechanical, chemical, nuclear and kinetic). When this energy affects the material’s molecular structure the result is a change of its properties, but when it is the energy state the one affected then the result is an exchange of energy. In one, the energy is absorbed and the material undergoes a transformation while in the other the material stays the same but the energy changes (Addington & Schodek 2005). At the macro-scale properties are changed through movable parts using the effect of forces for moving objects and involving the dimension of time (Crespo 2007). They operate according to ambient, scheduled or personal preferences and changes are triggered by a sensor that registers conditions and drives the data to be interpreted by a processor which subsequently sends a signal to the corresponding actuator for an action to be executed.

Whatever the adaptive mechanism is, it requires a time lag to change from one state to another which could happen from a matter of seconds to hours, days, seasons and so on. Moreover the mechanism driving the change not always performs the same on both directions, for example reactions activated through chemical means can return to the original state thermally or materials that obscure according to temperature perform differently when heating up than when cooling down; quality known as Hysteresis.

2.2. Physical Domains

In the realm of controlling external varying conditions to keep an ideal internal environment; skin has given the example to follow being object of multiple analogies in architecture (Vassela 1983), (Drake 2007). Human skin adapts to temperature and humidity, is waterproofed but permeable to moisture, feels draft and touch and repairs itself keeping organs healthy and comfortable (Wigginton & Harris 2002). Being the limit between outdoors and indoors, just as skin, the building envelope is exposed to a diversity of forces and therefore has the ability to regulate them as required. Loonen
distinguished four physical domains with their respective interdependencies on which CABS act in order to adjust internal conditions: Thermal, Optical, Air-flow and Electrical (See Figure 1) and suggested Sound and Moisture as possibilities not included for not existing yet an example (Loonen et al. 2013).

![CABS Physical Domains](image)

Figure 1. CABS Physical Domains

This categorization simplified the complexity embed in building adaptation but mixed an end-result with the means to achieve it. In terms of energy efficiency, Optical properties of materials can be adjusted to improve thermal comfort but adaptations that just end up in a change of visual perception are not relevant. The same case applies to the Electrical and Air-flow domains; adaptations that generate electricity are only relevant if it is actually used to improve building’s performance and the Air-flow ones only if they act on indoor air quality and thermal comfort. More over the scope should allow space for all the required needs regardless of whether or not examples exist, although materials that absorb moisture (Hygroscopic) have been known for years and research shows they can moderate indoor humidity conditions (Simonson et al. 2004). Products like hydrogel are being investigated to absorb/release air water vapour to control indoor humidity (Johnson & Kulesza 2007). Researches like “Building Things that Talk II” by the Responsive Skins Initiative (Yazdani et al. 2011) shows how an acoustic stimuli could trigger an actuator which could easily be translated into buildings that can control the decibel levels admitted.
To overcome these limitations a new scheme is proposed identifying five domains that adaptations targeting to reduce energy consumption and maximize comfort pursue (See Figure 2): Thermal, Visual, Moisture, Acoustic and Indoor Air Quality (IAQ), where each one is achievable through four different means or their interrelation: Electrical, Optical, Mechanical or by Reaction (Chemical, Radiant, Magnetic, Thermal, Fluid). Even though adaptation in buildings might have other targets such as communication or social connectivity those have not been explored in this work.

Figure 2. Adaptation Target Scheme

T – Thermal
M – Moisture
A – Acoustic
I – Indoor Air Quality
V – Visual
3. **Solving the Black Box**

A black box is an imaginary representation of a set of systems affected by a stimuli $S$ and out of which reactions $R$ emerge. The constitution and structure of the box are irrelevant and only the behaviour of the system matters. This is what one of the greatest second order cyberneticians referred to as “trivial machine”; one which couples a particular stimulus with a specific response (Foerster 2003). In his work he mentions that all machines we construct or buy are, hopefully, of this kind to perform the task they have been designed for.

Our search for buildings that do not require fossil fuels inevitably leads to the investigation of unusual devises (Glynn 2008); where cybernetics has several lessons for building designers as adaptive systems are intrinsically dynamic becoming the design of a process rather than an “artefact” (Moloney 2007).

The approximation to the black box depends on the problem one is looking to solve, for the simplest ones it is assumed that the intensity of the output $R$ at a certain time is determined by the intensity of the input $S$ at a prior time; from where three possible problems can be postulated (Bunge 1963):

![Figure 3. The Problem of Prediction](image1)

*Given the kind of box and the stimulus $S$, find the response $R$.*

![Figure 4. The Inverse Problem of Prediction](image2)

*Given the kind of box and the response $R$, find the stimulus $S$ responsible for the behaviour.*
Given the behaviour $R$ under a known stimuli $S$, find the kind of box that accounts for the behaviour.

In the case of buildings the problem might not be as “obscure” and could be better addressed as “Gray Box” due to the fact that they have enough internal constrains based on physical laws built into them (Reddy 1989). Architectural design has been treated as the kind of problem number 1 where once a design is proposed; its performance is calculated hoping to get the desired results. No wonder why we have failed in the design of a simple trivial machine and our buildings don’t behave the way we want.

Five years ago the Dutch FACET project was initiated with the objective to solve the question of: “What would be the ideal, dynamic properties of a building shell to get the desired indoor climate at variable outdoor climate conditions?” (de Boer n.d.); which has been the inspiration for the present work. This query specifically deals with the kind of problem number 3 and, as Bunge describes, is not well-determined and therefore does not have a unique solution.

3.1. Methodology
An ideal building would provide comfort with zero energy implications, dynamic adaptations of the fabric could absorb the ever changing external climate to keep internal conditions in the narrow comfort band with the lowest energy use. This work has focused on thermal and visual conditions as comfort indicators and cooling and heating loads as the energy ones. The desired thermal comfort will be based on ASHRAE 55-2004 humidity ratio and operative temperature parameters using a Clo level of 0.5 for summer and 1.0 for winter. While optimal visual comfort will be based on a maximum allowable discomfort glare index of 22 as recommended in (EnergyPlus 2013b) reference guide.

To find the parameters that a fabric should have in order to obtain the desired indicators a method called “System Parameter Identification” colloquially referred to as the “Inverse Approach” will be implemented. It is commonly applied to existing buildings as it is a technique where energy behaviour is identified from performance records while in actual operation (Reddy 1989). Input data typically includes static building information and dynamic (time dependent) weather and energy consumption reports (An et al. 2012). This time building information will be dynamic and energy consumption and discomfort static at zero (or to approximate zero) replacing thus metered reports and enabling the method to be used at a design phase.
The FACET project proposed the inverse approach as a feasible way to find ideal properties of adaptive shells (Boer et al. 2011), (Boer et al. 2012), (Bakker et al. 2009) but, while it was running, only got to evaluate comfort and energy independently and analysed adaptivity simply in terms of what smart façade glazing and adjustable shading options could offer disregarding opaque surfaces potential. It also proposed the implementation of multi-objective optimization (MOO) as a future step to visualize the performance benefits of CABS going beyond what static designs could offer towards a utopia point where comfort and energy don’t conflict (Boer et al. 2011) (See Figure 6).

Figure 6. CABS Improved Pareto Set (Boer et al. 2011)

This paper will built on their work but simultaneously consider both; visual and thermal comfort in association with building energy consumption while MOO will be used to evaluate those fabric variables that would offer optimal results to be the base on which an ideal dynamic building will be built. Two steps have been implemented in the process; first, different material properties will be optimised with three objectives in mind: reduce heating & cooling energy and minimize thermal and visual discomfort. Second, the best solutions from optimization results will be used to create an ideal dynamic behaviour by finding the best performance at each timestep of one hour and interchanging material properties accordingly. Chapter 4 (step 1) and Chapter 5 (step 2) will describe the particular methodology used to develop each step and their findings.
3.2. Model Description

Weather: To maximize the performance potential that dynamic buildings could offer, a location with half cooling and heating degree days along the year was looked for. This would mean that most of the time conditions would be outside of the comfort zone towards both margins representing a challenge for energy savings. Latitude and height variations are main determinants for weather conditions; the farther from the equator (specially the northern hemisphere), the more heating is needed. While the closer to the equator (and at low altitudes), the more cooling is required; therefore a proper weather for this work would be in-between the limits of the tropical area and the latitude line form where only heating is required. A weather complying with these parameters was found in Madrid-Spain and the input file obtained from the DOE database.

Figure 7. Madrid Dry-Bulb Temperature (°C) & Relative Humidity (%)
**Geometry:** A simple one zone building was built in EnergyPlus 8 m in length, 6 m wide and 2.7 m height (Area = 48 m² Volume = 129.6) with walls oriented perpendicular to each cardinal direction. Due to its northern location an opening was placed at the south maximizing passive solar heat gains in winter. Glazing ratio was kept at 50% with window dimensions of 5.4 m in length and 2 m height starting at 0.35 m above floor level. It is an open plan office for two people with walls and roof exposed to the external environment and no external shading from devices, vegetation or other buildings which could benefit internal conditions for results to show the effects of the fabric itself.

**Construction:** Glazing and building fabric were built in one layer setting their properties as a variable which could be substituted with values from a specified range according MOO criteria. This was done using jEPlus (Zhang et al. 2011) the parametric tool for EnergyPlus designed to test different model parameters simultaneously. The tool generates commands for EnergyPlus to run and collects the results afterwards. Even though the parametric pre-processor utility has been included in EnergyPlus since recent versions, not requiring coupling it to an external tool anymore; this method was used as the MOO software applied is designed to handle the process through jEPlus.

The idea was to set the ranges by finding the lowest and highest values for each variable existing in the world and extending beyond their limits allowing space for future development in material science (See Table 1). But during the process it was found that EnergyPlus has a limit on what it considers realistic and doesn’t allow very low conductivity with very high densities and specific heat capacities therefore conductivity lowest value was set at 0.65 W/m-K, not as low as many insulating materials but lower than what combined layers of an insulated wall could have while the highest boundary for density and specific heat capacity was set at 3000 kg/m³ and J/kg-K respectively. Not as high as desired for material innovation but still in the upper limit of common construction materials.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Lowest Name</th>
<th>Highest Name</th>
<th>Construction Ave.* Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conductivity W/m-K</td>
<td>0.024 Air</td>
<td>2,200 Diamond</td>
<td>0.028 - 0.04 Insulations</td>
</tr>
<tr>
<td></td>
<td>2,000 Graphite</td>
<td>0.75 - 1.10 Brick</td>
<td></td>
</tr>
<tr>
<td></td>
<td>100 - 400 Metals</td>
<td>10 - 110 Insulations</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.24 - 2.30 Concrete</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Density kg/m³</td>
<td>0.16 Graphene aerogel</td>
<td>22,600 Osmium</td>
<td>10 - 110 Insulations</td>
</tr>
<tr>
<td></td>
<td>0.20 Aerographite</td>
<td>11,340 Lead</td>
<td>1,300 - 2080 Brick</td>
</tr>
<tr>
<td></td>
<td>1.00 Aerogel</td>
<td>3,500 Diamond</td>
<td>2,700 - 8,600 Metals</td>
</tr>
<tr>
<td></td>
<td></td>
<td>520 - 2,500 Concrete</td>
<td></td>
</tr>
<tr>
<td>Specific Heat Capacity J/kg-K</td>
<td>100 Wood</td>
<td>4,186 Water</td>
<td>840 - 1,700 Insulations</td>
</tr>
<tr>
<td></td>
<td>440 Bone</td>
<td>800 - 921 Brick</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>280 - 880 Metals</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>840 - 1000 Concrete</td>
<td></td>
</tr>
</tbody>
</table>

* Source: CIBSE Guide A
Thicknesses were set fixed using widths common in construction practices (Walls = 0.5, Roof = 0.25, Floor = 0.6 m) leaving the calculated U-value and energy balance to rely entirely on the inherent properties of the material. Table 2 summarizes material input values. For glazing the simplified system in EnergyPlus was used setting U-Factor range in 1 – 6.8 and the SHGC in 0.06 – 0.84.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Walls</th>
<th>Roof</th>
<th>Floor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness</td>
<td>m</td>
<td>0.50</td>
<td>0.25</td>
<td>0.6</td>
</tr>
<tr>
<td>Conductivity</td>
<td>W/m-K</td>
<td>0.65*</td>
<td>3000</td>
<td></td>
</tr>
<tr>
<td>Density</td>
<td>kg/m3</td>
<td>0.1 - 3000*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Specific Heat Capacity</td>
<td>J/kg-K</td>
<td>100 - 3000*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thermal Absorptance</td>
<td>0.7</td>
<td>0.7</td>
<td>0.7</td>
<td></td>
</tr>
<tr>
<td>Solar Absorptance</td>
<td>0.7</td>
<td>0.7</td>
<td>0.7</td>
<td></td>
</tr>
<tr>
<td>Visible Absorptance</td>
<td>0.7</td>
<td>0.7</td>
<td>0.7</td>
<td></td>
</tr>
</tbody>
</table>

* Values not as low or high due to software limitations

Internal Conditions: The zone worked as a mixed mode system where natural ventilation is allowed through windows when indoor dry bulb temperature is above 22 °C but only if the outside temperature is at least 2 °C cooler than indoor conditions. Windows would close if wind speed is above 40 m/s when users normally would shut them to avoid papers to blow up. Mechanical cooling or heating was set to start whenever temperature falls outside 19 to 28 °C. The difference between the thermostat deadband and ASHRAE 55 parameters would be classified as thermal discomfort, even though the range would be acceptable for natural ventilation cases, the challenge is for dynamic buildings to reach the most stringent conditions.

As standard offices the building is fully occupied only on weekdays from 8:00 to 17:00 and partially occupied from 12:00 to 14:00 and one hour before and after working hours, simulating conditions were not everybody lunch at the same time and where a person arrives early or leaves late. Same wise equipment was set to work according to this schedule; the HVAC system operates only on weekdays from 5:00 to 20:00 while lighting operates 50% when there is partial occupation except for lunch time where it keeps operating at 100%. Infiltration flow rate was estimated in 0.5 ACH and internal heat gains according to Table 3.

<table>
<thead>
<tr>
<th>Building Type</th>
<th>Density person/m2</th>
<th>Sensible W/m2 People</th>
<th>Lighting Equipment</th>
<th>Fraction Radiant</th>
<th>Latent W/m2 People</th>
<th>Other</th>
</tr>
</thead>
<tbody>
<tr>
<td>Offices</td>
<td>24</td>
<td>5.6</td>
<td>10</td>
<td>15</td>
<td>30%</td>
<td>43%</td>
</tr>
</tbody>
</table>

* Source: CIBSE Guide A

4. Multi-Objective Optimization
Designers often use building energy simulations on a scenario by scenario basis; first a solution is proposed, then evaluated and subsequently a new solution is created based on results. This iterative trial-and-error process is time consuming, ineffective and limited as only few scenarios are able to be explored so the best solution is hardly
accomplished. One approach that assesses multiple scenarios is parametric study where the effect of selected design variables is explored by testing some options or all possible solutions. Despite its potential it requires long computing time and high storage capacity (Naboni et al. 2013), not to mention the brute-force necessary to analyse vast amount of results. The other approach is to reduce the number of simulations by implementing the same logic nature has used to evolve species over time; known as evolutionary optimization. Inspired by the Darwinian evolution theory this approach uses evolutionary algorithms (EAs) which randomly select an initial population group, evaluate it and then apply basic genetic operators (reproduction, crossover and mutation) according to the fitness ranking of each individual towards the established objective (Naboni et al. 2013).

The selection of the appropriate optimization algorithm depends on the problem one is looking to solve. A building can be optimized for one or multiple objectives but while single-objective problems offer a unique optimal solution, multi-objective optimizations are problems with conflicting criteria suited for stochastic methods where optimization aims at finding a set of Pareto solutions instead (Wang et al. 2005). A solution is Pareto-optimal if it is dominated by no other feasible solution, meaning that there are no other solutions equal or superior with respect to the objective values (Lartigue et al. 2013). No Pareto solution is better than the other, making the selection up to the trade-off relationship between benefits and their penalties.

MOO requires two stages: optimization of specified objectives for generating one or more Pareto solutions and ranking of trade-offs for selecting the best ones. Both steps can be performed either in sequence (known as Generating techniques), together (setting up trade-off preferences from the beginning) or iteratively (articulating preferences progressively) (Sharma et al. 2012). The algorithm used was NSGA-II which improved the NSGA by introducing elitism; it is of the Generating techniques type and therefore searches Pareto-optimal solutions before ranking them. For most MOO methods it is the ranking procedure the one that encapsulates all the tricks (Zhang 2012).


As described in section 3.2 the parametric solution space was carried out in jEPlus using 14 variables (1- Conductivity, 2- Density, 3- Specific Heat Capacity, 4- Thermal Absorptance, 5- SHGC, 6- Glazing U-Factor). Even though variables for opaque materials were the same, they were treated separately on each surface to allow walls, roof and floor having different properties from each other; turning variables 1, 2, 3 & 4 into 12 independent ones. With the ranges as presented in Table 2 the project resulted in 2.68x10^{17} design alternatives.

The files necessary to run EnergyPlus simulations are linked in jEPlus and once the variables are set, the EAs tool can be coupled with jEPlus to run the optimization. Many tools were found to use EnergyPlus with EAs but were either expensive or came in Java which is a language that architects usually don’t speak. jEPlus+EA is a tool that, even though is still in its Beta version, has been designed to reduce the initial effort curve that coupling EnergyPlus with generic optimization tools so far requires (See Figure 8 for process description).
Crossover rate was set to 1.0, mutation at 0.4 and the population size established in 10 for a maximum of 250 generations executing in total 2,500 simulations. The computing time required was 2 hours and 20 minutes in a 3rd generation dual core processor and 4.3 GB of storage capacity was required. A big improvement compared to what would have been necessary for the $2.68 \times 10^{17}$ jobs.

4.1.1. Optimization Results

The three objectives were stabilised after 130 generations showing minor improvements after generation 205 in thermal comfort and energy consumption (See Figure 9). Visual discomfort did not improve after the third generation; limiting the best performance to a minimum of 111.25 hours of glare during the year while thermal discomfort kept in a minimum of 1147.25 hours. Although none of the objectives reached zero; after splitting Total Sensible Energy into cooling and heating it was observed that cooling energy was totally eliminated thus energy’s best performance of 4.23 GJ/yr represents heating only.

The multi-objective algorithm found a set of 168 non-dominated individuals in the solution space. Figure 10 shows the Pareto front as displayed between energy and thermal comfort, it exhibits a fan shape where some solutions seem to overlap with dominated individuals due that it is a three objective problem and therefore is solved in three dimensions. It clearly represents the trade-off conflict where energy consumption increases as thermal discomfort minimizes. Figure 11 displays the case between energy and visual comfort where the Pareto front exhibits a non-continuous linear behaviour explained by the fact that glare is not related to heating or cooling energy demand.
The situation between thermal and visual discomfort looked similar but this time a diagonal trend was observed where, even though variables seem not directly related, lower visual discomfort solutions have a higher thermal discomfort penalty (Figure 12). Discomfort glare at a reference point happens due to high luminance contrast between a window and the interior surfaces (EnergyPlus 2013a). For all Pareto cases it occurred in the afternoon from 15:00 to 17:00 on January, November and December; months where the sun has the lowest altitude showing it would be controllable by a simple vertical shading device like blinds or louvers in winter, but not explaining the relation displayed with thermal discomfort.

For a better insight into the design space, Pareto solutions were normalized and plotted in parallel coordinates where each one is represented by a line (See Figure 13). Vertical axes 1 to 14 display the design variables evaluated while axes 15 to 17 the three objectives results. At first glance it clearly shows all cases have the lowest possible U-value on walls (1.09 W/m²K) and roof (1.75 W/m²K) by focusing on the lowest conductivity option of 0.65 W/m-K. This is understandable as these are the fabric surfaces exposed to external conditions bearing the biggest responsibility on energy balance. The wide range in floor conductivity could result from the ground coupling algorithm which is challenging for simulation software (Judkoff & Neymark 1995).
Figure 10. Objective 2 vs. Objective 3

Figure 11. Objective 1 vs. Objective 3
Using the “brushing” technique (Loonen et al. 2011), results were filtered according to the best performance on each optimization objective to visualize subsections of the solution space. Cases with a conditioning energy demand lower than 5 GJ/year are shown in Figure 14 where, besides conductivity, low Glass U-Factor (1.0 W/m²K) and high thermal absorptance (0.8) now appear as determinant variables to minimize heating and cooling needs; ratifying the importance of low U-values on exposed surfaces and solar contributions in minimizing heating demands.

Solutions where thermal discomfort did not exceed 1400 hr/year are visible in Figure 15; this time ultra-low density on external walls (0.1 kg/m³) and high specific heat capacity (2700 J/kg-K) on the roof were added to the low U-values. Meaning that external walls are excellent insulators while the roof which is exposed to direct solar radiation most of the time; has good thermal mass properties controlling fluctuations of internal conditions. Basically the walls are behaving close to aerogel (but lighter) while the roof could be asphalt, concrete or stone.

For visual comfort the best solutions were those that did not exceed 120 hours of glare/year (Figure 16). Once these individuals were isolated it was noticed that glazing properties such as very low SHGC (0.06) and very low U-Factor (1.0 W/m²K) were common variables, explaining the relation with thermal comfort in Figure 12 and denoting that while low Glass U-Factor is beneficial for both; low SHGC is convenient for visual but not so much for thermal comfort. Glazing with low SHGC darkens a room avoiding high surface contrast but also reduces solar energy transmittance lowering interior temperatures.
Figure 13. Parallel Coordinates – Pareto Optimal
Figure 14. Parallel Coordinates – Best Energy Performance

Vertical axes represent normalized values; for actual numbers refer to Appendix C.
Figure 15. Parallel Coordinates – Best Thermal Performance

Vertical axes represent normalized values; for actual numbers refer to Appendix C
Figure 16. Parallel Coordinates – Best Visual Performance

Vertical axes represent normalized values; for actual numbers refer to Appendix C
To properly visualize results, the solution space was plotted in a tridimensional chart picturing the three optimization objectives simultaneously. Dimension Z represents energy, X visual comfort and Y thermal comfort while the gradient scheme indicates where each solution stands in respect to Z with the green colour highlighting Pareto individuals. It is noted that solutions displace parallel to the Y axis in a series of curved rows that reduce as Y values get lower and where optimal solutions lie at the bottom of each row ranging from high to low energy consumption due to the trade-off dilemma previously described.

Figure 17. Tridimensional Solution Space
5. Ideal Dynamic Behaviour

In the first step using multi-objective optimization, those fabric properties offering the best performance were revealed along with the trade-off dilemma that exemplifies the inability to meet the objectives simultaneously. Results showed a set of solutions with remarkable performance representing the best that a static building could accomplish. Whereas static buildings can only offer optimal conditions for a limited amount of time; the Ideal dynamic building should be able to have the best fabric properties under any given condition thanks to its mutating ability. The objective of this second step is therefore to find the dynamic behaviour that a building with the conditions described in section 3.2 should have to improve its performance beyond the set of Pareto solutions.

5.1. Building the Fabric

Weather and internal gain inputs at a given timestep possess individual characteristics that would require different material parameters to obtain zero discomfort and energy consumption all the time; basically each timestep needs to be optimized. This could have been done using MOO but running the design space for a period of one hour instead of a year, although it would have signified running 8 760 optimization jobs each one containing 2 500 runs, resulting in 2.19x10^7 simulations and requiring a total 20 411 hours. With this limitation a simplified approach was used where timesteps of the best static buildings were combined to create a dynamic fabric capable to offer optimal performance at each hour of the year. The difficulty relied on how to choose which jobs were the best among the Pareto front as they are all best solutions and no one is better than the other.

Three ranking methods were analysed; the first weighted solutions according to a personal preference where energy consumption was considered the first priority followed by thermal comfort with visual comfort being least important as it would be manageable through blinds or louvers. Jobs where the three objectives had values below the average were filtered obtaining a new list of 17 solutions. A tabular view of the minimum, maximum and average values possible to obtain with this ranking demonstrated that the best possible value for each objective would not be achieved if these jobs were picked as parent ones and the dynamic building would not be the best it could be (See Table 4). A second option used the logic behind the performance indicators set-up, where the objective function was minimized for all three targets meaning that the closer results were to zero, the better the performance would be. Results were added and sorted in ascending order choosing the first five to represent the best solutions. A tabular evaluation showed that with this approach the minimum possible value for visual comfort and energy consumption would not be possible.

Other method used the ranking order proposed by the evolutionary algorithm taking the first five as the best solutions for; as it was mentioned in section 4, the ranking method for most MOO software encapsulates the tricks. The tabular evaluation showed that the maximum and minimum values were included in this sample and that their average was very similar to that of the whole Pareto set. This demonstrated that the combination of these five jobs would generate the best dynamic building behaviour.
These five jobs were simulated now in timesteps of one hour, to select which properties to use for the ideal fabric behaviour the “close to zero” method was used. If the sum of the objectives equal zero then that timestep could be considered ideal, in the case more than one job presented the same ideal timestep then the priority would be according to the EAs ranking while if the sum was different than zero then the timestep with the lowest value would be chosen.

5.2. Dynamic Building Results
The percentage of the year parent jobs achieved ideal conditions ranged from 61% to 69%; by having the capacity to adapt its fabric properties the new building exhibited ideal conditions along 75% of the year (See Table 5). When comparing annual energy consumption and comfort performance (See Figure 18), the difficulty to balance conflictive criteria with a static design is noticeable; case 4 exhibits the most balanced performance but whereas thermal discomfort is the best possible value; visual discomfort is the worst case condition. With the dynamic fabric the resulting heating demand was 21.01 GJ/yr while cooling was completely eliminated for a total energy consumption of 437.81 MJ/m². Thermal discomfort was reduced to 880.75 hr/yr and visual discomfort to 111.75 hr/yr. Even though this solution do not have the lowest energy consumption; it surely represents the best trade-off harmony and percentage of ideal conditions along the year. The Pareto front is a better way to visualize the dynamic building against the best static designs (See Figure 19), its location definitely denotes improved behaviour although it seems that reaching the utopia point described in (Boer et al. 2011) in which optimal comfort is achievable without conflicting with energy consumption remains Zeno’s dichotomy paradox.

Table 5. Static Parents vs. Dynamic Fabric

<table>
<thead>
<tr>
<th>Objective</th>
<th>EAs Rank</th>
<th>Dynamic Fabric</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ideal Timesteps %</td>
<td>0  1  2  3  4</td>
<td></td>
</tr>
<tr>
<td>Visual Dis (Hr)</td>
<td>111.25  146.25  111.25  144.25  146.25</td>
<td>111.75</td>
</tr>
<tr>
<td>Thermal Dis (Hr)</td>
<td>1498    1508.5  1897.75  1741    1147.25</td>
<td>880.75</td>
</tr>
<tr>
<td>Heating GJ/yr</td>
<td>38.78   6.81  5.66  4.23  19.21</td>
<td>21.01</td>
</tr>
<tr>
<td>Cooling GJ/yr</td>
<td>3.37    0.00  0.02  0.00  0.28</td>
<td>0.00</td>
</tr>
</tbody>
</table>
Figure 18. Static Parents & Dynamic Fabric Performance

Figure 19. Ideal Dynamic Building vs. Pareto Solutions
6. Conclusions
Pursuing a sustainable built environment requires designers to be able to find an optimal design efficiently. Evolutionary optimization allows Pareto solutions to be identified in a single run whereas conventional trial-and-error methods can hardly come up with the best possible solution. Despite its potential, MOO is not being widely used from the conceptual design phase due to the lack of Architect-friendly tools. Moreover building adaptation is a field in which the boundary between professions gets blurry requiring knowledge beyond what Architecture and Engineering commonly offer with close collaboration from disciplines like Chemistry, Programming and Cybernetics amongst others.

Building performance simulation stands as an indispensable tool to evaluate adaptive behaviours but current software specialize in the analysis of a certain physical domain (Thermal, Visual, Moisture, Acoustic or Indoor Air Quality) with very few exceptions covering a wider range and usually not strong in all. The domain interaction of adaptive buildings inevitably demands performance analysis using different tools presenting simulation coupling as an inevitable step.

Whereas most tools today include dynamic controls for shading and glazing; thermal mass variability still represents the biggest challenge to simulate dynamic conditions requiring advance simulation knowledge and creativity from the person that uses it (Loonen 2010). Fortunately research in this field is starting to reflect; EnergyPlus for example now allows total custom control of the envelope through the Energy Management System (EMS) feature, representing a significant improvement though there is still work needed to overcome the limitations of what software accept as realistic.

The results presented indicate that adaptive behaviour in buildings stand as a promising way to harmonize energy consumption and discomfort levels conflictive nature. Further work would need to evaluate visual discomfort according to illuminance levels instead of the glare index and include electric lighting control into the simulation settings, dimming lights according to daylight contributions and include their electricity use into the energy objective. This way energy consumption would be affected by both comfort indicators closing the relationship between the three variables. An additional step is to translate the analysis into a design proposal and employ a dynamic simulation to compare how close it gets to the ideal behaviour and validate the black box method as an architectural design principle.

References


