Judges' Commentary: Sustainable Cities

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Introduction

The ICM continued to challenge students to address real-world problems concerning environmental science in Problem E. This year's environmental problem called for teams to tackle the complications tied to urbanization of the world and the desire for communities to implement smart growth initiatives in an effort to consider long-range, sustainable planning goals for growing urban centers. Smart growth focuses on building cities that embrace the E's of sustainability—Economically prosperous, socially Equitable, and Environmentally sustainable. Due to the interdisciplinary nature of Problem E, teams who chose this problem had to leverage the strengths and skills of their individual members as they navigated this challenge.

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Problem Summary

Teams sought to understand and model the principles of modern urban planning in order to improve city operations. The ultimate goal was for teams to use the three E's tied to the 10 principles of smart growth as described in the problem prompt, to develop a measure for the success of the smart growth of a city. Since there are so many initiatives tied to these broad principles, there were diverse measures of success incorporating cities' demographics, growth needs, and geographical conditions in order to evaluate a community's unique needs to be effective.

To apply smart growth principles and to test their metric, teams were required to implement their growth theories into city design around the world by selecting two mid-sized cities on different continents and conducting research to gain an understanding of their growth plans. The judges saw smart growth analysis for cities all over the world in the set of over 3,600 submissions received for Problem E. Once teams understood the cities' current plans, they needed to measure the success of the plans with their self-developed metric.

No ICM challenge would be complete without the requirement to improve upon the current city growth plan with the ideals of the metric in mind. Teams supported their chosen smart growth initiatives for each city by discussing the reasoning behind the components of the plan based on geography, expected growth rates, and economic opportunities in the cities, and by using their metric to evaluate the success of their own smart growth plans. The problem then asked teams to identify initiatives within their plans that possessed the most potential and compare those between the two cities. This analysis gave judges insight into team's comprehension of urban sustainability.

The final test of a team's understanding of the complexity of this issue and the smart growth plans that they developed was to subject them both to stress. The problem supposed that the population of each city increased by an additional 50% by 2050. Teams needed to determine how their plan could support this level of growth. This analysis, which comes from the desire for understanding of the future needs of a growing community, highlights why we model and why problems like this year's ICM Problem E are relevant to world events.

Judges' Criteria

We describe the framework used to evaluate submissions for the environmental science problem. The judges who conducted this evaluation used a common assessment guide and represented a diverse set of fields, including sustainability, biology, geography, applied mathematics, statistics and engineering. Judges were looking for teams to answer all five tasks specified by the prompt but with focus in two areas that we deemed would show true understanding of the issues surrounding sustainable urban growth:

- an understanding of smart growth, beyond what was specified in the problem prompt, which would enable a team to develop a viable metric in line with the E's of sustainability and the 10 principles of smart growth; and
- actual relevant policy recommendations or implementable initiatives that the team specifically tailored to each of their cities.

The judges felt that a true understanding of smart growth and a linkage to the three E's of sustainability was critical for developing a metric to measure success associated with the smart growth of a city. The judges looked for analysis of factors involved in a team's metric. The discussion of the factors included in their model, the linkage to the 10 principles, and then how those are then related to the three E's of sustainability was crucial. Judges looked for papers that included qualitative analysis to augment the quantitative model. Ideally, judges wanted the best model to be developed, coupled with a discussion of the best proxy factor that then had to be incorporated into the model. This factor in turn had to be based on the data that the team had available and not the other way around. The best papers identified data that they wanted to use, then what they could find, and finally how those data might not match but how it would work anyway. A team's recognition of the limitations of the modeling process showed great maturity and confidence in their research and knowledge of smart growth.

Judges also looked carefully at how teams developed their growth plans for the cities. The best plans included components that were either built on existing smart growth plans for a city, or else were novel for the city but actually implementable based on the geography, expected growth rates, economic opportunities, or other factors unique to the chosen city. The primary goal of this problem was to develop a plan based on an understanding of smart growth and modern urban planning in order to improve city operations. This development required research into the city's current operations and its projected growth plan, as well as an understanding of additional initiatives that would assist the city in becoming more successful in the future. To accomplish this development plan, teams needed to target their approach to each city differently based on its needs, where it stands now, and how it plans on growing into the future. Teams needed to define success by the metric they had created earlier. Because of this layering, the impact of initiatives implemented in the redesigned smart growth plan developed by teams needed to be quantitatively determined for incorporation into the model.

The judges considered other factors beyond these two critical components. These included:

- **Data Utilization** Judges wanted the quantitative data to be used for both developing and evaluating the metric but not to drive what should be included or evaluated in an ideal measure of smart growth for a city. The creation of the ideal model should be the standard; but due to time and data constraints, the judges understand that it may not be feasible. The best teams acknowledged this and altered their original model based on the time available and the data that they could find, and then—most importantly—discussed what that change might have done to the model results. Judges were impressed with teams that discriminated between objective and subjective inputs, especially when teams proposed and implemented methods to address the subjective nature of certain parameters.
- **Analysis of Rankings** This component was a specified task in the problem prompt that was overlooked by many teams. Ideally, judges sought an objective ranking based on inputs to the metric; however, some teams presented a nice descriptive analysis of impact. The best papers ranked initiatives objectively and then explained why, realistically, these initiatives should have the greatest impact. This interpretation of results is a crucial component of the modeling process.
- **Comparison of Initiatives and Cities** This section took on different forms for different teams. Some approached it as the judges initially intended, as a comparison of the two cities and initiatives common to both cities. However, judges saw very creative comparisons, including the addition of other cities known for their sustainable practices as benchmarks, showing how the addition of new initiatives for their chosen cities would place them on track with these known "sustainable" cities. Others compared one of their cities to another city or group of cities that had similar attributes. Judges rewarded creative comparisons grounded in reasoning.
- **Motivation Behind Cities Chosen** Judges were pleased with teams that addressed the reasoning behind the cities chosen for analysis and included a discussion of the smart growth history of the city before analyzing the success of their chosen city's smart growth plan. Providing the motivation and explaining the critical research done on the city's attributes and plan showed the judges a level of understanding and sophistication that set the best papers apart from the rest.

As always, the following general modeling elements were expected by judges and found in good papers:

- **Written Communication** Every year, judges seek to highlight submissions that offer a balance of sound mathematics with well-written justifications for their approach. Judges looked for implementable smart growth plans that address all the aspects of sustainability and smart growth. The strongest submissions had a clear organizational structure, with equations—coupled with explanations, and, when appropriate, graphics—to help convey complicated ideas.

- **Modeling Basics** As teams developed their model, judges expected them to include definitions of their variables, state reasonable and necessary assumptions, and identify and appropriately cite sources for their data. After completion of the modeling, judges expected discussions of the strengths and weakness of the model and some concluding thoughts, versus just ending the paper after completing all of the tasks. In past years, the problem prompt specifically required teams to detail strengths and weaknesses of their model. This year's prompt did not do so explicitly, and therefore the inclusion of a discussion of strengths and weaknesses became an indicator of a deeper understanding of the aspects of modeling. Judges were encouraged by teams that provided the analysis throughout the submission, as opposed to right at the end of their report (thus seeming like an after-thought). Strengths and weaknesses are relevant to the entire modeling process.

- **Sensitivity Analysis** Sensitivity analysis could have been done in a variety of ways, so judges were looking closely at the rationale behind each team's approach. At a minimum, the expectation was a revisit of early simplifying assumptions. Judges also saw teams assessing the relative impacts of different types of model improvements. There was no one way, but teams that attempted a sensitivity analysis in order to determine the robustness, flexibility, or accuracy of their model demonstrated to the judges a higher level of knowledge concerning the impact and usefulness of their model.

- **Scalability Discussion** One task was designed for teams to showcase a scalability analysis, by increasing the population by 50% within the next few decades. Judges sought to understand if the models could adjust to greater populations and how teams would interpret the outputs from their model for their cities with a significantly larger population.

- **Model Validation and Verification** These aspects of modeling often set a great paper apart from just a good report. Validation is an important part of the modeling process, as it can instill confidence in results and help identify weakness in the model. Several papers presented a range of models from simple to complex and used a validation approach to justify the selection of one of those choices, considering the tradeoffs. Judges saw teams that removed some of the indicators in their model in order to see if the removal changed the output of their model. Other teams ran their model against other benchmark cities to see if it accurately predicted the success in that city's smart growth program, before using it on their two chosen cities. Judges understood the time constraint that teams were under and therefore appreciated teams that had given consideration to such model validation.

Modeling Techniques Used for This Problem

Teams used many methods to create a metric for analyzing the smart growth within a city. The judges determined that a well-researched and developed model should include an explanation of the reasoning behind the chosen approach, as well as detailing the assumptions used in developing the model. Outstanding teams motivated their model with background research before presenting their techniques.

Judges were impressed by the variety of ways that teams chose to create this metric. The foundation of the metric was the analysis of which factors to include. The expectation was that through research, a team would identify what had to be included within the framework of the three E's of sustainability and the 10 principles of smart growth. Some teams combined their factors without weights, treating all equally, while others chose mathematically rigorous weighting methods or even a hierarchical approach. Others created a coordination index and analyzed how the factors of sustainability and principles of smart growth were similar and how they differed from one another in order to determine what needed to be included. Still other metrics compared a city's current growth path to the optimal smart growth path. We saw a range of approaches and applaud teams for their innovation. The judges read papers from teams that developed completely original models, while other teams leveraged and improved upon models available from the literature. The best teams created a unique model and then conducted verification by testing it against a known metric identified through their research.

Discussion of the Outstanding Papers

Due to the nature of the environmental problem, the competing teams used many different modeling techniques in creating their metrics, which emphasized different aspects of smart growth and sustainability and selected diverse target cities for analysis. As a result, the submissions provided great innovations and excitement for the judging panel. The best papers focused on research-based development of their metric and then in-depth analysis of current and proposed smart growth plans for their two chosen cities. The Outstanding teams developed creative and relevant solutions to the complex questions provided in the specific tasks of the problem. The five Outstanding papers that we discuss in this section demonstrated a nice array of modeling techniques. They then showcased their model's capabilities to handle scalability, multiple types of initiatives with both objective and subjective inputs, and the ability to dynamically change over time.

Humboldt State University, USA

"A Tale of Two Smart Cities: Development of a Smart Growth Index"
Rachel Carson Award and Two Sigma Scholarship Award

This submission stood out for its excellent writing and descriptions of every step in the team's modeling process. The analysis of the problem, their solution, and the selection of the indicators were thoroughly explained and provided a clear understanding of the strengths and weaknesses of their model. The judges appreciated that the metric was not just a measure of sustainability, but an actual attempt to quantify smart growth principles into five metrics, which the team called Smart Land Use, Smart Housing, Smart Community, Smart Development, and Smart Transportation. The way they incorporated the 10 principles into the five metrics was displayed in **Figure 1**, which provided an excellent visualization of their approach.

Figure 1. The smart growth model of the Humboldt State team, including its 5 metrics created from the 10 principles.

Each of the five metrics is scored out of 20 points and the sum of the five metrics is the Smart Growth Index out of 100 points. The team used this equal weighting to compare the total Smart Growth Index, as well as to compare the individual metrics. Doing so was an advantage in their analysis, because they could see which metrics needed intervention and could discuss adjustments in their plan accordingly. The actual metrics, while well discussed, were designed simply by averaging two to four indicators for each metric and rescaling it. Since the team is using their index for direct comparison and not for a rating, they were able to argue that this was sufficient.

They did test two of their metrics (Smart Housing and Smart Transportation) on Los Angeles, USA (LA) and New York City, USA (NYC). While large cities develop differently from medium-sized cities, the team used this approach ensure that the values given by the metrics produce reasonable results. They selected these cities to be sure that these two metrics showed the low housing options in both cities, as well as the poor public transportation in LA and the good public transportation of NYC. Their metrics did show these results and provided benchmarks that allowed them to evaluate these scores for their chosen cities of Sacramento, California, USA and Edinburgh, Scotland, UK. Although they did not verify all five of their metrics, having confidence in these two was a good start. Many papers failed to test their model at all, so this certainly made the judges take notice.

Another aspect of this paper that was highly valued by the judges was their extensive research into the current growth plans of Sacramento and Edinburgh. Such research, missing in many papers, provides a lot of information about the growth initiatives of the area. The team discussed the content of the plans and also used them to provide data for the index. This was another unique aspect of the team's approach, which evaluated the effectiveness of the actual plan in achieving the goals set by the teams.

The team created initiatives for each of the five metrics as their smart growth plan for the two cities. In their discussion of the proposal, they could use current initiatives from the city's growth plan as well as add to them. Doing so tailors the plan for specific needs and capabilities of each city, rather than using the values of indicators to drive policy. Consequently, the team was able to estimate the change in the value of each indicator with justification based on the city's growth plan and potential for achieving. One example that was particularly thoughtful was that Sacramento is not likely to dramatically increase the percentage of public transportation users, since it is a drivable city and the U.S. has a vehicle-centric culture. Thus, their expectation for potential improvement in this indicator was much lower than they may want it to be. Realistic analyses, like this one, made this paper stand out among the others.

This Humboldt State team ended the paper with a strong evaluation of strengths and weaknesses. The index's simplicity does make it versatile but limits the values to just a comparison mechanism and not a measure. The team was aware that there are limitations to their model and for the evaluation of it. This is true for all models, so a thoughtful description allows the reader to understand the true utility of this model.

Anhui University, China

"Smart Growth Theories in City Design"
INFORMS Award

In a word, this Outstanding paper was organized. The team from Anhui University tackled this complex problem with a combination of an entropy weight method, a group decision method, and a weighted moving average. This helped them determine the various values of the many factors associated with their need to evaluate a smart growth city. Next, the team clearly laid out the myriad of parameters along with their units of measure. The team included a detailed flow chart in **Figure 2** of how they approached each part of the problem as they analyzed the cities of Pittsburgh (in the northeast United States) and Ningguo (in eastern China).

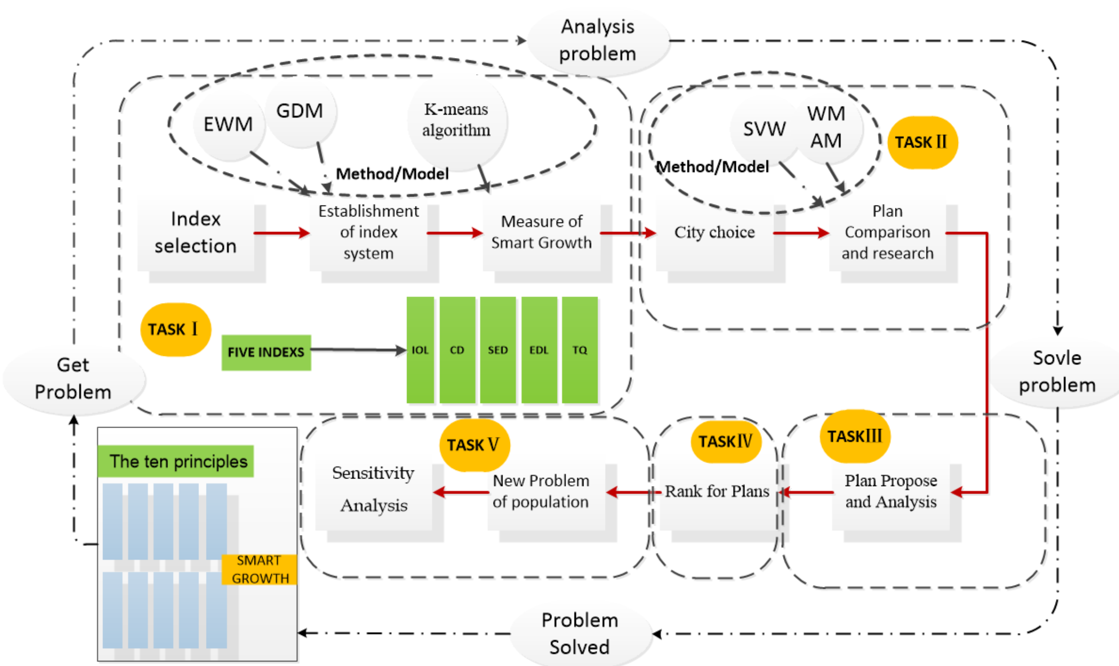


Figure 2. "Flowchart" of how the Anhui University team worked through and completed the problem.

After reading many team submissions, it was nice to see a paper with this level of organization. This flowchart clearly laid out how each specific task would be analyzed and where in the flow this would occur, as well how some insight gained along with process would be incorporated into other parts of the problem. Unfortunately, at this point many entries immediately dove into the modeling and analysis and did not take the time to orient the reader (and themselves) to how the team approached the problem.

After definitions of terms and a restatement of the problem, the team spent time discussing how they would handle incomplete or non-existent data—this was a very nice step and rarely seen. Often, the data that a team wanted were either unavailable or "dirty." Additionally, the modeling of the problem clearly laid out all the variables in units, a brief description of each, and to which parts of the problem they pertained. The team then moved on to normalize the data and determine a feasible weighting system for each variable for their linear model. Through a tree-like visualization, as well as other graphs, the team very clearly showed how the different input variables were grouped and related to their overall smart growth evaluation model.

The team finished with clear conclusions and specific policies for each city for smart growth based on their predicted models. Along with answering all problem parts, they also provided some sensitivity analysis of their model to test its robustness, which was very outstanding indeed.

Nanjing University of Aeronautics and Astronautics, China

"Sustainable Cities Needed!"

This paper exhibited highly creative modeling in the development of their smart growth metric and ensured that all aspects of good modeling were included in their report. This team distinguished themselves with their unique approach and polished presentation.

The team's model, the three dimensional baseline cube model, uses the three E's of sustainability as the three dimensions and maps a state of growth as a vector into this cube. The length of the vector represents the speed of growth of the city. The ideal smart growth is represented by the diagonal of the cube as shown in **Figure 3**. The angle between the city vector and the ideal vector indicates the degree of sustainability of a city.

This innovative approach was completely different from everything else that the judges had seen; but what really distinguished this paper was the research behind the model and the explanations provided throughout the paper. The descriptions of the metric, how the model was developed, and what indicators are accounted for in the model were concise and included throughout the paper.

The team's subsequent analysis was based on finding an optimal allocation of the total budget that a city could contribute to minimize the angle between their course of action and the optimal smart growth trajectory. While not all judges accepted the emphasis on the economic component to developing smart growth, the detailed analysis and linkage to the metric was especially appreciated. The budget had seven components that were all tied to initiatives so that the team could evaluate the effects. The team was able to find an optimal allocation of a budget that would move the city closer to the ideal smart growth vector, and then prioritize individual initiatives to provide both Wellington, New Zealand and Edinburgh, UK with the most influential factors.

The paper was well organized and researched with informative graphics. The team's report, due to the creativity used and the explanations given, was a pleasure to read for all judges.

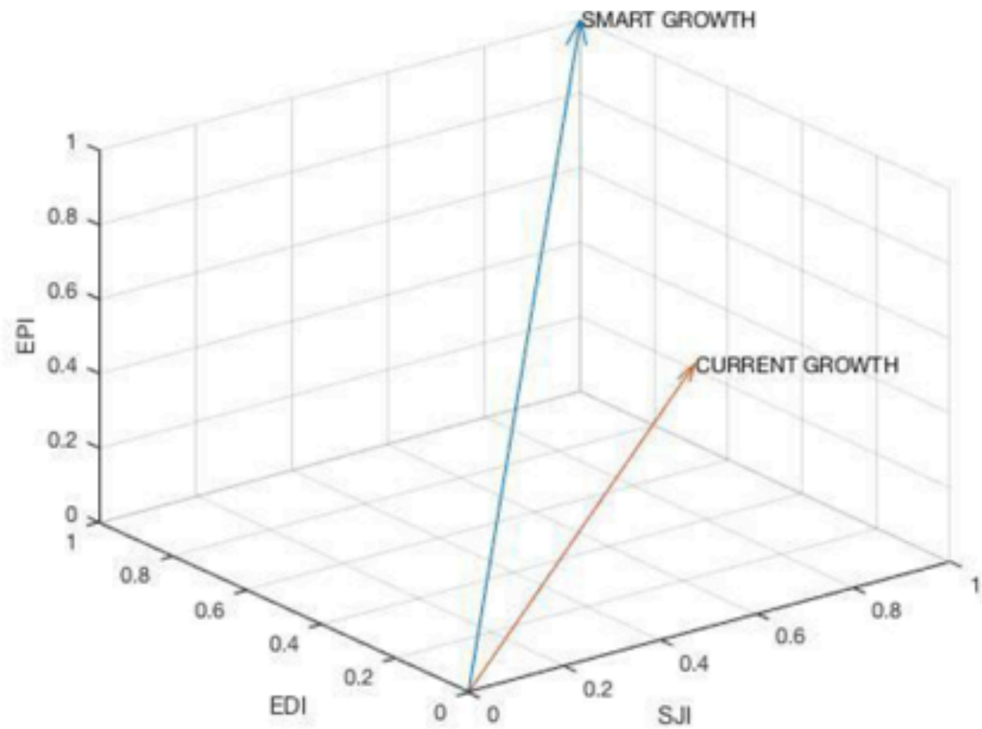


Figure 3. 3D baseline cube model from Nanjing University, comparing a city's current growth plan to the optimal smart growth trajectory.

University of Electronic Science and Technology of China, China

"Towards a Sustainable City"

The judges with expertise specifically in sustainability credited this team with the development of the best metric for smart growth that we had seen. Their understanding of smart growth and their ability to demonstrate that knowledge in the incorporation and development of a smart growth metric was superb. The team truly focused on how to evaluate the performance of a smart growth plan through the metric development and also how to formulate a smart growth plan for a city taking into consideration the unique needs of a city—which were the two main criteria of the judges.

The team's research started with the identification of the relationships among the goals of the three E's of sustainability and the 10 principles of smart growth. Their references and case study analysis from Smart Growth Theory, the Environmental Protection Agency, and Smart Growth America allowed them to gain an elevated level of understanding, which was then applied to their Success of Smart Growth metric. This metric consisted of three components tied to the three E's of sustainability, with three first-class indicators for each and then different quantities of second-class indicators to feed them.

Based on their analysis of Wellington, New Zealand and Anchorage, Alaska, the team calculated a rational grade for each metric and then compared these two cities to benchmark cities that have been implementing smart growth plans, as a reference standard to evaluate the success of the current cities' plans. This comparison, when researched well and conducted effectively, proved to be a very useful component in modeling for many teams. This analysis, shown in **Figure 4**, also included four degrees to indicate levels of smart growth development: high smart growth, smart growth, sprawl growth, and high sprawl growth.

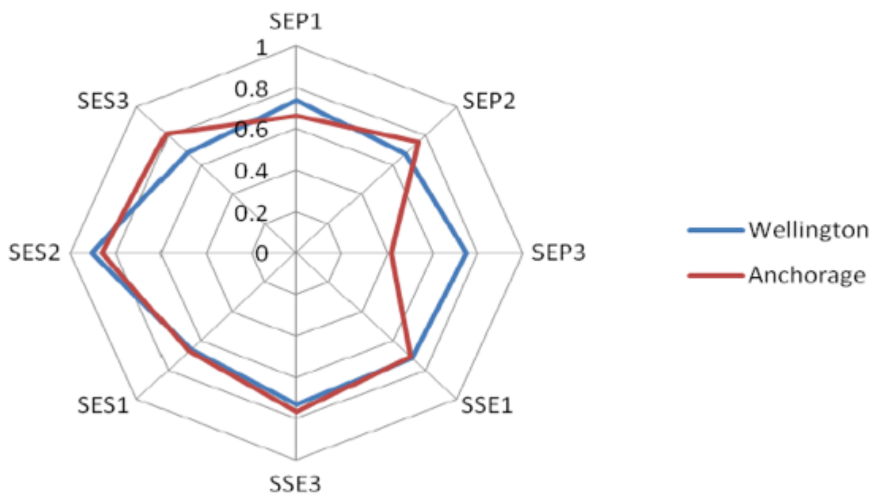


Figure 4. Ratings of cities using first-degree model indicators, by the team from University of Electronic Science and Technology of China.

The explanation of what a good score is for their model is something that should not be overlooked. Many teams simply created a metric and evaluated a city using that metric but never discussed what constitutes a good score and how they could objectively evaluate that score.

The team from the University of Electronic Science and Technology of China truly demonstrated the judge's notion that time invested in background research using reputable sources pays off in the development of the model due to the depth of understanding gained into the problem and knowledge of what the metric actually measures.

Harvey Mudd College, USA

"Applying Smart Growth Principles in Boulder, Colorado, USA and Canberra, Australia"[1]

This paper was Outstanding primarily for three reasons:

- It recognized that the 10 principles of smart growth design emerge from the 3 E's of Sustainability;
- the initiatives suggested were relevant, realistic, and reflective; and

[1]This paper appears in this issue of *The UMAP Journal.*

- it was one of the only papers that tackled task 4 effectively (see below for details).

In addition, the model itself uses mathematics accessible to many audiences. This feature is important because it shows that ICM students need not take advanced mathematics to do good modeling work.

This paper started with a very thorough examination of the 10 principles of smart growth, followed by a clear explanation of why and how each of these principles was measured. In the explanations, the team was clear in their link with the three E's as well as other relationships that the principles have with one another. This organization allowed each correlated cluster to be described by a single combined metric, thereby avoiding redundancy in measurement. However, it also has the added benefit of communicating the relationship of principles in helping one another achieve smart-growth-principle goals with some natural clustering around three-E ideas.

The two cities examined were Boulder, Colorado, USA and Canberra, Australia. Each was researched and recommendations were made. The judges were particularly impressed with the thoughtfulness of each recommendation. As one judge commented, it "represented the relevant, realistic, and reflective type of work that would come out of a planning department." Again, the consistent and reflective connection back to the 10 guiding principles, treating each city uniquely, really made this paper stand out in terms of its recommendations.

Lastly, recall that task 4 focused on using the metric developed to help prioritize proposed initiatives and comparing each initiative between each city. The results of this task were very concisely represented by Table 1. It allowed judges to see the results clearly, and allowed the team to then engage in a very thoughtful discussion of which initiatives would be better for each city. As one can see from **Table 1**—it is not a one-size-fits-all solution.

Table 1.

Effects of individual initiatives on success levels for cities, from the report from the team from Harvey Mudd College.

	Boulder		Canberra	
Initiative	L	ΔL	L	ΔL
A	0.7549	-0.0204	0.6351	0.0469
B	0.7319	-0.0434	0.5436	-0.0456
C	0.7893	0.0140	0.5995	0.0113
D	0.7786	0.0033	0.6543	0.0661
E	0.7970	0.0217	0.6678	0.0796

No model is perfect, and the judges always expect there to be weaknesses. The sign of a good team is to acknowledge the weaknesses not just of information availability, but also of their own mathematical model.

This team choose to use a total metric that was equally weighted between clusters of related principles. The team appropriately discussed their own mathematical assumptions, and then went on to provide a very nice final conclusion and summary. We were impressed throughout the paper at the level of reflection and synthesis the team put forward, and for that reason, it made it to the top of our entries.

Conclusion

While the quality of the modeling is very important, it is perhaps even more important that the work is communicated in a clear and convincing manner. Occasionally, the judges see papers that appear to have applied very advanced mathematical techniques, but the writing does not justify the use of that model. Similarly, a team might produce numerous results; but if those results are reported only in a large paragraph filled with undefined symbols and never put into context, then the value of those results is lost. Conversely, even a simple model can be powerful if the design of the model is well-reasoned, the simplifying assumptions and their expected impact on the results are discussed, and the results are explained in a meaningful way (that often includes some data visualization).

Perhaps the most important portion of the paper, the executive summary, is a place where teams have a chance to really demonstrate their strong exposition skills, as this one page description needs to introduce the problem, overview the methodology, and highlight the key findings.

This problem presented challenges to teams in the form of understanding the principles of smart growth and sustainability and incorporating those into a model to help analyze and improve urban growth plans. Many teams had innovative and useful ideas for some parts of the problem, but were unable to satisfy all the tasks required in the problem within the time constraints. The five Outstanding teams fulfilled all the required tasks the best and were able to effectively communicate the results.

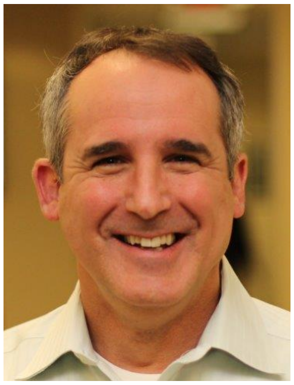
Members of all of the competing teams are to be congratulated for their excellent work and dedication to interdisciplinary modeling and problem solving. The judges were truly impressed by the ability of so many to combine great modeling, well researched science, and effective written communication skills in order to address the critical issues of sustainability and smart growth which are so vital to the future of our developing, more urban world.

About the Authors

Kristin Arney is pursuing her Ph.D. in Industrial Engineering at the University of Washington. Kristin began her military career after graduating with a B.S. in Mathematics from Lafayette College. During her career, she has served in assignments all over the globe, received her M.S. in Operations Research from North Carolina State University, and taught as an Assistant Professor at the U.S. Military Academy, where she returned and rejoined the faculty in January 2017.

Amanda Beecher is an Associate Professor of Mathematics at Ramapo College of New Jersey, where she has taught for 7 years. She earned her Ph.D. from the University at Albany, SUNY in commutative algebra. Before Ramapo, she had a three year post-doc at the U.S. Military Academy, where she first began coaching for the MCM and judging for the ICM. She has served as a triage grader for the ICM for 10 years, a final judge for 5 years, and head judge of the Environmental problem for all 3 years. She looks forward to being an Associate Director of the ICM in 2018.

Carrie Diaz Eaton is an Associate Professor of Mathematics at Unity College, a small environmental liberal arts college with a focus on sustainability. She has been teaching at Unity College for seven years, with a particular focus on teaching modeling in life and environmental science. Dr. Eaton earned her Mathematics Ph.D. from the University of Tennessee and her M.A. from the University of Maine in the areas of evolutionary theory and computational neurobiology, respectively. She has served for two years as an ICM judge for Problem E.



Jack Picciuto is currently the Director of Operations Analysis and Planning at IT Cadre in Ashburn, VA. He served over 20 years as an army attack helicopter pilot and assistant professor at the United States Military Academy (USMA) in the Dept. of Mathematical Sciences. He earned his B.S. from USMA, his M.S. in Operations Research from Georgia Tech, and his Ph.D. in Industrial Engineering from the University of Central Florida. This is Jack's first year judging the ICM, but he has been a judge for the MCM, HiMCM and Moody's M3 for several years.