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HYBRID METAHEURISTIC EXPERIMENTS OF REAL-TIME ADAPTIVE OPTIMIZATION OF PARAMETRIC SHADING DESIGN THROUGH REMOTE DATA TRANSFER

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ABSTRACT

The author seeks a practical approach to complement deterministic design optimization in environmental performance-based building design. This study investigates algorithms and scripted processes to test and monitor the dynamic optimal control of building components. To this end, an integration of wireless data transfer equipment (nRF24L01) and a customized metaheuristic hybrid optimization algorithm (Tabu-based adaptive pattern search simulated annealing, T-APSSA) through a parametric visual programming language (VPL) interface (Rhino grasshopper®) is presented with experimental design of a responsive kinetic shading device. To demonstrate the performance of the algorithmic hybridization and early design integration, T-APSSA is compared to simulated annealing and pattern (direct) search, and two different approaches to daylight-optimized design solutions are tested: a deterministic optimization based on historical weather data and a site-specific adaptive optimization according to real-time monitoring of incident solar radiance. The suggestion of a seamless environmental building design workflow through remote data communication contributes to strengthening intelligent architectural design decisions.

1 INTRODUCTION

Introduction of computational logics and software in the architecture industry is fast transforming building design processes innovatively. The emergence of building information modeling (BIM) methods, tools, and three-dimensional (3D) visualization techniques has enabled architects and engineers easily to access a great deal of complex building data during design phases (Kroner 1997; Howe 2000). Particularly, algorithm-integrated approaches to environmental building design help to find better architectural solutions with rapid prototyping of various options. Nowadays, the development of user-friendly interfaces and platforms supporting parametric design, also called generative or algorithmic design, accelerates environmental information-driven form-making or performance-based design as a new trend in architecture (Díaza 2017). Recently, beyond 3D BIM, the rapid spread of sensor and mobile technologies to the design industry is now advancing environmental design to the 4D or even *n*D paradigm coupled with a real-time coordinate (Fukuda 2016).

In the environmental building *design process*, however, the integration of dynamic information from the real-world and BIM-building performance simulation (BPS) has not yet been fully highlighted. A key to bring more actualities and accuracies to BPS and design is unfolding the standalone working of a single-purpose simulation, thereby coupling it with real-world parameters so as to strengthen the responsive mechanism between the digital environment and actual representation. This concern raises cross-disciplinary technical issues, such as tether-free data communication, sensing of physical systems, remote visualization, self-adjustment in data transmission and so on. This study addresses this gap-in-knowledge in architectural design, and therefore suggests a practical schematic design method based on CPS coupled with an optimized responsive control of parametric building façade through the dynamic sensor data transfer within a unified design interface. In this BPS-design system using a digital building model coupled with physical system measurement, and a data communication technique aims to make the building design process far more interactive and dynamic, envisioning a new possibility in the use of BPS to creating a more sustainable and healthier built environments.

2 ENVIRONMENTAL BUILDING DESIGN: OPTIMIZATION, AND DYNAMIC ADAPTATION

2.1 Automation in building design

Buildings are purposely designed to provide occupants and urban communities with shelters and services of dwelling best-coordinated to internal and external conditions, and then, a building becomes a containers of complex environmental, communal functions and meanings. Due to the overwhelmingly mixed contexts and factors engaged in design, construction, and operation, actual building functions are hardly predictable. Nevertheless, increasing awareness of global sustainability calls for a holistic, self-organized interconnection of buildings, humans, and environments through intelligent technologies to decrease the uncertainty of building operation (Andia and Spiegelhalter 2015), and in this demand, design work takes the greatest responsibility on the final building performance. It is thus progressively required for architects to investigate the controllability or adaptability of building components quickly and assuredly through automated processing of design and planning. Although building automation system (BAS) has been developed earlier for the optimal and remote control of mechanical (air-conditioning and signal) systems, intelligent design has just recently resulted in witnessing some responsive environmental buildings such as Al Bahar Towers in Dubai (2012). Due to the heightened awareness of design automation, visual programming languages (VPLs) and BIM plug-ins have been spread for collaborative data exchange between design and engineering, but architectural VPL/BIM platforms have yet to be fully integrated with efficient optimization algorithms and physical information systems.

2.2 Optimization in building studies

In building study, computational optimization techniques have been widely adopted to a variety of design issues such as building envelope design (Yi 2014; Yi et al. 2015), composition of building materials (Pal et al. 2017), space allocation (Yi and Yi 2014; Yi 2015; Dino 2016), and so on. Since explicit objective functions are unknown in most cases, and variables are subject to high-dimensional constraints, heuristic or meta-heuristic approaches are preferred to find optimal solutions. The recent active marriage of building performance simulation (BPS) and global optimization algorithms such as evolutionary (or genetic) algorithm (EA or GA), simulated annealing (SA), or pattern search (PS), through design process, benefit architecture to be more evidence-driven and scientifically justified. Despite various methodological suggestions regarding metaheuristics of optimal performance, a down-to-earth barrier in this approach, however, is that it suffers from heavy computational loads and slow convergence; the global search with hundreds of BPS runs and large number of variables, without high-performance computing (HPC), is very CPU-intensive and significantly delays design processes, which disqualify its utility in practice. More importantly, objective costs, constraints, and input values of BPS tools (EnergyPlus, CFD, Radiance, etc.) are usually set deterministically while in optimization process. During runtime, a result of each simulation run does not offer any feedback or information about optimization/BPS parameters. This deterministic approach weakens the final quality of solutions.

3 HYBRIDIZATION OF OPTIMIZATION ALGORITHMS: TABU-BASED ADAPTIVE PATTERN SEARCH SIMULATED ANNEALING (T-APSSA)

3.1 Performance comparison of algorithms

In design optimization coupled with BPS, efficient (quick and precise) search for an optimal solution is very important. For this study, a hydrid metaheuristic named tabu-based adaptive pattern search simulated annealing (T-APSSA), is proposed and applied to design problems. T-APSSA making the best of three popular algorithms: Tabu search algorithm, pattern search, and SA. Although SA is straightforward to encode with a few parameters and universally applicable to any type of functions and variables, it takes fairly long to converge, due to its entire randomness. The quality of a final solution and computational intensity also depend largely on the setting of an initial annealing temperature and a cooling rate whose optimal values are unknown before running simulation. On the other hand, Pattern search (PS, a.k.a direct search) is also a well-known global optimization algorithm. PS reduces time complexity significantly, as PS explores only feasible candidates through discretization of a continuous variable domain (mesh grid). An ineffective selection of the mesh parameter (mesh size), however ends up with local optima. Simple performance tests with an artificial landscape (Eggholder function: $f_{\min}(x,y) = -959.6407$, where $-512.0 < x, y < 512.0$) in Figure 1 show such different characteristics of algorithms.

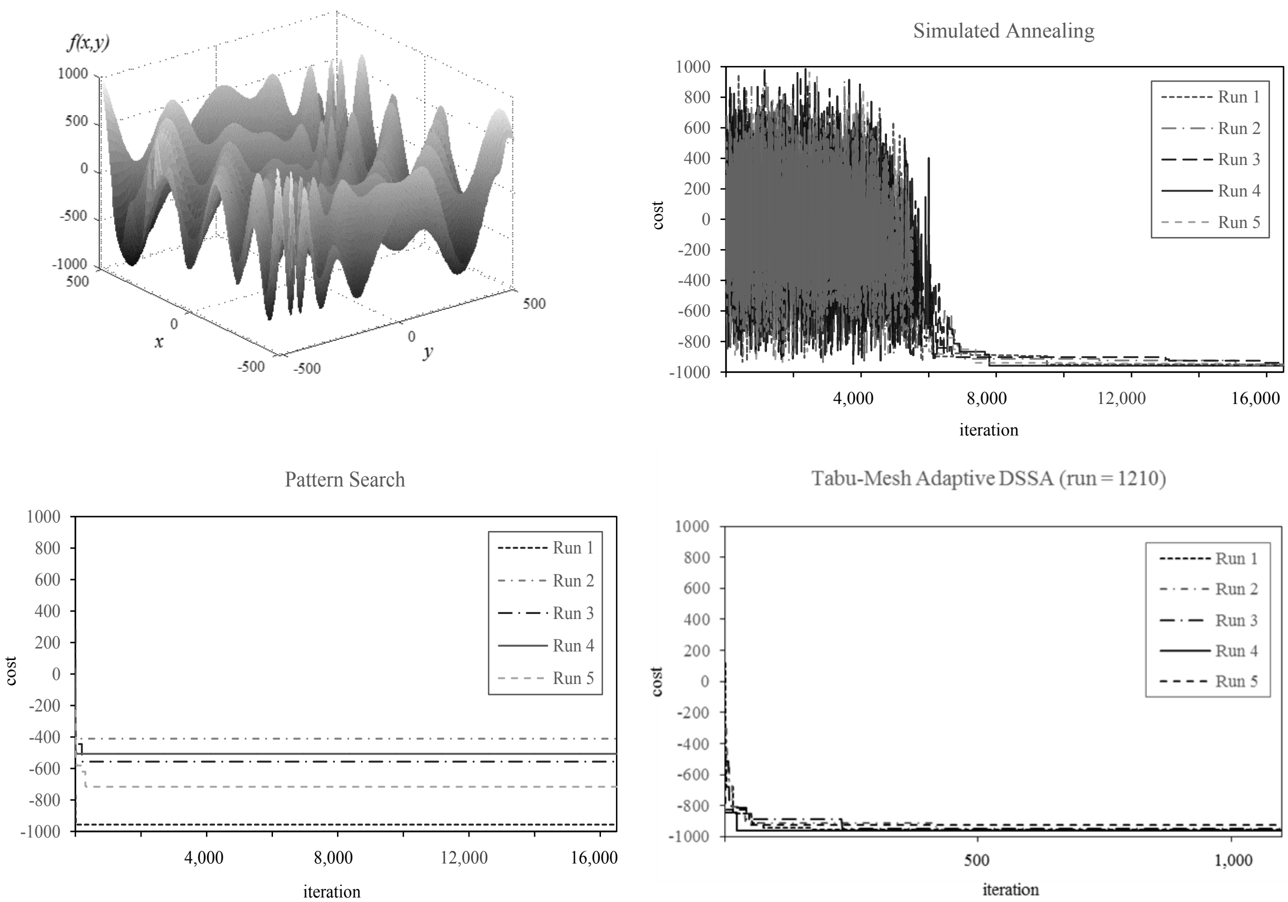


Figure 1: Eggholder function for the full convergence tests of SA, PS, and T-APSSA.

To overcome the PS's tendency falling easily into a local minimum, a method using a flexible mesh size per each run was suggested as mesh adaptive direct search (MADS) (Audet and Dennis 2006).

MADS apparently outperforms PS, but is not completely finding global optima, as it is also mesh-dependent (Figure 2). To activate global moves in direct search, PS or MADS can be combined with SA so that local minima are escaped through stochastic transitions rather than always finding better solutions. The hybridization of PS with SA (PSSA) was suggested with the demonstration of superior performance (Hedar and Fukushima, 2002). The potential of PSSA can be strengthened far more by taking advantage of a set of search rules such as data logging (Tabu direct search; Hedar and Fukushima. 2006) and mesh adaptivity. At each iteration, a Tabu list records individual candidates and the best cost so that discrete random walks will not explore neighborhoods previously visited in a search space. The last result in Figure 2 exhibits the high performance of the mesh adaptive PSSA integrated with TS (memory size = 50). While SA converges after about 12,000 iteration, T-APSSA finds optima at around 200 iteration (6~8 times faster than SA).

3.2 Encoding T-APSSA into BPS and test results

In order to verify actual performance of T-APSSA in BPS, T-APSSA and other algorithms were scripted to an architectural BPS tool, Ecotect®. Before then, using the Eggholder function again, efficiencies of the algorithms were compared within a limited iteration (300). Results in Figure 2 show that a mesh adaptive hybrid of PS with SA yields better solutions by escaping local pitfalls with early probabilistic changes, while SA and MADS hardly converge to the optimal cost. T-APSSA (initial temperature = 50,000K, termination = 0.001K, internal iteration = 3, and cooling rate: 0.85) reached global optima in 150 iteration.

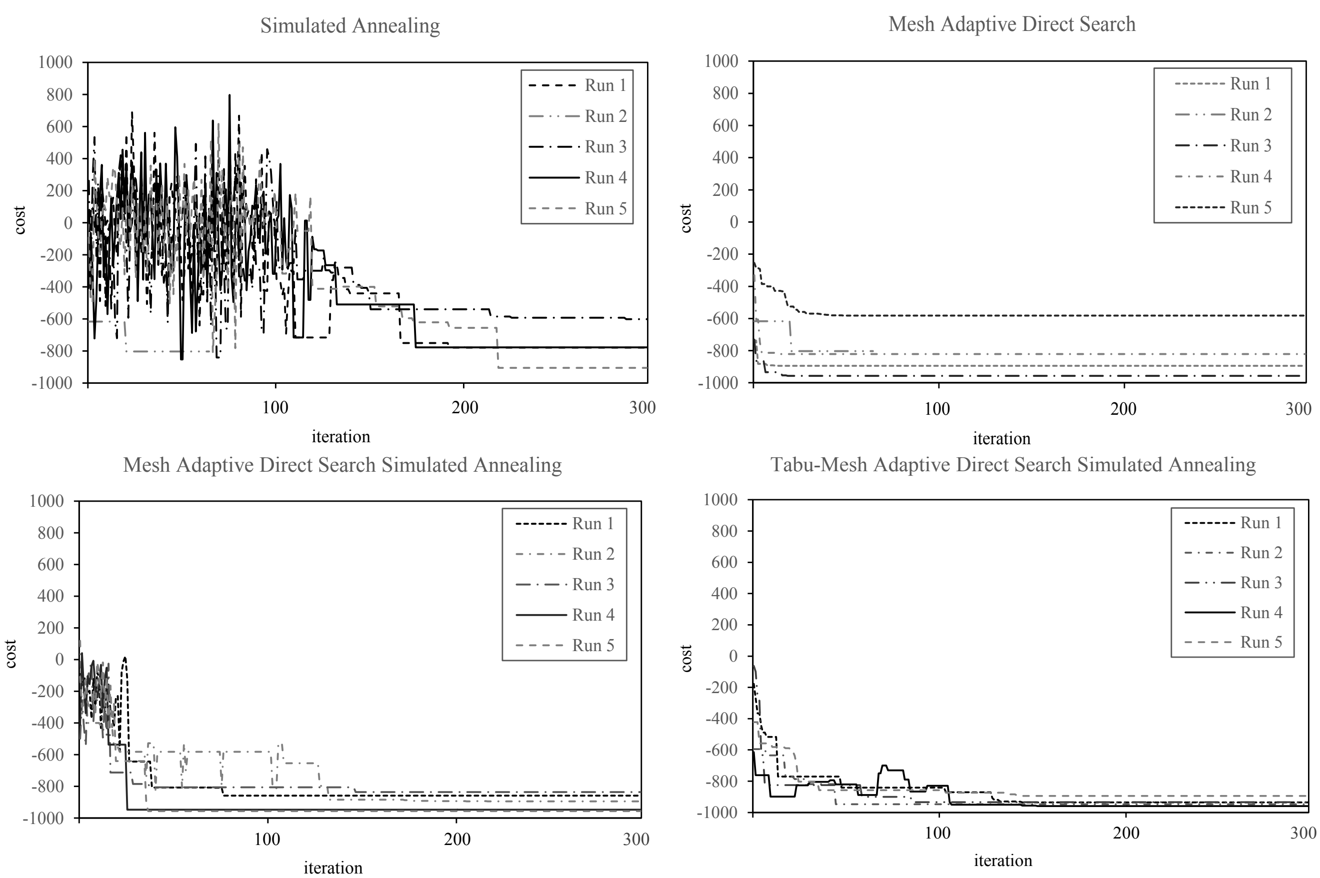


Figure 2: Comparison of optimization performance within 300 iteration.

Performance of the metaheuristics in multi-objective building performance optimization (MOBPO), a simple space volume was tested with 10 geometrical variables regarding the glazing size and surface area such as: $2.00 \leq wd_{\text{floor}}, ln_{\text{floor}} \leq 6.00$, $0.10 \leq w_{g1}, h_{g1}, w_{g2}, h_{g2}, w_{g3}, h_{g3}, w_{g4}, h_{g4} \leq 0.90$ where $wd_{\text{floor}} \cdot ln_{\text{floor}} = 9.00$ (m^2) and the ceiling height is 3 (m). The goal of this experiment was to characterize behavior of the algorithms within the very limited iteration of 20. The first MOBPO was tested under Miami climate, to determine an optimal form minimizing both annual end-energy use and surface irradiance with the same weight. As expected, the best building form must minimize both surface and window area to avoid overheating. Figure 3 presents that SA performs worse than others, while PS and T-APSSA converge very quickly. MADS is also better than SA, but mesh adaptivity degrades search quality in this case. In this test, we identify that, for a simple convex function with a limited number of variables, flexible stochastic moves prevent rapid convergence, and this weakness can be offset by memorizing search traces (Figure 4 (a)). Secondly, to test a more complex MOBPO case, conflicting performance goals were set with the same variables and constraints: minimizing energy use and surface radiation, while maximizing interior daylight (Figure 4 (b) and 5).

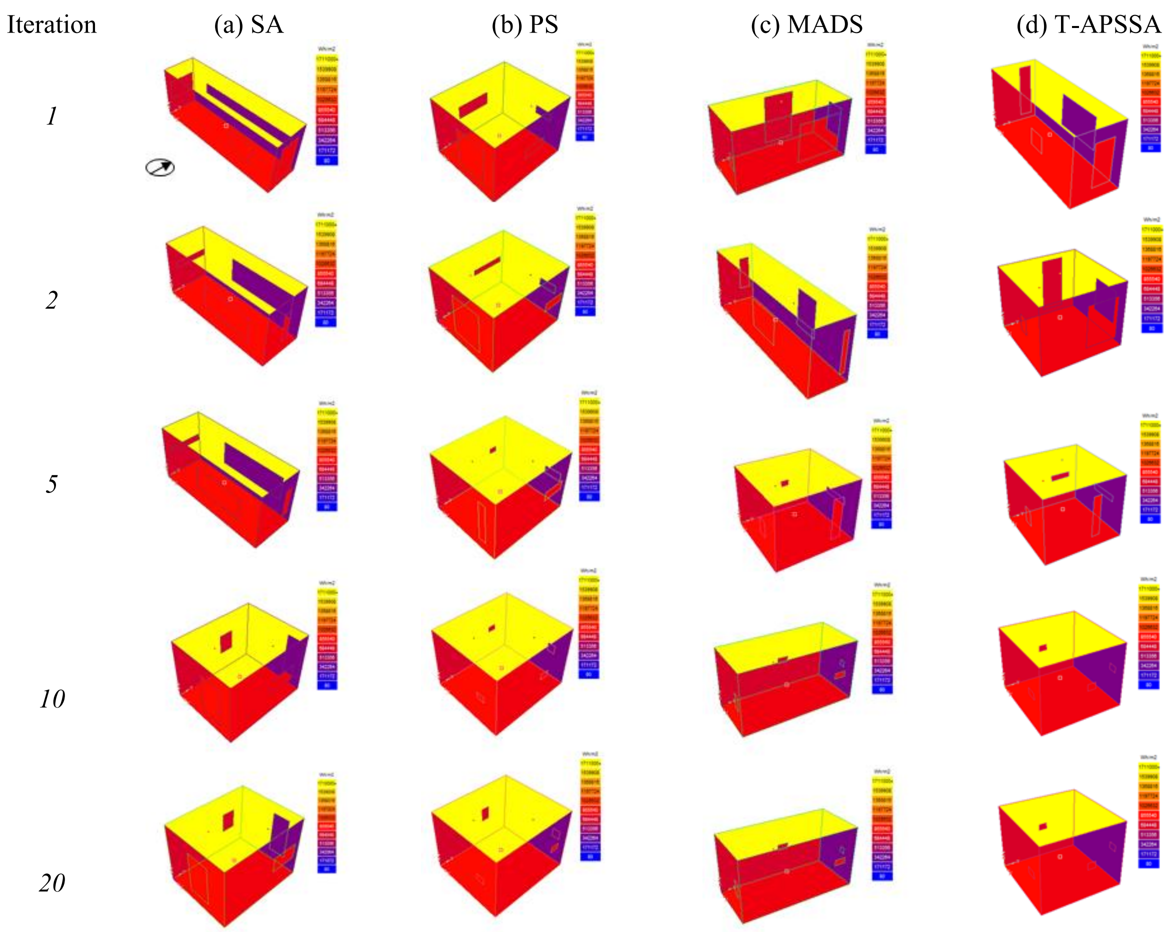
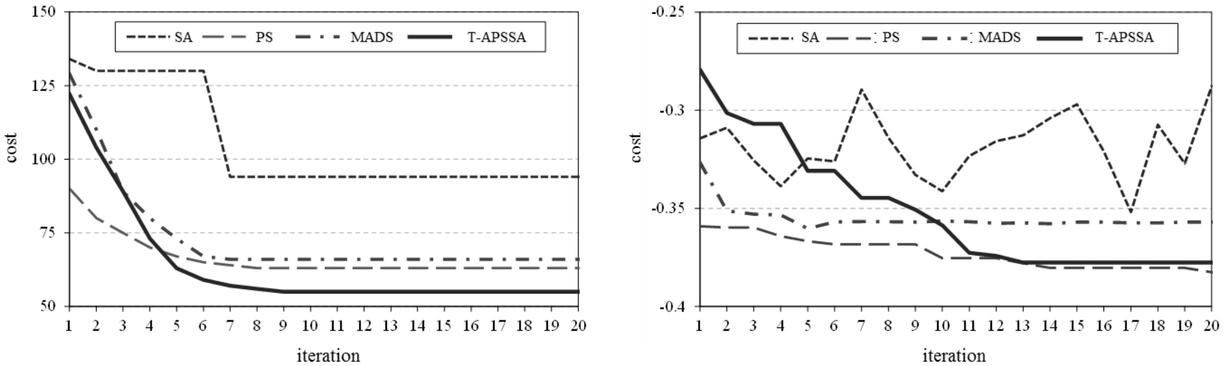


Figure 3: Multi-objective building performance optimization test 1 (Energy and irradiance).



(a) Energy and irradiation

(b) Energy, irradiation, and daylight

Figure 4: Comparison of algorithm performance.

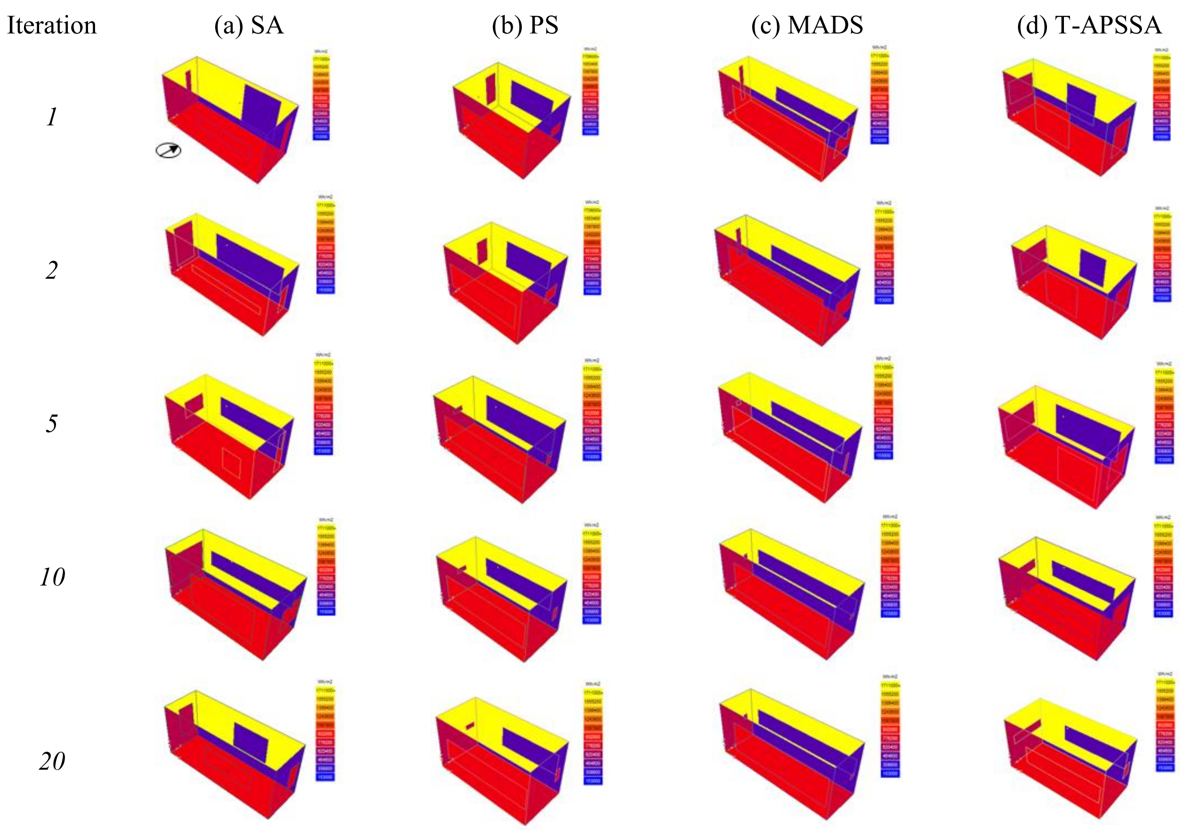


Figure 5: Multi-objective building performance optimization test 2 (Energy, irradiance and daylight).

As shown in Figure 4 (b), SA does not converge within this short-term search, showing the worst performance. Discrete search performs better as well. In Figure 5, building forms evolve to minimize glazing on the east and west to reduce energy loss and heat gain, while compromising with daylight availability on the north and south. PS found an optimal solution rapidly. MADS, however, converged at a vicinity of a local optimum. It should be noted that T-APSSA approximated a global optimum, although an initial solution was the poorest. Findings of these two tests follow that T-APSSA solves MOBPO problems well even within a limited iteration.

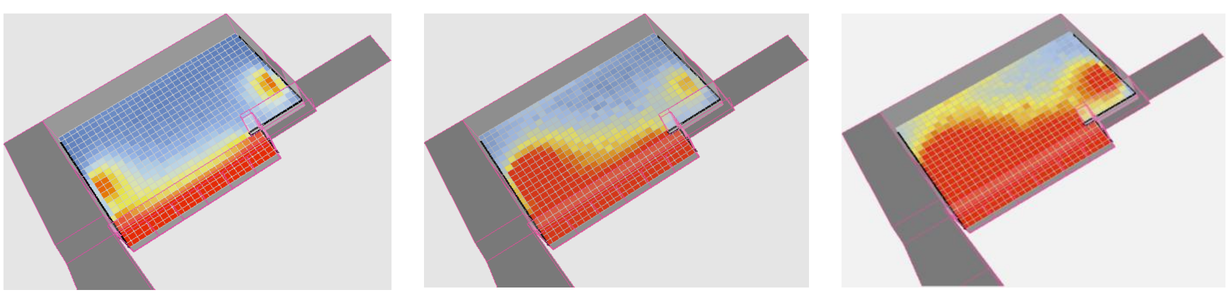
4 COMPARATIVE EXPERIMENTS: DETERMINISTIC VS. DYNAMIC ADAPTIVE OPTIMIZATION USING T-APSSA

For the purpose of dynamic optimization during the architectural design process, the developed algorithm was applied to the optimal, kinetic design of a façade shading device. External shading devices are an important component of building envelop design, and also largely impact illumination and heating/cooling, particularly in sunny, hot climate. Due to this significance, optimal shading design has been a major topic of design research. Algorithmic approaches (Arumì-Noè 1996; Henriquesa et al. 2012) or performance study about kinetic shading (Lee et al. 2016) were suggested. In this study, as part of the responsive energy-retrofitting plan of an existing facility, a building in Miami, U.S. was selected to redesign façade with parametric design modules. For the seamless automation and rapid interoperability of design work and BPS, Rhino Grasshopper® (GH), a generative design tool, was selected to design and simulate a façade shading device. The effectiveness and flexibility of GH as a BPS/parametric design platform was identified by Shi and Yang (2013). Simulation of illuminance in GH was enabled with DIVA, a Radiance-based GH plug-in, and the sky model and radiance data of a weather file were customized according to on-site sensor (photoresistor) data.

4.1 Test case study

The test building is part of an architecture school complex of Florida International University, located in southwest Miami, Florida, U.S. The design target is a fixed-glazing façade of an interdisciplinary facility, called structural and environmental technologies lab (SETlab), dedicated to teaching and research (Figure 6). This space is exposed to overheating and glare during daytime, as the façade faces a large courtyard.

Figure 6: Test building (SETLab, Florida International University, Miami, FL, USA).



(a) Overcast sky model

(b) Customized sky model with on-site real-time data (Feb 15, 13:15)

(c) Customized sky model with on-site real-time data (Feb 15, 13:19)

Figure 7: Geometry modeling and radiance daylight simulation results in different sky models.

Baseline illuminance simulation results in Figue 7 show indoor daylight levels depend highly on input sky models. For the illuminance simulation under an actual sky, the Perez sky model reconstructed with real-time radiation data was imported. Illuminance (lux) measured from an on-site photoresistor was converted to solar radiation (W/m^2) using a daylight luminous efficacy factor of 121.5 lm/W (Fakra et al. 2011). Deterministic optimization.

In most cases of optimal building design using BPS, design objectives and parameters of building models and simulation are deterministically predefined or assumed (Díaza et al. 2017). This gives rise to a lot of uncertainty in optimization, which may end up with even biased results. To compare a conventional deterministic design optimization with a dynamic process, a baseline model was established. Referring to the indoor environmental quality (IEQ) credit 8 option 1 of the Leadership in Energy and Environmental Design (LEED) building certification standard, the baseline is a static form of exterior shading to satisfy spatial daylight autonomy (sDA) of 50% at 300 lux of no less than 55% of an analyzed space and annual solar exposure (ASE) of no more than 10% of the space that receives above l,000 lux for 250 hours throughout a year.

4.1.1 Cyber-physical BPS interface: real-time data transfer through VPL in a design interface

A cyber-physical interface integrating Arduino microcontrollers, sensors, GH, and BPS was constructed and tested with a simple box shading model, and developed for the dynamic adaptive optimization process (Figure 8). A microcontroller with a transceiver (RF24L01) and a photoresistor was installed in the outside of the test building. Outdoor natural light levels are sent to a remote computer wirelessly, and logged in a data file every ten minutes. The design interface reads real-time sensor data and reconstructs a local weather file using the database.

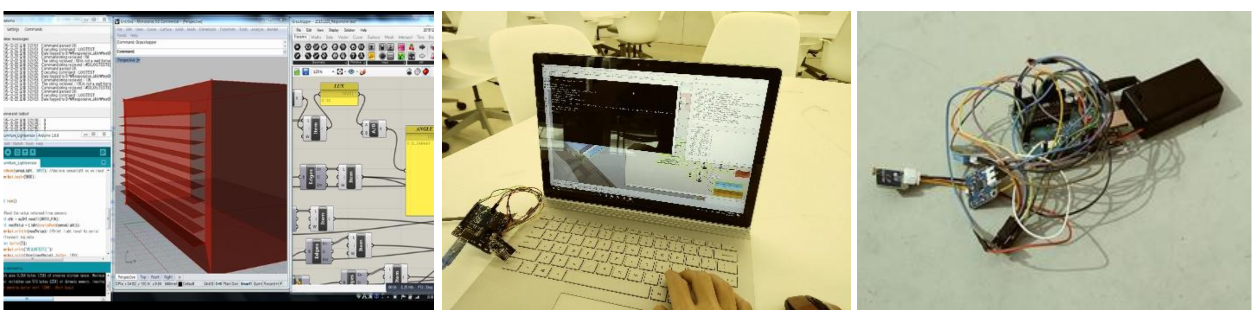
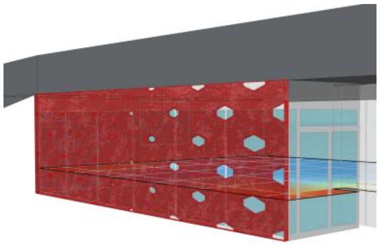


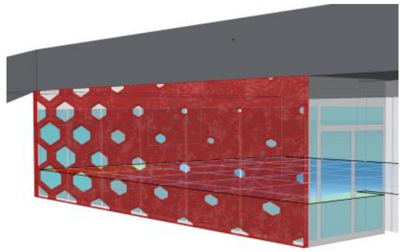
Figure 8: Interface integrated with remote sensor communication, BPS, and parametric design process.

4.1.2 Application and results

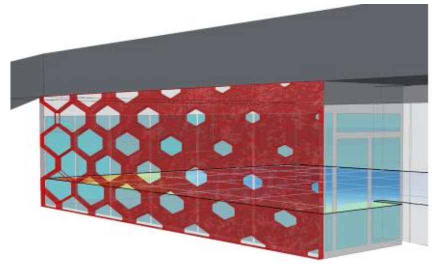
T-APSSA was coded to both deterministic and dynamic optimal shading design. Figure 9 (a) presents a deterministic optimal solution obtained by annual daylight simulation based on predefined weather data, and Figure 9 (b) ~ (g) show dynamic optimal parametric forms specific to real-time outdoor weather data. For dynamic optimization, at each ping from RF24L01, daylight simulation and T-APSSA optimization run with geometry parameters. Optimal geometry parameters are found in order to let the minimum illuminance of 300 lux in the space (LEED IEQ credit option 2). Results show that the dynamic adaptation creates various building skins, while the deterministic solution allows only a small portion of perforation in the façade. Figure 10 plots dynamic simulation results. This demonstrates the robustness of T-APSSA that terminates optimal search sufficiently enough within a ping interval and the final façade forms actively varies according to the external data transfer, while indoor daylight levels are optimized to 300 lux.



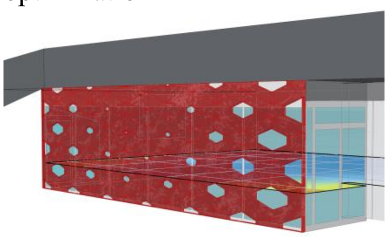
(a) Annual deterministic optimization



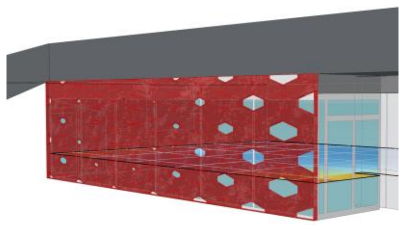
(b) 10:10 AM (March 4th, 2017)



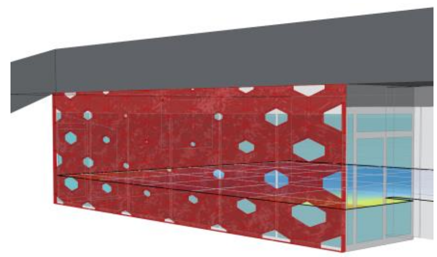
(c) 10:20 AM (March 4th, 2017)



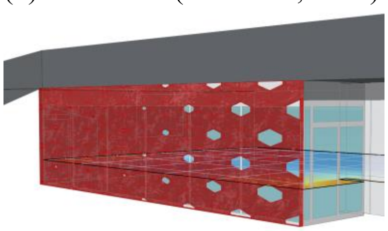
(d) 10:30 AM (March 4th, 2017)



(e) 10:40 AM (March 4th, 2017)



(f) 10:50 AM (March 4th, 2017)



(g) 11:00 AM (March 4th, 2017)

Figure 9: Comparison of dynamic optimal solutions.

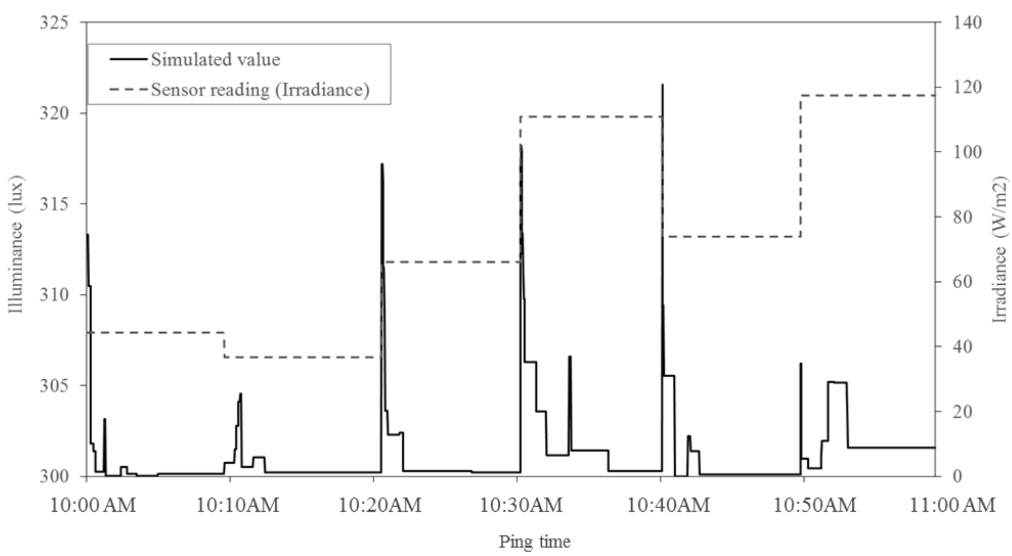
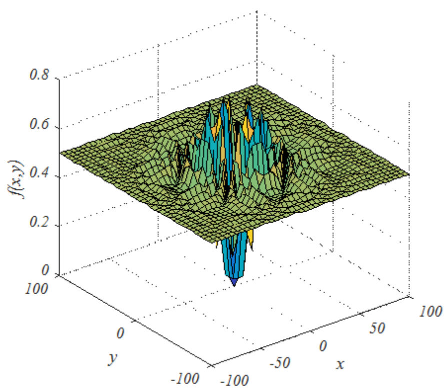


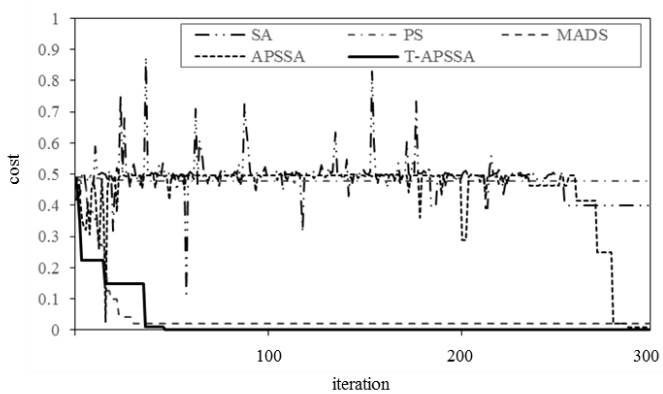
Figure 10: Results of real-time dynamic optimization (13th March, 2017).

5 CONCLUSIONS

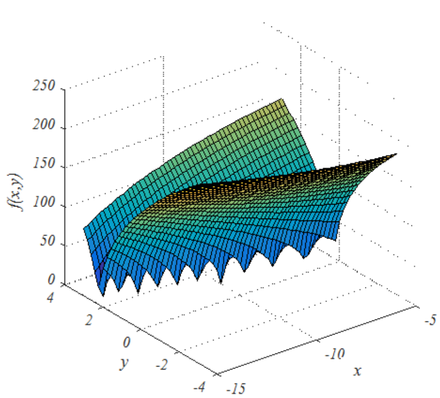
The contemporary architecture industry is transforming towards smart and intelligent environmental building design, and it has been a growing issue to find the best way to integrate BPS into design process to assure rapid feedback and data precision. Digitalized automation of environmental building design and optimization of performance during early phases benefit to inform better decisions, offering architects confidence in sustainable design. In an effort to provide a better solution about performance-based design optimization, this study presented a comparative study of deterministic (or static) and dynamic optimization with the suggestion of an advanced hybrid metaheuristic. For bi-directional parameter updates of BPS, physical remote data communication equipment was interfaced with a virtual parametric design tool using VPL. Experiments on the shading design process demonstrate that a deterministic approach to design optimization with predefined simulation parameters may be ill-suited to dynamic climatic adaptation due to the uncertainty of parameters. It also implies that dynamic formal responses of a building façade benefit the comfort and sustainability of building spaces. The developed framework based on a physical-cyber interfacing system can be used for various pretests of the remote optimal controllability of parametric design process as well as rapid prototyping of kinetic building components. This study must be followed by further experiments with incorporation of various real-time meter data, co-simulation of lighting, energy, and air-flow, algorithmic advancements to set dynamic parameters (annealing temperature and cooling rate of SA, Tabu list size, etc.), and MOBPO with different forms of façade/shading design modules.

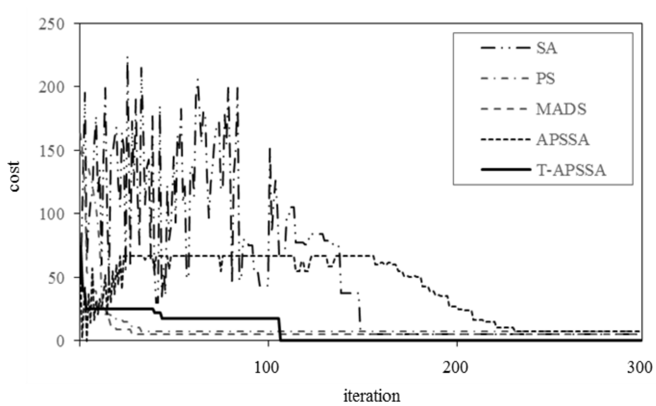
A APPENDIX: Metaheuristic performance comparisons using test functions for optimization





Schaffer function: $f(x,y) = 0.5+sin^2(x^2-y^2)-0.5/[1+0.001(x^2+y^2)]^2$, $f_{min} = f(0,0) = 0$, $-100 \leq x, y \leq 100$





Bukin function: $f(x,y) = 100\sqrt{(|y-0.01x^2|)}+0.01|x+10|$, $f_{min} = f(-10,1) = 0$, $-15 \leq x \leq -5$, $-3 \leq y \leq 3$

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