In Search of an Intelligent Methodology for Designing Sustainable Cities

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The GEnUSiS (Green Environmental Urban Simulations for Sustainability) project aims to empower urban planners, decision-makers, and other stakeholders with the necessary state-of-the-art tools to implement science-based sustainability solutions to better urban designs.

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The concept of a good urban design means different things to different people—from walkable communities to aesthetically pleasing building layouts to green and clean communities, or a healthy combination of such factors. If it were ever to be undertaken, the task of building consensus on what constitutes a good urban design would be an unenviable one. The problem is especially challenging not only due to the multiple conflicting objectives of the various stakeholders, but also because the stakeholders need the opportunity to experience the various possible solutions (urban forms or layouts) before being asked to choose one of the several alternatives. Moreover, the infrastructure decisions that planners must make have economic, social, and environmental repercussions that entire communities must live with for many years to come.

While a wide variety of approaches to decision-making exist, trying to bring science into the process along the way can be extremely challenging. The GEnUSiS (Green Environmental Urban Simulations for Sustainability) project at the University of Utah and University of Minnesota, Duluth is attempting to meet these challenges by equipping and empowering urban planners, decision-makers, and other stakeholders with the necessary state-of-the-art tools to assess the impact of and implement science-based sustainability solutions.

Problems with complex interacting physical, chemical, biological, and social components often result in unintended consequences that can really only be forecasted by planners with extensive experience or by computer modeling tools that include these interactions. Any approach identifying good urban design should be multi-disciplinary. It should include interactions amongst engineers, biologists, chemists, atmospheric scientists, computer scientists, planners, and social scientists.

A potential methodology for attacking these types of problems is illustrated in Figure 1. The process shown should be based on sound, well-validated computational models that are regional and site-specific. The problems that one might face in New York, for example, are different than those that a manager might be dealing with in Phoenix. Hence, the models should be generalizable. Even with an appropriate modeling strategy, finding good urban designs is extremely daunting due to the number of variables that are at play.

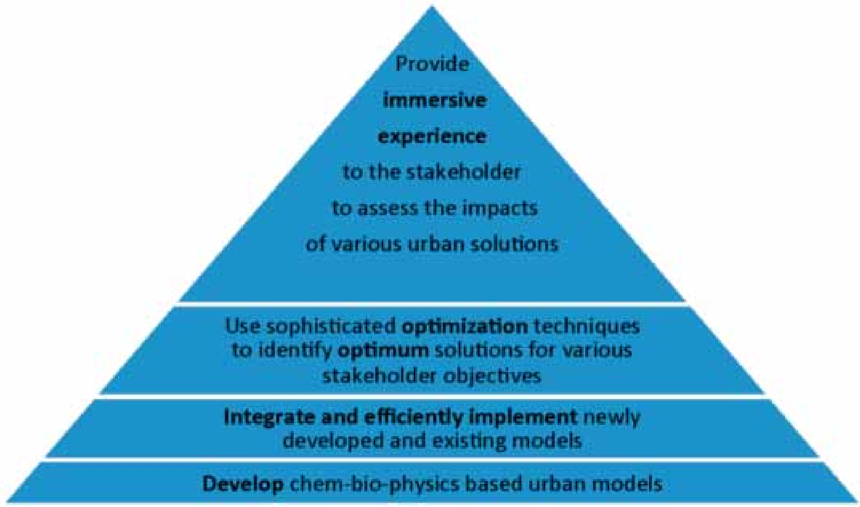


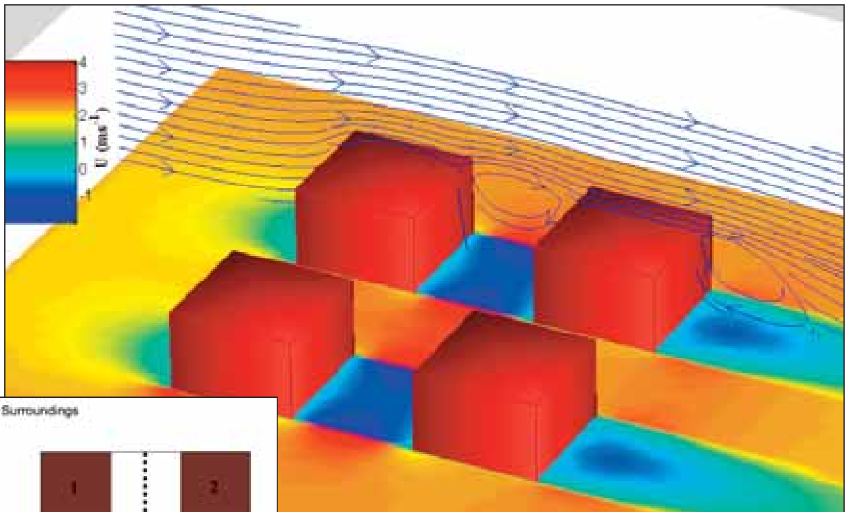
Figure 1. The over-arching framework of the GEnUSiS project. This decision pyramid strategy shows how the decision process ultimately relies on sound multi-disciplinary models that communicate complex physics to planners in a concise way.

Another more realistic option is to use design optimization strategies. Optimization strategies have been used for a long time in engineering design to find minima or maxima of some desired outcome. For example, finding the optimal thickness of insulation on a pipe or an optimal pipe diameter that minimizes annual costs. These simple types of optimization problems often utilize classical gradient descent methods that follow the slope of simple functions to its minima or maxima. Urban problems, however, are more complex and have mathematical quirks that prevent such simple solutions. Hence, more sophisticated techniques are needed.

A key component of the process is experiencing the urban design. While multi-criteria methodologies allow for flexibility in determining what a manager

« Illustration of the interactive and immersive visualization platform utilizing virtual environments for understanding dispersion characteristics in cities.

Notes: Particles are colored according to their instantaneous direction of motion. For example, blue particles are moving upstream toward the buildings (indicating recirculation zones), while yellow particles are moving downstream in the direction of the main flow above the buildings. Green and red particles are moving outward from the centerline of the domain–green particles are moving to the right in the top left panel, while red particles are moving to the left.



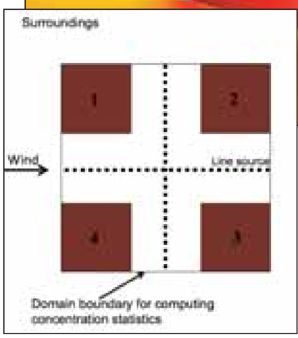


Figure 2. (inset) Schematic of the 2x2 building array problem. The buildings are labeled 1-4 and the pollution sources are shown as dashed lines between the buildings. Illustration of the 3D velocity field used to drive the pollution dispersion. Colored contours are velocity component in the mean wind direction.

might want, the results may have "surprises" or may produce results that are not practical within the constraints of a real city. Interactive and immersive visualization tools can enable the stakeholder or manager to experience the impact of multiple optimum urban layouts to select the ones that best suit their needs. In the following text, we describe how this methodology has been applied to a simple urban air quality problem to optimize urban design.

Illustrating Urban Form Optimization

The process of hunting for good urban designs or desired outcomes for a city can also be called an urban form optimization problem, or UFOP. The outcome may be reduced emissions, lower pollution concentrations, reduced building energy use, and so forth. To illustrate the process, a simplistic real-world UFOP is considered within the framework of the GEnUSiS project. To achieve the element of fast and accurate physical modeling, the GEnUSiS project methodology employs the Quick Urban and Industrial Complex (QUIC) dispersion modeling system.[1-3] QUIC has been jointly developed at Los Alamos National Laboratory and the University of Utah and consists of a diagnostic wind model (QUIC-URB),[1] a random-walk dispersion model (QUIC-PLUME),[3] and a graphical user-interface (QUIC-GUI). QUIC-URB computes spatially resolved 3D mean wind fields in urban domains (see Figure 2).

The standard QUIC dispersion model runs extremely fast. When compared to other models used to simulate flow and urban dispersion, QUIC runs two to three orders of magnitude faster, and produces similar results.[4] However, QUIC is still not fast enough to be used in the solution of realistic UFOPs, which require simulation of many thousands of urban configurations. Therefore to use QUIC to solve UFOPs, it has been adapted to graphics processing units (GPUs) to take advantage of the massive low-cost parallelism afforded by GPUs. Using GPUs, we have been able to speed-up particle dispersion computations by two orders of magnitude.[3]

To identify optimum solutions under various objectives simultaneously, GEnUSiS utilizes well-established techniques from the field of multiple criteria decision-making.[5,6] Specifically, to identify the set of all possible trade-off solutions (formally

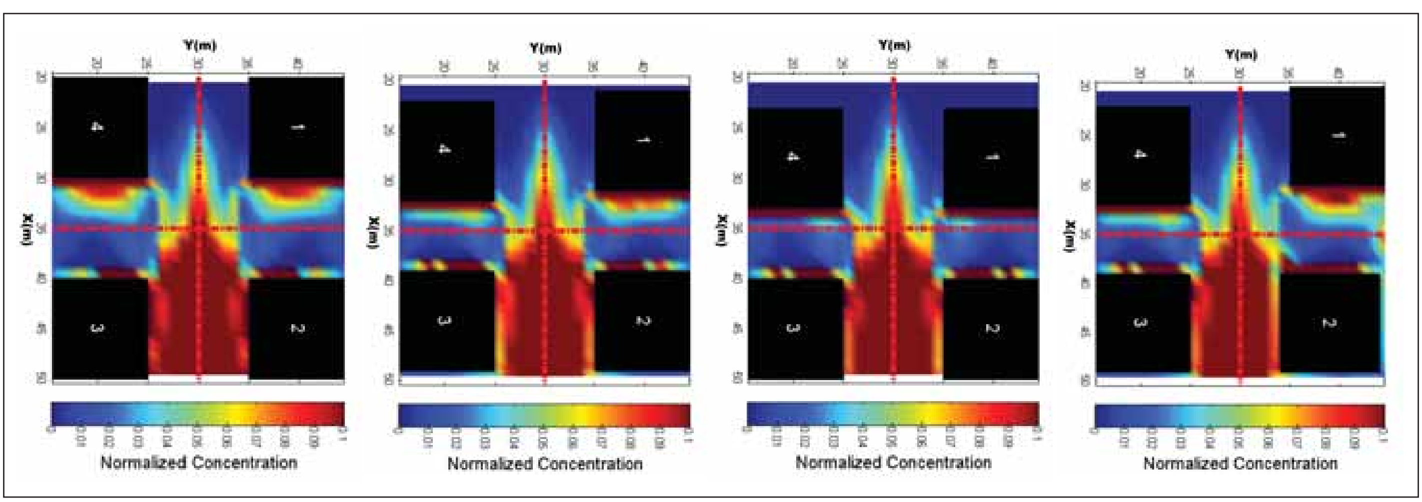


Figure 3. Four of the trade-off solutions for the 2x2 array problem. For the test problem, the wind is blowing from left to right and the normalized concentrations are shown at approximately the breathing height of a person.

referred to as Pareto optimal solutions in the literature) we have tested non-dominated sorting genetic algorithms (NSGA).[7] All of the trade-off solutions produced by the NSGA can be visualized through a virtual environment platform developed by the GEnUSiS team (see Figure 3 and the background image on page 28).[3]

Consider the fictitious 2x2 urban design problem shown in Figure 2, where planners would like to determine the building positions leading to the best air quality in the mock city. After considering a list of objectives, the stakeholders narrow down the problem to two end-goals, but are unable to decide which among the two is better. The stakeholders decide that minimizing the average and maximum pollutant concentrations at breathing height are the two objectives that they would like to achieve. For our simulations, each building is allowed to explore the lot space around the intersection. In particular, each building is allowed to move to four unique locations in each coordinate direction within its quadrant. The relatively simple-looking problem is, in fact, eight-dimensional (8D), with 4^8 (= 65,536) possibilities, for a single objective!

Figure 3 illustrates some of the trade-off solutions. If the stakeholders were to choose one of the trade-off solutions, it would implicitly indicate the relative importance of the two objectives (minimizing average and maximum pollutant concentrations). Figure 3 and the the background image on page 28 indicate how the GEnUSiS project provides end-users with an opportunity to explore and experience potential trade-off solutions before arriving at a consensus.

From the 2x2 building array example, it should be clear that in real cities, where each urban object can have several degrees of freedom, trying to determine the optimum configurations through exhaustive enumeration soon becomes infeasible, and optimization techniques are the only hope. The infeasibility is compounded by the fact that any scientifically sound urban flow and dispersion model employed would only increase the computational complexity of the problem, and thereby its overall execution time.

Our experience has unearthed the following urban optimization challenges that really should be addressed by any UFOP system:

- real-life UFOPs are comprised of high-dimensional decision variable spaces, and an astronomical number of urban layouts to choose from;
- high-fidelity results require sound physics-based urban models, which are computationally expensive;
- optimization procedures must take into account multiple (and possibly) conflicting objectives is needed; and
- stakeholders should be given the opportunity to experience optimum solutions under various objectives before they decide on a final design.

Current and Future Directions

Our current work includes developing and integrating urban energy-use physics into QUIC via GPUs. For example, ray-tracing tools (e.g., NVIDIA's OptiX software development kit) are being used to rapidly compute radiation transfer. Sky view factors, which are critical to understanding urban heat island dynamics (see Figure 4), are easily computed using this framework. This system allows vegetation (which is often neglected in urban simulations) to be included. For example, we are currently adding the ability to spatially resolve trees so that their impact on pollution and microclimate can be evaluated. QUIC is also being coupled with the Weather Research and Forecasting (WRF) model[8] to provide QUIC with more realistic meteorological forcing conditions. Ultimately, the goal of this current work is provide decision-makers with tools that can take into account place specific characteristics (e.g., local climate) to optimize green infrastructure (e.g., urban vegetation) for their own cities to meet environmental needs. **em**

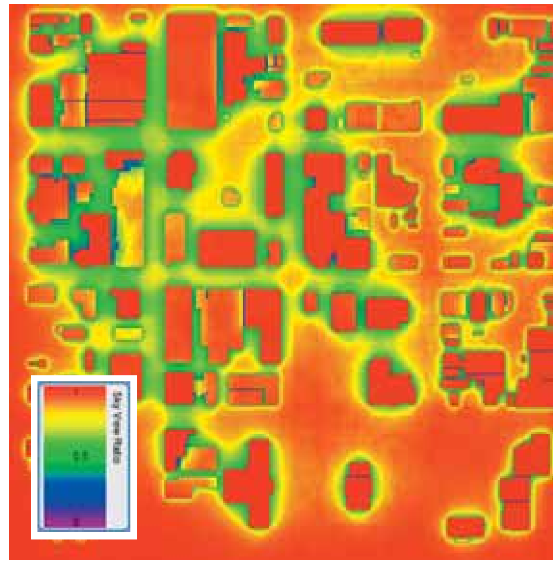


Figure 4. Illustration of contours representing sky view factors or the fraction of the sky that each surface can radiate to in downtown Salt Lake City, UT. Sky view factors were computed for Salt Lake City using NVIDIA's OptiX ray-tracing engine and are critical to understanding urban heat island characteristics. Regions of low sky view are unable to easily radiate heat to space and hence tend to trap heat locally.

References

1. Pardyjak, E.R.; Brown, M.J. Evaluation of a Fast-Response Urban Wind Model–Comparison to Single-Building Wind-Tunnel Data. In *Proceeding of the 2001 International Symposium on Environmental Hydraulics, Tempe, AZ, 2001.*
2. Singh, B.; Hansen, B.S.; Brown, M.J.; Pardyjak, E.R. Evaluation of the QUIC-URB Fast Response Urban Wind Model for a Cubical Building Array and Wide Building Street Canyon; *Environ. Fluid Mech.* **2008**, *8*, 281-312.
3. Singh, B.; Pardyjak, E.R.; Norgren, A.; Willemsen, P. Speeding-up Urban Fast Response Lagrangian Dispersion Simulations Using Video Game Technology; *Environ. Mod. Soft.* **2011**, *26*, 739-750.
4. Flaherty, J.E.; Allwine, K.J.; Brown, M.J.; Coirier, W.J.; Ericson, S.C.; Hansen, O.R.; Huber, A.H.; Kim, S.; Leach, M.J.; Mirocha, J.D.; Newsom, R.K.; Patnaik, G.; Senocak, I. Evaluation Study of Building-Resolved Urban Dispersion Models. In *Proceedings of the Seventh Symposium on the Urban Environment September 10-13,* 2007, San Diego, CA; PNNL-SA-56788.
5. Deb, K. *Multi-Objective Optimization Using Evolutionary Algorithms*; Wiley, 2001.
6. Miettinen, K. *Nonlinear Multiobjective Optimization*; Kluwer Academic Publishers, 1999.
7. Addepalli, B.; Pardyjak, E.R.; Willemsen, P.; Johnson, D.E. Development of a Multiple Criteria Decision-Making (MCDM) Tool for Urban Form Optimization. Presented at the 92nd AMS Annual Meeting, New Orleans, LA, 2012.
8. Skamarock, W.C.; Klemp, J.B.; Dudhia, J.; Gill, D.O.; Barker, D.M.; Wang, W.; Powers, J.G. *A description of the Advanced Research WRF Version 2;* NCAR/TN–468+STR; Mesoscale and Microscale Meteorology Division, National Center for Atmospheric Research, Boulder, CO, 2005.