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Editorial

New Developments for the ICM/MCM Contests

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One-Time Add-On Spring Contest

Unfortunately, many teams were unable to participate on the prescribed weekend for the 2023 Interdisciplinary Contest in Modeling (ICM®) and the Mathematical Contest in Modeling (MCM®) due to covid and scheduling issues. While it was impossible to change the February contest dates, the Contest Directors decided to provide the ICM/MCM experience for these teams by instituting—this year only—a one-time Spring ICM/MCM contest. This contest was as challenging as the regular ICM/MCM contest and ran from March 30 through April 3.

Teams participating in the Spring ICM/MCM contest chose to complete either an MCM problem (Problem Y: Understanding Used Sailboat Prices) or an ICM problem (Problem Z: The Future of the Olympics). This contest and its judging were run by experienced ICM/MCM leadership to ensure the same level of rigor in problem development and judging that teams have come to expect from COMAP's undergraduate contests. Results of both the February ICM/MCM and the Spring ICM/MCM are available at COMAP's website https://www.mcmcontest.com.

The ICM Director's report and Judges' Commentaries for the February ICM appear in this issue. A Contest Director's Report and a Judges' Commentary for each of the Spring problems will appear later. The corresponding materials for the MCM will appear in the next issue, Vol. 44, No. 4.

The 2024 ICM Contest is scheduled to take place February 1–5, 2024.

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New Approach to Reporting Outstanding Papers

In the past, this *Journal* has published one Outstanding paper for each of the ICM/MCM contest problems, and each paper tended to run to about 25 print pages. The number of Outstanding papers has grown with the number of participating teams, and it has become more and more difficult to select just one paper for each problem. Instead, we will now publish the Summary Sheet for every Outstanding paper, with the hope that doing so will give readers a more-comprehensive view of the diversity of solution approaches.

The Summary Sheets are reproduced as they were submitted, including use of italic and boldface emphasis. Minor spelling and usage errors have been corrected.

New Internship Opportunities

COMAP is pleased to announce new ongoing partnerships with two financial firms:

Two Sigma

Two Sigma https://www.twosigma.com has been a supporter of the ICM/MCM for many years. Two Sigma is an investment manager that uses a variety of technological methods, including artificial intelligence, machine learning, and distributed computing, for its trading strategies. Two Sigma is excited to welcome members of ICM/MCM Outstanding and Finalist teams for consideration in its internship program.

Two Sigma, headquartered in New York City, offers internships in quantitative research and in software engineering. The internship experience offers:

- Professional skill building, with workshops on technical skills, public speaking, and writing.
- Mentorship: Be paired with a mentor from your first day in the program.
- Visibility: Interact and engage with our senior leaders at events ranging from small group lunches to company-wide talks.
- Customized curriculum based on your internship area.
- Adventure: Explore New York City through community events and social outings, such as Broadway musicals and food tours.

After the ICM/MCM contest results are announced, COMAP contacts those teams that meet the requirements with information on how to apply for a Two Sigma internship. This opportunity is open to team members from any country/region. However, being selected and notified by COMAP of eligibility does not guarantee participation in the program.

Anzu Partners

COMAP is pleased to announce a new partnership with Anzu Partners https://www.anzupartners.com, a venture capital and private equity firm that invests in breakthrough industrial technologies and life sciences. Anzu is excited to welcome members of ICM/MCM Outstanding and Finalist teams residing in the U.S. for consideration for their Summer Analyst Program. These Summer Analysts will be responsible for both investment team and portfolio support. This is a unique opportunity to gain exposure into venture capital while putting your technical degree to use.

Key activities in investment include:

- Conducting initial screening on potential investments
- Diligence with company, customer, and competitor interviews when appropriate
- Analyzing financial projections and proposed deal terms

Key activities in portfolio support include:

- Building and testing prototypes for entry into new markets
- Analyzing product fit to the target market and any potential adjustments needed
- Developing commercial strategies (e.g. channels, pricing, etc.) for growing companies

Each position reports to an Anzu Investment Team member, as part of a small, cross-functional team with strong personal and professional development opportunities.

After the ICM/MCM contest results are announced, COMAP contacts those U.S. teams that meet the requirements with information on how to apply for the paid summer internships. Being selected and notified by COMAP of eligibility does not guarantee participation in the program.

Editorial Note: Caution and Disclaimer

Please Take Care

There was concern among some judges about an isolated phrase in one ICM team's paper because it suggested to them a colonial perspective of cultural superiority on the part of the team.

Contest participants come from varying cultures and social perspectives, as do the judges. Contest participants may not be native speakers of English nor be conversant with terminology considered undesirable (or even utterly unacceptable to some) in current U.S. societal discourse.

Judges must look beyond their own views and any discomfort with the social, cultural, or political perspectives—expressed or implied—that a paper appears to exhibit. The judges evaluate papers based on the modeling effort exhibited; as related in the contest instructions, "MCM/ICM judges are primarily interested in the team's thought processes, analysis of the problem, modeling approaches, and mathematical methods."

Nevertheless, contest participants are urged to take special care, in terminology and in sense of meaning, to avoid disparaging or offending—intentionally or unintentionally—any group or individual.

Disclaimer

The above caution occasions a thorough reminder to readers.

Non-editorial content of this issue was prepared by authors solely in their personal capacities. The views, thoughts, opinions, and recommendations expressed by authors are those of the individuals involved and are not intended to reflect (and do not necessarily reflect) official or unofficial policies or positions of

- the authors' associated institutions,
- the authors' employers,
- COMAP, its governing board, the supporting professional societies, its executive publisher, its staff, or the editor of *The UMAP Journal*.

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No contents are intended to disparage or offend members of any race, religion, nation, region, ethnic group, culture, language, gender/sexual orientation, political party, company, organization, or association; or any individual.

ICM Modeling Forum

Results of the 2023 Interdisciplinary Contest in Modeling

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Introduction

A total of 9,564 teams from 13 countries/regions spent a weekend working on an interdisciplinary modeling problem in the COMAP's 25th Interdisciplinary Contest in Modeling (ICM®). This year's contest ran from Thursday, February 16 to Monday, February 20. Unfortunately, many teams were unable to participate in the 2023 ICM/MCM on the contest weekend due to covid and scheduling issues. While it was impossible for us to change the February contest dates, we decided to provide the ICM/MCM experience for these teams by instituting, for this year only, a one-time Spring ICM/MCM contest. This contest was as challenging as the regular ICM/MCM contest and ran from March 30 through April 3. Its judging was run by experienced ICM/MCM leadership to ensure the same level of rigor in problem development and judging that teams have come to expect from COMAP's undergraduate contests. An additional 1,359 teams from 12 countries/regions took part in the Spring ICM.

During these weekends, teams of up to three undergraduate or high school students researched, modeled, analyzed, solved, wrote, and submitted their solutions to an open-ended interdisciplinary modeling problem. After the weekend, the solution papers were sent to COMAP for judging.

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COMAP, whose educational philosophy is centered on modeling, supports the use of mathematical and scientific concepts, methods, and tools to explore real-world problems. COMAP's goal is to serve society by developing students as problem solvers in order to become better informed and prepared as citizens, contributors, consumers, workers, and community leaders. The ICM is an example of COMAP's efforts toward this goal.

The 2024 ICM Contest is scheduled to take place February 1–5, 2024.

A companion Mathematical Contest in Modeling (MCM®) takes place simultaneously with the ICM and offers problems whose solutions can feature continuous mathematics, discrete mathematics, or data analysis. Results and details about the 2023 MCM Contest and its results will appear in Vol. 44, No. 4 of this *Journal*.

Descriptions of the 2023 ICM Problems

- **The D Problem** comes from the subjects of **operations research or network science**. This year's D problem involved creating a network of relationships among the 17 United Nations (UN) Sustainable Development Goals (SDGs). Teams chose how to determine what constitutes a relationship and used either a directed or an undirected network. Teams needed to use their network to set priorities for the UN to best achieve its goals, as well as to understand how outside factors, such as technology, climate change, pandemics, migration, and wars may impact those priorities. Teams concluded their analysis by looking at how thinking about goals as a network could lead to better results than thinking of each goal to be achieved individually. This approach could be advantageous to many organizations beyond the UN.
- **The E Problem** focuses on a **sustainability** topic. This year's E Problem asked teams to develop a broadly-applicable metric to determine the light pollution risk level of a location. Since relevant considerations for this metric may vary widely depending on the population density of a location, teams were required to apply their metric to a protected land location, a rural community, a suburban community, and an urban community. Additionally, teams were asked to discuss three possible intervention strategies and to use their metric to determine which of the strategies would be most effective in two of their locations. Thus, the problem required teams to have a multifaceted understanding of the factors contributing to light pollution and its effects.
- **The F Problem** focuses on issues in **policy** modeling. This year's F Problem asked teams to understand how the way we measure national economies has the potential to impact our world. In particular, teams analyzed how including environmental resources ("Green") as a part of the Gross Domestic Product calculation may help with climate mitigation

initiatives. Teams selected an existing Green Gross Domestic Product (GGDP) to create a way to measure the potential global impact on climate mitigation. They also selected one country as a case study, to see the value and limitations for that nation. Overall, many teams struggled to make a case to national leaders, in a nontechnical way, for or against such a change. Skill in exposition and persuasion is particularly important, because to make real changes, many policy makers need action items—with clear reasoning and without technical jargon—that can appeal to a broad audience.

- **The Z Problem** in the Spring contest was also a **policy**-modeling problem. Teams were asked to explore the phenomenon of a decreasing number of bids to host the summer and winter Olympic Games that the International Olympic Committee (IOC) has been experiencing, as cities and nations decide that the costs of hosting the games far outweigh the benefits. Teams were asked to consider from multiple viewpoints impacts of hosting the Olympic Games. Teams developed one or more metrics to measure these impacts. Many teams were creative in using their metric to explore options, strategies, and policies to ensure that the Olympics continue to be successful, in fulfilling the Olympics' mission to bring the world together through sport. Finally, teams were required to explain their findings and make recommendations for the future, in a memorandum addressed to the IOC.

For all the problems, teams searched for pertinent data and grappled with how phenomena internal and external to the system under study needed to be considered. The teams developed creative and relevant solutions to complex questions facing modern societies and built models to handle the specific issues addressed in the problems. These problems also had the ever-present ICM requirements to use data analysis, creative modeling, and scientific methodology, along with effective writing and visualization, to communicate results in a 25-page report.

This year's judges remarked that due to the multidisciplinary nature of the problems, teams solved these problems using a variety of methods and tools. Doing so allowed teams to showcase their strengths in many diverse areas, including climate science, data science, dynamical systems, economics, environmental science, network science, policy, statistics, and sustainability.

The full problem statements are given in separate sections later in this issue. Eighteen ICM papers from the two weekends were designated Outstanding. The summaries of those papers are featured in this issue, along with commentaries from problem authors and judges. All results of both the February ICM/MCM and the Spring ICM/MCM are available at the COMAP website https://www.mcmcontest.com. A Contest Director's Report and a Judges' Commentary for each of the Spring problems will appear later.

Problem Authors

The problems were written by:

- Problem D (Prioritizing the UN Sustainability Goals): Amanda Beecher (Ramapo College of New Jersey).
- Problem E (Light Pollution): Kayla Blyman (Saint Martin's University) and Wesley Hamilton (MathWorks).
- Problem F (Green GDP): Jessica Libertini (Joint Special Operations University).
- Problem Z (The Future of the Olympics): Chris Arney (US Military Academy) and Kayla Blyman (Saint Martin's University)

Honesty Is Demanded

The ICM requires teams to be honest in their research and presentation. However, in this year's contest, 646(!) papers—almost 6% of all papers—were disqualified due to plagiarism. The ICM expects contestants to be honest and careful about doing their own work and attributing their resources and references properly. Submitted papers must be the team's own effort; and when data, methodology, figures, or ideas are used from others, attribution must be carefully and clearly given to the sources of those data, methods, figures, and ideas. We find that a large number of teams are not properly documenting images taken from external sites. So, practice referencing all images in your other reports this year to prepare for next year's ICM!

Resources for Interdisciplinary Modeling

The ICM seeks to develop interdisciplinary modeling skills in the contest's participants by giving opportunities for teams to solve a modern interdisciplinary problem and receive a category (Outstanding, Finalist, Meritorious, Honorable Mention, Successful, or Unsuccessful) that reflects the quality of the team's performance. At https://www.mathmodels.org, COMAP publishes examples of Outstanding submissions from past contests, plus commentaries on the interdisciplinary modeling elements discovered by the expert judges as they read and evaluated the submissions of the teams. Other online resources at COMAP with problems worthy of investigation are Interdisciplinary Lively Application Projects (ILAPs) and UMAP Modules.

A Brief History of the ICM

Looking at the range of topics over the 43 problems given over the 25 years of the ICM (provided in **Table 1**), the contest shows its interdisciplinarity, with problems involving themes from banking, biology, business, chemistry, climate science, cooperative systems, cultural preservation, data science, ecology, economics, education, engineering, environmental science, finance, food science, history, information science, international relations, medicine, music, network science, operations research, physics, policy, political science, sports, and sustainability.

Over its 25 years, the ICM has had more than 89,000 teams submit papers from more than 265,000 contestants.

This year, China had the most entries by far, with the United States, Malaysia, and the United Kingdom in the next three spots. There were dozens of schools from China with more than 100 teams each.

Judges' Expertise in Interdisciplinary Modeling

A listing of the final judges' names and affiliations appears later in this report.

The judging is done in two phases:

- In the first (triage) phase, all the papers are judged and scored by at least two judges.
- In the second (final stage), the papers with the highest triage scores are given more attention from a panel of final judges who meet and discuss the merits of these papers.

The judges consider many perspectives in modeling and problem solving to determine final rankings and categories of the papers. This year, the 32 final judges came from 26 institutions and organizations and possess advanced degrees in disciplines such as applied mathematics, biology, chemistry, computer science, education, electrical engineering, geography, international studies, law, mathematics, operations research, physics, political science, sociology, statistics, and sustainability. The ICM's 194 triage judges were an even more diverse group, from more than 100 schools and organizations, with degrees representing more than 55 disciplines.

An Outstanding ICM paper requires a team to use knowledge, constructs, and tools from a different discipline and integrate it with their mathematical model to solve a problem, while also realizing the strengths and limitations of their modeling choices. This effort may also require that a solution include contextual understanding of the time, resources, and

Table 1. ICM problems and numbers of entries since inception of the contest.

Year	Number of teams	Topic
1999	40	Controlling the spread of ground pollution
2000	70	Controlling elephant populations
2001	83	Controlling zebra mussel populations
2002	106	Preserving the habitat of the scrub lizard
2003	146	Designing an airport screening system
2004	143	Designing information technology security for a campus
2005	164	Harvesting and managing exhaustible resources
2006	224	Modeling HIV/AIDS infections and finances
2007	273	Designing a viable kidney exchange network
2008	380	Measuring utility in health care networks
2009	374	Balancing a water-based ecosystem affected by fish farming
2010	356	Controlling ocean debris
2011	735	Measuring the impact of electric vehicles
2012	1,329	Identifying criminals in a conspiracy network
2013	957	Modeling Earth's health
2014	1,028	Using networks to measure influence and impact
2015	641	Measuring churn and human capital in an organization
2015	1,496	Measuring sustainability for least-developed countries
2016 D	863	Measuring evolution and influence in information networks
2016 E	3,208	Are we heading towards a thirsty planet?
2016 F	952	Modeling refugee immigration policies
2017 D	3,664	Optimizing passenger throughput at airport security
2017 E	3,621	Sustainable cities needed!
2017 F	800	Migration to Mars: Utopian workforce of the 2100 urban society
2018 D	3,158	Out of gas and driving on E (for electric, not empty)
2018 E	6,176	How does climate change influence regional instability?
2018 F	598	The cost of privacy
2019 D	5,728	Time to leave the Louvre
2019 E	4,852	The cost of environmental degradation
2019 F	682	Universal decentralized digital currency
2020 D	2,089	Teaming strategies
2020 E	2,528	Drowning in plastic
2020 F	2,586	Settlement of refugees
2021 D	5,551	The influence of music
2021 E	3,521	Re-optimizing food systems
2021 F	6,987	Checking the pulse and temperature of higher education
2022D	955	Maturity assessment of a data and analytics system
2022E	8,181	Forestry for carbon sequestration
2022F	2,964	Equity in asteroid mining
2023D	1,057	Prioritizing the UN Sustainability Goals
2023E	5,781	Light pollution
2023F	2,726	Green GDP
2023Z	1,359	The future of the Olympics

industries in which the problem is being addressed. To judge accurately the success of a team in reaching these diverse objectives and effectively integrating and communicating them, we must have judges able to evaluate the authenticity of a team's work from their disciplinary and modeling viewpoints.

However, it is only through the collective of multidisciplinary and interdisciplinary judging perspectives that a paper can be evaluated and a truly Outstanding paper can be identified. The final judging team is formed with this interdisciplinary perspective goal in mind. During the many rounds of final judging, papers are appraised from the multifaceted perspectives of the judges, in an effort to find the few papers that contain a sufficient mix of the ingredients that form an Outstanding paper—one that exemplifies the best of the different interdisciplinary approaches seen in the papers.

To judge a growing number of papers with the high standards and consistency expected by the ICM, many schools have created ICM judging teams, where several people meet and discuss the merits of papers, reflective of the discussions in the final judging round. In addition to the benefit of standardizing judging, this process also allows each judge to become more interdisciplinary. The judging teams discuss the value of a particular approach, the necessary assumptions for a particular construct, or the ability of a participating team's recommendations actually to be implementable. This discussion strengthens the knowledge and understanding of our judges but also creates a more comprehensive evaluation system for the papers.

2023 ICM Statistics

- 10,923 Teams participated
- 1,057 Problem D submissions (10%)
- 5,781 Problem E submissions (53%)
- 2,726 Problem F submissions (25%)
- 1,359 Problem Z submissions (12%)
- 18 Outstanding Winners (<1%)
- 299 Finalist Winners (2%)
- 702 Meritorious Winners (6%)
- 2,288 Honorable Mentions (21%)
- 6,816 Successful Participants (62%)
- 139 Unsuccessful Participants (1%)
- 646 Disqualified teams (6%)
- 15 Not judged (e.g., entries corrupted) (<1%)

The Results

The 10,923 solution papers were coded at COMAP headquarters so that names and affiliations of the authors were unknown to the judges. Each paper was then read preliminarily by triage judges. At the triage stage, the summary, the one-to-two page report (if applicable), the model description, and overall organization are the primary elements in judging a paper. Final judging by a team of modelers, analysts, and subject-matter experts took place in early May (February contest) or June (Spring contest). The judges classified the papers as shown in **Table 2**.

Table 2. Overall results of the 2023 ICM.

Problem	Outstanding	Finalist	Meritorious	Honorable Mention	Successful Participant	Total Entries
D	3	75	65	194	714	1,057
E	8	118	366	1,301	3,553	5,781
F	4	84	165	516	1,697	2,726
Z	3	22	106	277	852	1,359
Total	18	299	702	2,288	6,816	10,923

Eighteen teams were designated as Outstanding, representing the following schools (with team number indicated):

- Problem D (Prioritizing the UN Sustainability Goals)
  - 2304962 China University of Petroleum — INFORMS Award
  - 2303967 Shanghai Jiao Tong University, China — AMS Award
  - 2300229 University of Electronic Science and Technology of China — Leonhard Euler Award
- Problem E (Light Pollution)
  - 2312411 Chang'an University, China —– Rachel Carson Award
  - 2308000 China University of Geosciences Beijing, China —– INFORMS Award
  - 2305598 Liaoning University, China
  - 2301428 Nanjing University of Posts & Telecommunications, China
  - 2314354 Southwest Jiaotong University, China
  - 2314817 Sun Yat-Sen University, China
  - 2320131 Tianjin University, China — SIAM Award and COMAP Scholarship Award and
  - 2307336 Wuhan University, China —– AMS Award

- Problem F (Green GDP)
  - 2305794 Beijing Institute of Technology, China — COMAP Scholarship Award and INFORMS Award
  - 2311517 Renmin University of China —– Vilfredo Pareto Award
  - 2315018 Soochow University, China —– SIAM Award
  - 2311258 Xidian University, China —– AMS Award
- Problem Z (The Future of the Olympics)
  - 2330760 Northeastern University at Qinhuangdao, China —– COMAP Scholarship Award
  - 2330610 University of Science and Technology of China —– AMS Award
  - 2330003 Xi'an Jiaotong University, China — Frank Giordano Award

Awards

Each successful participant received a certificate with the team's rating (Outstanding, Finalist, Meritorious, Honorable Mention, or Successful Participant).

Leonhard Euler Award

The Leonhard Euler Award is presented to a team solving the network science/operations research problem (Problem D) that performs especially creative and innovative modeling while showing good understanding of interdisciplinary science. The award honors the 18th-century Swiss applied mathematician who was known for the breadth of his research applications, his considerable contributions to sciences and mathematics through his written work, his excellent teaching, and his interdisciplinarity. This year's Euler Award went to team 2300229 from University of Electronic Science and Technology of China.

Rachel Carson Award

The Rachel Carson Award honors the American conservationist whose book *Silent Spring* initiated the global environmental movement and whose work spanned many disciplines concerned with the local and global environments. This award for excellence in using scientific theory and data in environmental modeling (Problem E) went to Team 2312411 from Chang'an University, China.

Vilfredo Pareto Award

This award for outstanding modeling in the policy modeling problem (Problem F) honors the work and legacy of a famous social-science problem solver, who at various times was an engineer, sociologist, economist, political scientist, mathematician, and philosopher. For this award, the head judges seek to highlight a paper that best models the more dynamic and challenging contextual human elements that make simplification or refinement of policy models so difficult. This year the award went to Team 2311517 Renmin University of China.

Frank Giordano Award

Having worked on the contest since its inception, Frank Giordano served as Contest Director for 20 years. This award goes to a paper that demonstrates a very good example of the modeling process in a problem featuring discrete mathematics. The Frank Giordano Award went to Team 2330003 from Xi'an Jiaotong University, China (Problem Z).

American Mathematical Society (AMS) Awards

The American Mathematical Society Award recognized the teams:

- 2303967 Shanghai Jiao Tong University, China (Problem D).
- 2307336 Wuhan University, China (Problem E).
- 2311258 Xidian University, China (Problem F).
- 2330610 University of Science and Technology of China (Problem Z).

INFORMS Awards

The Institute for Operations Research and the Management Sciences (INFORMS) designated three Outstanding teams as INFORMS Winners. This year's winners were the teams:

- 2304962 China University of Petroleum (Problem D).
- 2308000 China University of Geosciences Beijing, China (Problem E).
- 2305794 Beijing Institute of Technology, China (Problem F).

Mathematical Association of America Award

The Mathematical Association of America (MAA) designated two North American teams as MAA Winners. The teams were:

- 2310776 (Finalist) Pacific Lutheran University, WA, USA (Problem D).

- 2309766 (Finalist) Seattle Pacific University, WA, USA (Problem E).

Each team member was presented a certificate by an official of the MAA Committee on Undergraduate Student Activities and Chapters.

Society for Industrial and Applied Mathematics Awards

The Society for Industrial and Applied Mathematics (SIAM) designated three Outstanding teams as SIAM Winners:

- 2315321 (Finalist) National University of Defense Technology, China (Problem D).
- 2320131 Tianjin University, China (Problem E).
- 2315018 Soochow University, China (Problem F).

Each team member received a complimentary one-year student membership in SIAM. The team's faculty advisor received a certificate recognizing the team members.

International COMAP Scholarship Awards

The International COMAP Scholarship Award was awarded this year to five top ICM/MCM teams: $10,000 per team, with $9,000 to the team members and $1,000 to the school, in the name of the advisor.

The winning teams in the ICM were:

- 2320131 Tianjin University, China (Problem E).
- 2305794 Beijing Institute of Technology, China (Problem F).
- 2330760 Northeastern University at Qinhuangdao, China (Problem Z).

Judging

Problem D: Prioritizing the UN Sustainability Goals

Problem Directors
Chris Arney, COMAP, Bedford, MA
Michelle L. Isenhour, Johnson & Johnson, New Brunswick, NJ

Final Judges
Hilary Fletcher, Richmond, VA
Kira Graves, TRADOC G2 Fort Leavenworth, US Army
Eric Marland, Mathematics, Appalachian State University, Boone, NC
Amy Richmond, Geography & Environmental Engineering,
US Military Academy, West Point, NY

Csilla Szabo, Mathematics, Skidmore College, Saratoga Springs, NY
Robert Ulman, Network Sciences Division, US Army Research Office,
Research Triangle Park, NC

Problem E: Light Pollution

Problem Directors
Kayla Blyman, Mathematics, Saint Martin's University, Lacey, WA
Wesley Hamilton, MathWorks, Boston, MA
Kasie Hartling, onsemi, East Fishkill, NY

Final Judges
Ann Baldwin, Civil Engineer, Worton, MD
Jonas D'Andrea, Mathematics, Westminster College, Salt Lake City, UT
Michelle Guinn, Mathematics, Belmont University, Nashville, TN
Rebecca Hardenbrook, Applied Mathematics, University of Utah,
Salt Lake City, UT
Mary Jo Hartman, Biology, Saint Martin's University, Lacey, WA
David McMorris, Mathematics, Christopher Newport University,
Newport News, VA
Veena Mendiratta, Data Analytics, Northwestern University, Evanston, IL
Marie Meyer, Mathematics, Lewis University, Romeoville, IL
Katherine Pinzon, Mathematics, Georgia Gwinnett College,
Lawrenceville, GA
Csilla Szabo, Mathematics, Skidmore College, Saratoga Springs, NY
Jie Wang, Computer Science, University of Massachusetts Lowell,
Lowell, MA

Problem F: Green GDP

Problem Directors
Jessica M. Libertini, Joint Special Operations University, Tampa, FL
Troy J. Siemers, Applied Mathematics, Virginia Military Institute,
Lexington, VA

Final Judges
Heather Bloemhard, Division of Government and Community Relations,
Vanderbilt University, Washington, DC
Luke Castle, Mathematics, North Carolina State University,
Raleigh, NC
Keith Erickson, Mathematics, Georgia Gwinnett College,
Lawrenceville, GA
Sarah Iams, Applied Mathematics, Harvard University, Cambridge, MA

Eleanor Abernethy Ollhoff, Mathematician, Bonn, Germany
Victor Piercey, Mathematics, Ferris State University, Big Rapids, MI

Problem Z: The Future of the Olympics

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Acknowledgments

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- the Institute for Operations Research and the Management Sciences (INFORMS) for providing prizes for teams;
- the Mathematical Association of America (MAA) for providing awards for teams;
- the Society for Industrial and Applied Mathematics (SIAM) for providing awards for teams;
- Anzu Partners https://www.anzupartners.com for welcoming members of ICM/MCM Outstanding and Finalist teams residing in the U.S. for consideration in their Summer Analyst Program; and
- Two Sigma https://www.twosigma.com for welcoming members of ICM/MCM Outstanding and Finalist teams for consideration in its internship program.

Cautions

- **To the potential ICM Advisor:** It might be overpowering to encounter in the Outstanding papers such output from a weekend of work by a small team of undergraduates, but the Outstanding solution papers are atypical. A team that prepares and participates will have an enriching learning experience in modeling and problem solving, independent of what any other team does.
- **To the potential ICM team member:** The ICM will test you and your team's knowledge, creativity, skill in modeling, and skill in producing a good report on your work. ICM will also develop your modeling and communications skills and ability to work in a team. A tremendous amount of effort goes into a successful contest and report. A good solution may be approximately equal parts cooperating, thinking, modeling, calculating, analyzing, explaining, writing, and formatting.

About the Authors

Amanda Beecher is Associate Professor of Mathematics at Ramapo College of New Jersey. She serves as the founding department head of the Data Science undergraduate program and Program Director of the Master's in Applied Mathematics program at Ramapo College. She earned her Ph.D. from the University at Albany, SUNY. Before arriving at Ramapo, she had a three-year post-doctoral appointment at the United States Military Academy, where her interests in applied mathematics were fostered. Her research interests include combinatorics, graph theory, commutative algebra, modern applied mathematics (including data analysis), and mathematical modeling. Her educational endeavors include bringing interdisciplinary modeling opportunities to colleagues and students. As the Director for Undergraduate Contests at COMAP, she helps organize the Mathematical Contest in Modeling and the Interdisciplinary Contest in Modeling, which annually offer more than 75,000 students a real-world modeling experience. She serves in many roles in the Mathematical Association of America, including the Chair of the NJ Section and the Vice Chair of the Special Interest Group on Environmental Modeling.

Kayla Blyman is Assistant Professor of Mathematics at Saint Martin's University in Lacey, Washington. She holds a Ph.D. in STEM Education and an M.A. in Mathematics, both from the University of Kentucky, as well as a B.A. in Mathematics from Messiah College (now Messiah University). She has taught at the US Military Academy at West Point, Berea College, Midway College (now Midway University), and the University of Kentucky. With COMAP, Kayla wears multiple hats: She is director of the Middle Mathematical Contest in Modeling (MidMCM); co-director, problem director, problem author, final judge, judges' commentary author, triage judge coordinator, and triage judge for the Interdisciplinary Contest in Modeling (ICM); associate editor for the Teaching Modeling Department of *The UMAP Journal*; and lead developer for the Introduction to Modeling course for the COMAP Certificate in Modeling (CiM). Kayla's research is focused on the development and implementation of new and creative ways to teach and assess undergraduate mathematics, with a goal of better developing creative problem solvers for our future. An avid explorer—both professionally and personally—Kayla loves spending time in the great outdoors, partaking in the arts, traveling to new places, and trying new food.

2023 ICM Problem D: Prioritizing the UN Sustainability Goals

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Background

The **United Nations (UN)** has set 17 **Sustainable Development Goals (SDGs)**. Achieving these goals would ultimately lead to an improved life for many people around the world. These goals are not independent of one another. So, often positive gains in some goals have an impact (positive or negative and sometimes both) on other goals. This interconnectedness makes the achievement of all goals a fluid process where funding limitations and other national and international priorities may take precedence. Additionally, the impact of technological advances, global pandemics, climate change, regional wars, and refugee movements have had serious implications on many of the goals.

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Requirement

To explore the relationships among the goals:

- Create a network of the relationships among the 17 SDGs.
- Use the individual SDGs, as well as the structure of your network, to set priorities that can most efficiently move the work of the UN forward. How did you evaluate the effectiveness of each priority? What could be reasonable to achieve in the next 10 years if your priorities are initiated?
- If one of the SDGs is achieved (for example, there is no poverty or no hunger), what would be the structure of the resulting network? How would this achievement impact your team's priorities? Are there other goals that should be included or proposed to the UN for inclusion?
- Discuss the impact of technological advances, global pandemics, climate change, regional wars, and refugee movements, or other international crises on your team's network and your team's choice of priorities. What are the significant effects on the progress of the UN from a network perspective?
- Discuss how your network approach may help other companies and organizations set priorities of their goals.

UN Sustainable Development Goals [United Nations 2015]

- GOAL 1: No Poverty
- GOAL 2: Zero Hunger
- GOAL 3: Good Health and Well-being
- GOAL 4: Quality Education
- GOAL 5: Gender Equality
- GOAL 6: Clean Water and Sanitation
- GOAL 7: Affordable and Clean Energy
- GOAL 8: Decent Work and Economic Growth
- GOAL 9: Industry, Innovation and Infrastructure
- GOAL 10: Reduced Inequality
- GOAL 11: Sustainable Cities and Communities
- GOAL 12: Responsible Consumption and Production

- GOAL 13: Climate Action
- GOAL 14: Life Below Water
- GOAL 15: Life on Land
- GOAL 16: Peace and Justice Strong Institutions
- GOAL 17: Partnerships to Achieve the Goals

Note: The ICM has a 25-page limit. All aspects of your submission count toward the 25-page limit (Summary Sheet, Table of Contents, Reference List, and any Appendices). You must cite the sources for your ideas, images, and any other materials used in your report.

Glossary

- **United Nations (UN)**: The United Nations (UN) is an intergovernmental organization whose stated purposes are to maintain international peace and security, develop friendly relations among nations, achieve international cooperation, and be a center for harmonizing the actions of nations.
- **Sustainable Development Goals (SDGs)**: The Sustainable Development Goals (SDGs), or Global Goals, are a collection of 17 interlinked objectives designed to serve as a "shared blueprint for peace and prosperity for people and the planet now and into the future."

Reference

United Nations. 2015. *Transforming Our World: The 2030 Agenda for Sustainable Development*. https://sdgs.un.org/sites/default/files/publications/21252030%20Agenda%20for%20Sustainable%20Development%20web.pdf.

About the Author

Amanda Beecher is Associate Professor of Mathematics at Ramapo College of New Jersey. She serves as the founding department head of the Data Science undergraduate program and Program Director of the Master's in Applied Mathematics program at Ramapo College. She earned her Ph.D. from the University at Albany, SUNY. Before arriving at Ramapo, she had a three-year post-doctoral appointment at the United States Military Academy, where her interests in applied mathematics were fostered. Her research interests include combinatorics, graph theory, commutative algebra, modern applied mathematics (including data analysis), and mathematical modeling. Her educational endeavors include bringing interdisciplinary modeling opportunities to colleagues and students. As the Director for Undergraduate Contests at COMAP, she helps organize the Mathematical Contest in Modeling and the Interdisciplinary Contest in Modeling, which annually offer more than 75,000 students a real-world modeling experience. She serves in many roles in the Mathematical Association of America, including the Chair of the NJ Section and the Vice Chair of the Special Interest Group on Environmental Modeling.

Summaries of UN Goals Outstanding Papers

Connecting the Dots: Unpacking the Network Systems of SDGs

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College of Science

Team members: Xiaotian Zhu, Jingwen Liu, and Xinjie Liu
Advisor: Hua Chen

The Sustainable Development Goals (SDGs) are not just a call to action, but a vision of hope for a better world where all people can thrive, nature can flourish, and societies can prosper in harmony with one another. To achieve sustainable development, it is critical to study relationships among SDGs and select the most effective priority goals.

For problem one, a multi-layer network approach was employed to establish a model for analyzing the interrelationships and impacts of SDGs, which improved upon the UN's goal-target-indicator model by obtaining separate networks for each SDG. The final model was derived by computing the Pearson correlation coefficient matrix and network connections. The network models for 10 regions were visualized, revealing that in the WLD region, SDG8 had a positive impact on other SDGs, particularly on SDG4, while SDG17 had a negative impact on 14 SDGs.

For problem two, we proposed a network-based evaluation algorithm, which considers feedback mechanisms and time impact to identify achievable goals and assess project effectiveness. Scores for each SDG were visualized for 10 regions, recommending SDG4 in five regions, including WLD and ARB. Achievable goals within 10 years were identified for 9 regions achieving SDG1 and 2 regions achieving SDG17.

For problem three, we proposed a revised plan to analyze the impact of network model changes when implementing a specific SDG, identifying new feasible goals with smaller impact on other SDGs. Using WLD as an example, we modified the network model to account for the one-way impact of achieved SDGs on other SDGs, visualizing and analyzing the results. We used an evaluation algorithm to determine the optimal priority

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target, finding that when implementing SDG4 in WLD, the optimal priority shifted to SDG8. We also recommend incorporating technology and digitalization as new development goals, given their positive impact on SDG2, SDG3, SDG7.

For problem four, we modified the model to respond to crises/opportunities by introducing a perturbation matrix to represent event impact and exploring its effect on optimal development goals. In the case of WLD/local wars, the optimal goal shifted from SDG1 to SDG17. Analyzing SDG9 under 7 events, we determined that natural disasters had the greatest impact on the UN's work.

For problem five, our hierarchical network modeling approach can be promoted to analyze goal connections and select priority development goals in other fields. It can refine business goals into targets, indicators, and data in companies. We used business goals as an example, established a network model, and determined the optimal priority development goals. Our method is not limited to the SDG field but can also help other organizations and individuals achieve their goals.

We have concluded that our model has strong robustness, high stability, and good interpretability. This provides scientific guidance and support for achieving the SDGs.

Keywords: SDG, multiple complex networks, Pearson correlation coefficient, system dynamics

DIGNP: Dynamic Indicator-Goal Network for Prioritization

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Advisor: Xiaofeng Gao

The UN has established 17 Sustainable Development Goals (SDGs) to address global challenges related to economic, technological, and environmental issues, among others. To make the world a better place, in order to grasp the priority relationships of SDGs, we develop the **Dynamics Indicator-Goal Network for Prioritization (DIGNP)**.

First of all, to create a network of the SDGs that can capture the complex and dynamic relationships between the different goals and their linkages over time, we utilize system dynamics modeling. To begin our model, we first select several most influential indicators of each SDG using correlation. Then we lay out the Indicator Network and the correspondent Goal Network. The relationships between the goals are assessed by comprehensively analyzing the correlations between indicators and the impact of indicators on the goals.

Next, we establish a **priority evaluation system** that prioritizes SDGs and predicts their impact and achievement over the next decade following the initiation of priority. Based on the topology of the constructed SDG Network, we develop **five key indicators** for measuring the priority of each goal. Using the **Entropy Weight Method**, we then develop our SDG Priority Ranking System. **The first five SDGs are SDG 17, SDG 3, SDG 1, SDG 4, SDG 13, ranked by priority.** Based on the priority, we forecast the future evolution of the SDGs by **Auto Regressive Integrated Moving Average (ARIMA)**. Our analysis indicates that if our priorities are initiated, SDGs will improve faster by a **priority term**.

Furthermore, considering the goal adjustment, our dynamic SDG Network automatically adjusts its topology and priority rankings based on changes in any indicator or goal nodes. **Goal accomplishment** causes **subtraction of the node** in our networks, which alters edge weight and the priority score. **Goal addition** leads to **addition of the node** in our networks. Our results show that incorporating **Access to Information and Communication Technologies** as a new SDG is critical to enhancing the connection between SDGs and advancing their achievement.

Meanwhile, the network topology and priority of the SDGs can also be significantly impacted by various international crises, influencing the progress of the UN. In the case of forest fires, SDG 13, SDG 15, SDG 11 are underlined, and they call on the UN to implement SDG-aligned initiatives that foster resilience and sustainable development. It is crucial for the UN to recognize these potential impacts and adjust its strategy to address the most urgent challenges as they emerge.

Finally, we promote the construction of our SDG Network and prioritization to a general model **Dynamics Indicator-Goal Network for Prioritization**. With reasonable data input, a **global, dynamic and automatic** Indicator and Goal Network can be constructed and priorities can be figured out. What's more, we design a User Interface for those who utilize our DIGNP model.

Keywords: sustainable development goals, system dynamics, dynamic network, priority evaluation, correlation coefficient, CVM, EWM, ARIMA

Methods of Measuring Priority via Graph Models: Who Is the Top 1?

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Team members: Honglin Cao, Zijian Zhou, and Yongqi Hu
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In 2015, the United Nations set 17 Sustainable Development Goals (SDGs). If these goals are achieved, we could ultimately improve life of people all over the world. The 17 SDGs are not independent of one another. Their connections make the achievement of all goals much easier. In this paper, we construct three distinctive models to study how to prioritize the SDGs.

First, to find out relationships and priorities among the 17 SDGs, we propose a **Relationship Graph Model**. In the model, we build a graph of the 17 SDGs. Vertexes of the graph are the 17 goals. Edges of the graph are correlations between goals via **Spearman Correlation Analysis Algorithm**. To measure the graph, we use Betweenness Centrality, Closeness Centrality and Eigenvector Centrality. We respectively calculate centralities of positive edges and negative edges. Hence, each goal has 6 indexes. We use **Entropy Weight Method** to calculate weights of the 6 indexes. Then we use **Weighted TOPSIS** to get the priorities of the 17 goals. Goal 3 and Goal4 rank in top 5 priority list for all three countries we study. This means that most countries should put health and education on the priority list of development.

Then we study the development of the 17 SDGs in next 10 years. We propose a **Temporal Champagne Tower Model**. This model not only considers resource allocation based on priorities, but also the synergistic and trade-off relationships between goals. We use a **Time Series Algorithm** to predict the development of SDGs in next 10 years. We allocate resources according to the method of first satisfying the highest priority goal. When a goal is achieved, we raise its priority to the highest priority queue (complete goal queue) to preferentially maintain the complete goal. We do simulation on Indonesia. In the next 10 years, Indonesia can achieve 5 goals. It can achieve 82% of SDGs, which is 4% higher than the result of its current plan.

Moreover, to study the impact of unexpected events like COVID-19, we make some adjustment to our models. We add two parameters to measure the impacts. Models about the priorities and allocated resources are adjusted based on the two parameters. We rerun our models. According to the simulation, in the next 10 years, Indonesia can only achieve 3 goals. It can achieve 78% of SDGs, which is 4% lower than the previous result.

Finally, we perform sensitivity analysis on the hyperparameters C and D in the Temporal Champagne Tower Model. The maximum variation ranges of the model results caused by the changes of C and D are 0.041 and 0.028, respectively, which indicates that our model has a strong robustness.

Keywords: sustainable development goals, graph centrality, TOPSIS, Entropy Weight Method

Judges' Commentary: Prioritizing the UN Sustainability Goals

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Introduction

In 1962, Rachel Carson told graduates at Scripps College in California to "go out into a world where mankind is challenged, as it has never been challenged before, to prove its maturity and its mastery—not of nature, but of itself" [Fingal 2005].

The topic for this year's Problem D of the Interdisciplinary Contest in Modeling (ICM®) resembles the call given by Carson: Analyze and prioritize the 17 United Nations Sustainable Development Goals (SDGs) using networks and data analysis to improve the world. The final judges for this problem found great breadth in the modeling approaches and techniques used by the teams in their solutions. Since this year's problem

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2023 ICM Problem E: Light Pollution

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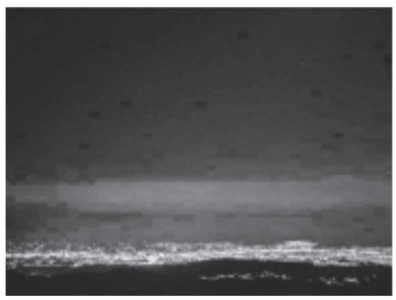

Photo credit: K. Blyman

Background

Light pollution is used to describe any excessive or poor use of **artificial light**. Some of the phenomena that we refer to as light pollution include **light trespass**, **over-illumination**, and **light clutter**. These phenomena are most easily observed as a glow in the sky after the sun has set in large cities; however, they may also occur in more remote regions.

Light pollution alters our view of the night sky, has environmental impacts and affects our health and safety. For example, plant maturation may be delayed or accelerated, and migration patterns of wildlife affected. Excessive artificial light may confuse our **circadian rhythms**, leading to poor sleep quality and perhaps physical and mental health issues. **Glare** caused by artificial lights may contribute to some motor vehicle accidents.

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Community officials or local groups may implement **intervention strategies** to mitigate the negative effects of light pollution. Artificial light, however, has both positive and negative effects, which impact different locations in different ways. For example, to avoid the negative impacts of light pollution listed above, some communities opt for low-light neighborhoods, which in turn might lead to increased crime. The impacts of light pollution may depend on factors such as the location's level of development, population, biodiversity, geography, and climate. Therefore, assessing the extent of the effects and the potential impacts of any intervention strategies must be tailored to a specific location.

Requirement

COMAP's **I**llumination **C**ontrol **M**ission (ICM) is working to promote awareness of the impacts of light pollution and develop intervention strategies to mitigate those impacts. In support of this ICM work, your task is to address measuring and mitigating the effects of light pollution in various locations, incorporating both human and non-human concerns. Specifically, you should:

- Develop a broadly applicable metric to identify the light pollution risk level of a location.
- Apply your metric and interpret its results on the following four diverse types of locations:
  - a **protected land** location,
  - a **rural community**,
  - a **suburban community**, and
  - an **urban community**.
- Describe three possible intervention strategies to address light pollution. Discuss specific actions to implement each strategy and the potential impacts of these actions on the effects of light pollution in general.
- Choose two of your locations and use your metric to determine which of your intervention strategies is most effective for each of them. Discuss how the chosen intervention strategy impacts the risk level for the location.
- Finally, for one of your identified locations and its most-effective intervention strategy, produce a one-page flyer to promote the strategy for that location.

Your PDF solution of no more than 25 total pages should include:

- One-page Summary Sheet.

- Table of contents.
- Your complete solution.
- One-page promotion flyer.
- Reference list.

Note: The ICM Contest has a 25-page limit. All aspects of your submission count toward the 25-page limit (Summary Sheet, table of contents, report, one-page promotion flyer, reference list, and any appendices). You must cite the sources for your ideas, images, and any other materials used in your report.

Glossary

- **Artificial light**: Any non-naturally occurring source of light.
- **Circadian rhythms**: The natural 24-hour sleep-wake cycle on which humans and other organisms operate.
- **Glare**: Excessive brightness that decreases one's ability to see.
- **Intervention strategies**: Policies and/or actions that could be taken to disrupt the negative impacts of light pollution.
- **Light clutter**: Excessive grouping of lights.
- **Light trespass**: When light enters unintended areas.
- **Over-illumination**: Lighting at an intensity higher than what is needed for an activity or location.
- **Protected land**: Areas that governments or private entities protect from development due to their ecological, cultural, and/or natural importance.
- **Rural community**: A community located in one of the least-densely populated parts of a country or region, and not easily accessible from an urban community.
- **Suburban community**: A community located in a moderately-densely populated part of a country or region, or easily accessible from an urban community.
- **Urban community**: A community located in one of the most-densely populated parts of a country or region.

About the Authors

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Wesley Hamilton is a STEM Outreach engineer at MathWorks, supporting and developing K-12 outreach programs. He received his B.S. in Mathematics from the Ohio State University, and his Ph.D. in Mathematics from the University of North Carolina at Chapel Hill with a focus on network analysis and PDEs. Prior to joining MathWorks, he was a Wylie Assistant Professor at the University of Utah. Wesley got involved with the ICM as a graduate student, coaching teams and then serving as a triage judge, before joining as a final judge for the 2022 ICM Problem D.

involved modeling the interconnections of the 17 goals as well as measuring their importance and challenges, the teams had many choices in finding and using data, comparing and contrasting goals, and forming and making priority-based measurements. The problem merged analytics, network science, and data science. It was interesting that this problem also included considerable environmental and public policy modeling and therefore could have been offered as Problem E or Problem F.

The judges were pleased to find that, from a modeling education point of view, the breadth and scope of the problem provided teams of various levels of experience and expertise excellent opportunities to use their skills and develop new ones. This was especially evident in the network models, which included a range of measures from basic social network centrality measures to more-sophisticated correlations, network structural analysis, and game-theoretic approaches. And from the data modeling point of view, the challenges of finding, cleaning, and manipulating data sets added to the value of the problem, requiring new data science skills. The judges fully realized that data collection and preparation took time; then, through thorough analysis, the stage was set for the modeling. Since this is the first time that an ICM problem has asked students to build a network without data, data modeling was a challenge for some teams. Consequently, finding, organizing, and cleaning suitable data was a big part of this year's challenge.

This Year's Problem

This year's problem concerned the important societal challenge to develop a cooperative plan to efficiently achieve and sustain the development goals recently developed by the UN. Without an effective plan, goal programs and organizations could interfere or compete with one another to disrupt their achievements, jeopardize their sustainability, and cost too much for the countries of the world to help their citizens. The hope is that by following the priorities and plans made by the teams, countries and organizations would make great progress to improve society over the next decade.

Problem D specifically asked students to do the following:

- Create a network of relationships among the 17 Sustainability Development Goals (SDGs).
  - Teams were expected to define the connections, edges, or relationships to build a network, determine weights for the relationships, determine correlation signs (positive, negative, or neutral), and manage incomplete data and uncertainty.
  - Since there are many ways to build a network, the judges looked for sound and clearly documented methodologies.

- Use the individual SDGs, as well as the structure of your network, to set priorities that can most efficiently move the work of the UN forward. How did you evaluate the effectiveness of each priority? What could be reasonable to achieve in the next 10 years if your priorities are initiated?
  - Teams needed to be clear on how they formulated their priorities and evaluated efficiency. Many teams found effectiveness difficult to quantify and measure.
  - The judges looked for the 10-year achievement targets to be based on the previously-established network and priorities and looked for those targets to lead to actionable results.
- If one of the SDGs is achieved (for example, there is no poverty or no hunger), what would be the structure of the resulting network? How would this achievement impact your team's priorities? Are there other goals that should be included or proposed to the UN for inclusion?
  - This requirement emphasizes the dynamic nature of a network. The judges expected teams to discuss the structure of the network and the impact of changes on the network—to showcase their understanding of the topic beyond just the construction of the network.
- Discuss the impact of technological advances, global pandemics, climate change, regional wars, and refugee movements, or other international crises on your team's network and your team's choice of priorities. What are the significant effects on the progress of the UN from a network perspective?
  - These real-world challenges have the potential to impact the achievement of the SDGs. The judges expected the students to consider the impact these external influences would have on both their network and their previously established priorities.
- Discuss how your network approach may help other companies and organizations set priorities of their goals.
  - The judges expected the teams to communicate and demonstrate the extensibility of their modeling work. Translating work from one setting to another is a valuable skill. This was a challenging element in this problem.

Modeling Essentials

Modeling is both a science and an art, so there is never a set structure in approaching a problem. However, the judges felt that the following elements were helpful to the reader of the solution:

- A reasonable (addressed the problem well) and creative (had the potential to provide contextual insight) approach to solve the problem.

- Well-justified assumptions used to scope the real-world problem appropriately in the development of the mathematical model.
- Creativity in building and using the model to address the problem.
- A discussion of the sensitivity of the model when applying the model in the context of the real-world problem.
- A discussion of the strengths and weaknesses of the team's models which helps the judges understand the intent and effectiveness of the model and the assumptions used.
- The exposition of the results provided a clear understanding of the modeling performed and the results of the model.

Other Elements of Modeling and Judging

Even though not required, good interdisciplinary modeling often provides insight to questions that are not specifically stated. When evaluating a team's performance of modeling, the final judges looked for papers that used good science, had clearly articulated model-based analysis, and offered logically defined outcomes. Specifically, the judges noticed papers that contained some of the following elements:

- The constructed network empowered the team to better understand and demonstrate how they could move the work of the UN forward towards its final goals.
- Creativity in model development, measure design, and/or method to define the relationships, edges, or connectors between the SDGs.
- Sufficient detail and complexity to capture the various relationships between the SDGs.
- Contextual discussion of intermediate and final results, related clearly back to the meaning of the SDGs.
- Meaningful real-world validation of the results of the model.
- Clear visualizations that enhanced the written prose and clarified the work.
- Visually displaying the network and model results to provide a geometric understanding of the problem and the solutions.
- Consideration of the complexity of network dynamics. This was a demanding element of this problem and may have separated the best papers from others.
- A model-based demonstration (not just discussion) of the impact of external influences on the network.

- Discussion of the nature of cooperation needed between goals.
- Creation of multilayer networks to provide different levels of context for the model.

Often, the papers that stand out to the judges are the ones that "break the mold" and do something to distinguish themselves, even if the paper as a whole does not rise to the level of Outstanding.

- A Finalist team from Shenzhen University intrigued the judges with their unique approach. The team developed specific functions for each measure and goal, providing specific justifications for their assumptions and processes. A big stumbling block for many teams was how to handle the dynamics once a goal was achieved. By using directionality of changes (positive/negative values) with a zero for achievement, the measures developed by the Shenzhen University team modeled the dynamics well.
- Similarly, a Finalist team from Xidian University stood out by providing a step-by-step model to process the data sets they used to best fit their prioritization model. They also used individual time series to model each goal, enabling them to dynamically compare one goal to another.
- The Finalist SIAM Award-winning team from the National University of Defense Technology caught the attention of the judges by employing an impressive game-theory approach in which each goal plays in the game of contribution and cooperation. The team used Shapley values to measure cooperation of goals to the overall measure of progress. This model enabled effective discussions of developed and developing countries, with the data guiding what happens over time. This game-theoretic model considered achievement of all goals at once and seamlessly handled trade-offs.

We highlight these examples of how uniqueness and creativity in interdisciplinary modeling might catch the judges' attention. The judges encourage teams to be innovative and deviate from conventional approaches where possible.

Judges' Criteria

The main thrust of ICM problem judging is finding and evaluating modeling that includes good science and leads to measurable outcomes and a viable solution. The general framework for evaluations included the following features:

- **Executive Summary:** It was important in the summary that teams succinctly and clearly explained the highlights of their submissions. The executive summary should contain brief descriptions of both the problem and the bottom-line results. The better papers had a well-connected and concise description of the methodology, results and recommendations, written so that it was understandable even by someone unfamiliar with the problem.

- **Modeling:** Many teams started with standard measures and modified them to produce more-appropriate measures. Some teams used network analysis software packages for calculations and visualizations. No matter the modeling framework, the assumptions needed for these models and the careful and appropriate development of the dynamics in the models were important.
- **Science:** Some teams did effective background research and analysis and included elements in these areas in making strong, insightful connections among the data, model measures, and the SDGs. The interdisciplinary nature of this problem was revealed in the discussions of model and the results.
- **Data/Validity/Sensitivity:** Sensitivity analysis to determine the effects of assumptions was empowering for some teams. This kind of sensitivity analysis is important for data-based models like networks.
- **Strengths/Weaknesses:** Discussion of the strengths and weaknesses of the models is where teams demonstrated their understanding.
- **Communication/Visuals/Charts:** Many teams used multiple modes of expression, including diagrams and graphs and clearly-written English. Judges often gained more insight into a team's modeling from well-labeled charts and graphs that explained both models and results. The graphics shown in **Figures 1–3** provide a glimpse of this kind of visual presentation.

Discussion of the Outstanding Papers

Despite the common background and tasks, ICM teams used many different approaches to model various aspects of the problem. As a result, the judges read a variety of very interesting submissions. Overall, this year's submissions demonstrated sound modeling with creative and insightful elements. The papers that did not reach final judging typically treated the requirements in a strictly rote manner with little-to-no connection among them or generally failed to clearly communicate the modeling process.

Since there is no correct solution to these problems, it is essential that teams explain their choice of model and of methods used to construct the model. For example, take the first requirement outlined earlier, "create a network of relationships among the 17 Sustainability Development Goals

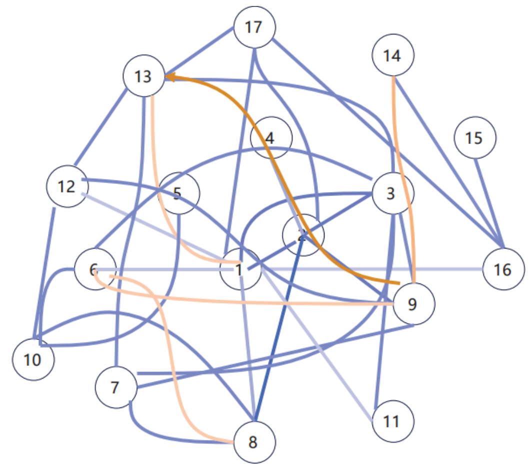

Figure 1. This is a common graphic for the SDG network. (Team 2303196 from Harbin Engineering University, China).

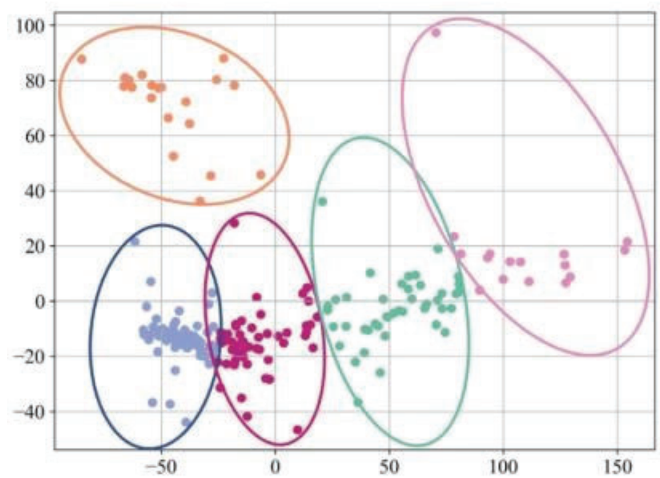

Figure 2. Because the data to measure the achievements for the goals were so scattered and incomplete from a world perspective, some teams clustered the countries into groups (sometimes using regional geography and other times using socio-indicators). (Team 2303913 from Chang'an University, China).

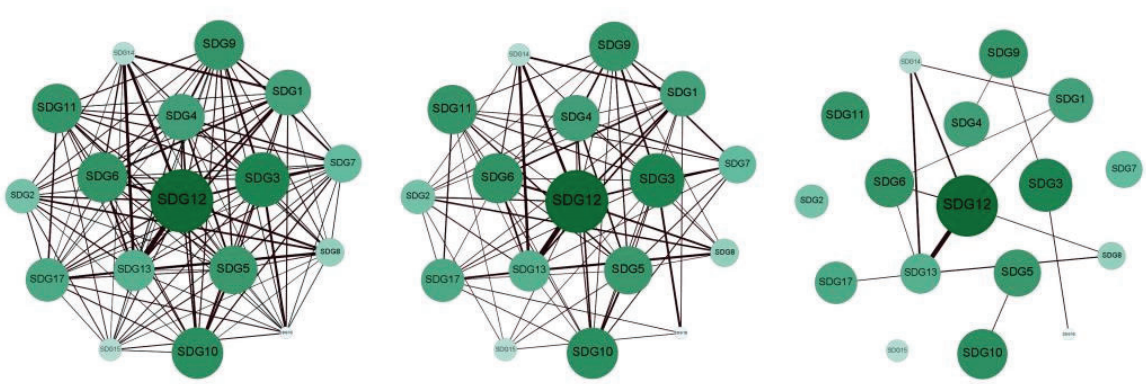

Figure 3. The teams that used correlation factors to establish links needed to set thresholds. These network diagrams show the differences based on the threshold values (high, medium, low). (Team 2311146 of Northeastern University, China.)

(SDGs)." When communicating this requirement, many papers simply focused on visually displaying the network; but those papers often lacked a clear explanation, providing only superficial details rather than a complete description of the model, how it was constructed, and its purpose as it relates to the SDGs. Other teams failed to connect their models to the aspects and basic elements of the network or organizational science.

In general, *communication of the modeling process was the most significant discriminator* in determining which papers reached the final judging stage. Although the three Outstanding papers highlighted below used different methodologies, they all addressed the problem in a comprehensive way. These Outstanding papers were generally well-written and presented clear explanations of their modeling procedures. In some papers, a unique or innovative approach distinguished them from the rest of the finalists. Others were noteworthy for either the thoroughness of their modeling or the significance of their results. Summaries of the three Outstanding papers follow.

China University of Petroleum, China — INFORMS Award

"Connecting the Dots: Unpacking the Network Systems of SDGs"

This paper is particularly strong in the network modeling, using a multilayer network and utilizing a dynamic model to propagate the model state. It also includes insightful discussion of the interactions among the SDGs, made easier to read and understand by the usage of the SDG names versus just the numbers. The paper is easy to read and contains strong analysis. The judges appreciated papers like this where the reader could understand the SDGs without referring to the problem statement.

This paper starts with a four-layer network. The top layer is the SDGs, which break down into a second layer of 169 targets. The targets, in turn, break down into a third layer of one or more indicators, totaling 241. The last layer of the network is the data itself for the individual indicators. Further, the data were collected for ten different regions, allowing for differences between regions of the world. One of the things that is missing from this paper is a description of the data preprocessing that was likely required.

For the network model, the team creates a four-level complex network: SDG, Targets, Indicators, and Data, with the layers interacting between each other. Each relationship is found using the Pearson correlation between the data, so that the SDG correlations are found at the base data level of the multilayer graph. Similarly, Indicator to Indicator correlations and Target to Target correlations can be found within the SDGs. The correlations are rolled up to build an undirected weighted correlation graph between the SDGs.

The graphs are produced for the 10 regions, together with a world-wide graph; and a short but interesting discussion of one of the differences in regions is included. The team does not, however, discuss any thresholds for when a link would not be included in the graph.

The paper has an interesting approach to determine the most influential SDG by considering the dynamics of the SDGs over time. A discrete-time dynamic model is developed with the network adjacency matrix used as the state transition matrix. The team notes that when two time periods have passed (presumably years), there is a second-level effect among SDGs, even if they are not directly connected, called *cascading effects*. Using this fact, the team raises the covariance matrix to a large power, finds the column with the largest L1 norm, and considers the corresponding SDG the most influential. Using the dynamic model, the SDGs' states are projected over the next 10 years. The submission contains a very good discussion of the interaction of the different SDGs, calling out SDGs by name versus number, making the paper more understandable.

The team does a good job of relating their model to a company, mentioning four goals that a company might have, and breaking down one of the goals, market objective into several subgoals. Noting that if this was done for each of the goals and each of the subgoals were further broken down, the team has a multilayer network and their model could be applied.

University of Electronic Science and Technology of China — Leonhard Euler Award

"Methods of Measuring Priority via Graph Models: Who Is the Top 1?"

This team introduces three models that contribute to the prioritization and study of the 17 Sustainable Development Goals (SDGs) established by the UN.

- The first model employs a graph-based approach, utilizing correlation analysis algorithms and centrality measures to determine goal priorities based on their relationships.
- The second model, known as the Temporal Champagne Tower Model, focuses on predicting the development of the SDGs over 10 years, considering resource allocation, synergies, and trade-offs among the goals. This model also incorporates a priority-queue system designed to track goal achievement effectively.
- The third model accounts for unexpected events, such as the impact of COVID-19, by introducing additional parameters and modifying the previous models to assess their influence on the overall achievement of the SDGs.

The paper offers a comprehensive approach that provides insights into the prioritization and analysis of the SDGs. By examining three countries—Indonesia, Mexico, and Turkey—the authors demonstrate how goal priorities vary depending on country-specific circumstances. This comparative analysis highlights the dynamic nature of goal achievement. Furthermore, the paper delves into the relationships among the SDGs and companies/organizations, providing valuable insights into the alignment of SDGs with various stakeholders. The authors demonstrate a strong understanding of data selection and processing techniques, supporting the credibility of their findings. Including a discussion comparing Spearman and Pearson correlation coefficients adds robustness to their analysis.

There are a few areas where the paper could be improved, such as the discussion of assumptions and their justifications. Additionally, a solid conclusion is necessary for the reader's ability to grasp the paper's main contributions and findings.

In summary, the paper's strengths lie in its comprehensive approach, clear explanations, and exploration of the dynamics of goal achievement. The paper's impact and overall quality would be enhanced by addressing the identified weaknesses, such as providing more robust assumptions and a solid conclusion.

Shanghai Jiao Tong University, China — AMS Award

"Dynamic Indicator-Goal Network for Prioritization"

This team focuses on the goal to create a network of relationships among the 17 United Nations Sustainable Development Goals (SDGs). Their paper clearly shows how their network could help the UN achieve its goals. Their model captures the complex and dynamic relationships among the United Nations (SDGs) over time—demonstrating how their network evolves and changes over time. Their unique approach establishes an evaluation that prioritizes the SDGs and predicts impact and achievement over the next decade. The paper is thorough in that it discusses in clear steps the data sourcing and preprocessing and addresses the challenges of the SDGs using a regional perspective. This submission provides realistic considerations to achieving the goal of the challenge. The judges commend the team on its inclusion of a thought-provoking discussion and consideration of additional SDGs (communications and information technology). The authors add value to their model analysis with the insightful consideration of cultural prosperity.

Conclusion

This year's Problem D presented modeling opportunities and challenged the ICM teams to explore the design, implementation, and future achievement of the UN's Sustainable Development Goals. Many teams used creativity, science, mathematics, and analysis to find appropriate data, analyze their data, model the SDGs network, build measures, and determine the policies to progress and achieve the goals in an efficient manner. The teams found data and built viable networks to understand the interconnectedness of the goals. Many teams were able to convert qualitative measures to quantitative measures and through correlation or language processing build a network and determine goal priorities. The outstanding teams were comprehensive in their analysis and were able to effectively communicate their modeling process and results.

There were many strong and innovative submissions that made judging both exciting and challenging. It was very gratifying to see so many students with the ability to combine modeling, science, analysis, and effective communication skills in order to understand such a complex issue. The final judges valued papers that were organized thematically rather than task-by-task. Strong papers presented their models in a logical sequence, cohesively incorporating the requirements without specifically calling them out task-by-task. The judges valued creativity, innovation, soundness, and appropriateness of modeling approaches, as well as clarity in modeling and analysis decisions and interpretation of results.

The panel of final judges congratulates the members of the ICM teams for their excellent work and dedication to interdisciplinary modeling, network science, data modeling, and problem solving.

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About the Authors

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Hilary Fletcher earned her Ph.D. and M.S. in Applied Science from The College of William and Mary. She currently serves as the Associate Director of the Interdisciplinary Contest in Modeling as well as the Reviews Editor of *The UMAP Journal*. She has worked with ICM triage grading and commentary writing for more than 10 years. Previously, Dr. Fletcher was an Associate Professor Mathematical Sciences at the United States Military Academy. Her research focused on Markov chain models of intracellular calcium channels as well as pedagogical practices for advancing faculty development within the community of mathematics educators.

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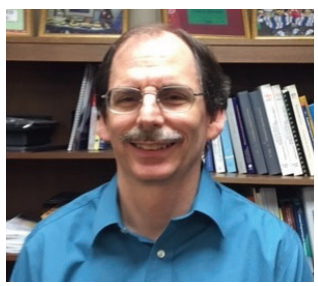

Robert Ulman received his B.S. in electrical engineering from Virginia Tech, his M.S. from The Ohio State University, and his Ph.D. from University of Maryland. He worked as a communications system engineer and research engineer at the National Security Agency from 1987 to 2000. Currently, he is the program manager for Wireless Communications and Human Networks at the Army Research Office (ARO). At ARO, his program includes wireless multihop communications networks and social networks, emphasizing the application of information theory to analyze vast amounts of data created by the internet revolution. His program also investigates the interaction and interdependence of social and communications networks.

2023 ICM Problem E: Light Pollution

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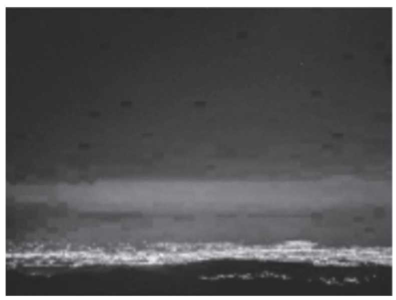

Photo credit: K. Blyman

Background

Light pollution is used to describe any excessive or poor use of **artificial light**. Some of the phenomena that we refer to as light pollution include **light trespass**, **over-illumination**, and **light clutter**. These phenomena are most easily observed as a glow in the sky after the sun has set in large cities; however, they may also occur in more remote regions.

Light pollution alters our view of the night sky, has environmental impacts and affects our health and safety. For example, plant maturation may be delayed or accelerated, and migration patterns of wildlife affected. Excessive artificial light may confuse our **circadian rhythms**, leading to poor sleep quality and perhaps physical and mental health issues. **Glare** caused by artificial lights may contribute to some motor vehicle accidents.

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Community officials or local groups may implement **intervention strategies** to mitigate the negative effects of light pollution. Artificial light, however, has both positive and negative effects, which impact different locations in different ways. For example, to avoid the negative impacts of light pollution listed above, some communities opt for low-light neighborhoods, which in turn might lead to increased crime. The impacts of light pollution may depend on factors such as the location's level of development, population, biodiversity, geography, and climate. Therefore, assessing the extent of the effects and the potential impacts of any intervention strategies must be tailored to a specific location.

Requirement

COMAP's **I**llumination **C**ontrol **M**ission (ICM) is working to promote awareness of the impacts of light pollution and develop intervention strategies to mitigate those impacts. In support of this ICM work, your task is to address measuring and mitigating the effects of light pollution in various locations, incorporating both human and non-human concerns. Specifically, you should:

- Develop a broadly applicable metric to identify the light pollution risk level of a location.
- Apply your metric and interpret its results on the following four diverse types of locations:
  - a **protected land** location,
  - a **rural community**,
  - a **suburban community**, and
  - an **urban community**.
- Describe three possible intervention strategies to address light pollution. Discuss specific actions to implement each strategy and the potential impacts of these actions on the effects of light pollution in general.
- Choose two of your locations and use your metric to determine which of your intervention strategies is most effective for each of them. Discuss how the chosen intervention strategy impacts the risk level for the location.
- Finally, for one of your identified locations and its most-effective intervention strategy, produce a one-page flyer to promote the strategy for that location.

Your PDF solution of no more than 25 total pages should include:

- One-page Summary Sheet.

- Table of contents.
- Your complete solution.
- One-page promotion flyer.
- Reference list.

Note: The ICM Contest has a 25-page limit. All aspects of your submission count toward the 25-page limit (Summary Sheet, table of contents, report, one-page promotion flyer, reference list, and any appendices). You must cite the sources for your ideas, images, and any other materials used in your report.

Glossary

- **Artificial light**: Any non-naturally occurring source of light.
- **Circadian rhythms**: The natural 24-hour sleep-wake cycle on which humans and other organisms operate.
- **Glare**: Excessive brightness that decreases one's ability to see.
- **Intervention strategies**: Policies and/or actions that could be taken to disrupt the negative impacts of light pollution.
- **Light clutter**: Excessive grouping of lights.
- **Light trespass**: When light enters unintended areas.
- **Over-illumination**: Lighting at an intensity higher than what is needed for an activity or location.
- **Protected land**: Areas that governments or private entities protect from development due to their ecological, cultural, and/or natural importance.
- **Rural community**: A community located in one of the least-densely populated parts of a country or region, and not easily accessible from an urban community.
- **Suburban community**: A community located in a moderately-densely populated part of a country or region, or easily accessible from an urban community.
- **Urban community**: A community located in one of the most-densely populated parts of a country or region.

About the Authors

Kayla Blyman is Assistant Professor of Mathematics at Saint Martin's University in Lacey, Washington. She holds a Ph.D. in STEM Education and an M.A. in Mathematics, both from the University of Kentucky, as well as a B.A. in Mathematics from Messiah College (now Messiah University). She has taught at the US Military Academy at West Point, Berea College, Midway College (now Midway University), and the University of Kentucky. With COMAP, Kayla wears multiple hats: She is director of the Middle Mathematical Contest in Modeling (MidMCM); co-director, problem director, problem author, final judge, judges' commentary author, triage judge coordinator, and triage judge for the Interdisciplinary Contest in Modeling (ICM); associate editor for the Teaching Modeling Department of *The UMAP Journal*; and lead developer for the Introduction to Modeling course for the COMAP Certificate in Modeling (CiM). Kayla's research is focused on the development and implementation of new and creative ways to teach and assess undergraduate mathematics, with a goal of better developing creative problem solvers for our future. An avid explorer—both professionally and personally—Kayla loves spending time in the great outdoors, partaking in the arts, traveling to new places, and trying new food.

Wesley Hamilton is a STEM Outreach engineer at MathWorks, supporting and developing K-12 outreach programs. He received his B.S. in Mathematics from the Ohio State University, and his Ph.D. in Mathematics from the University of North Carolina at Chapel Hill with a focus on network analysis and PDEs. Prior to joining MathWorks, he was a Wylie Assistant Professor at the University of Utah. Wesley got involved with the ICM as a graduate student, coaching teams and then serving as a triage judge, before joining as a final judge for the 2022 ICM Problem D.

Summaries of Light Pollution Outstanding Papers

Evaluation and Optimization of Light Pollution Based on EWM-TOPSIS

2312411 Chang'an University
School of Mathematics and Statistics
Team members: Dingkai Wei, Yuecheng Wang , and Weilong Zhu
Advisor: Yuchao Lin

In order to alleviate the more and more serious light pollution phenomenon, this paper will analyze the issues related to the evaluation of light pollution risk levels and light pollution treatment by establishing mathematical models.

For problem 1, firstly, a hierarchical interactive evaluation index system with 7 factors that impact the risk level of regional light pollution is established in this paper. After that, an **Evaluation Model of Light Pollution Risk Level** is established based on this. A combination of the **Entropy Weighting Method** and **TOPSIS** is used to evaluate the selected specific locations that aim to formulate the metrics of light pollution risk level.

For problem 2, in order to visually reflect the light pollution risk levels of the four types of locations, this paper takes Shaanxi Province, China, as the research area, and utilizes ArcGIS geographic information software to calculate the geometric shape centers of the plots and extract the data of each index. On this basis, the constructed light pollution risk level model is applied to measure the light pollution level of the four types of locations and produce a map of light pollution risk distribution in Shaanxi Province in 2022. The results showed that urban communities, represented by Xi'an, Shaanxi Province, had the highest light pollution risk level of **0.407**. Light pollution risk scores in protected land, rural and suburban communities were **1.1%, 6.8%, and 68.6%** of urban communities, respectively.

For problem 3, this paper proposes three light pollution treatment strategies and quantitatively analyzes the impact of the three light pollution

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treatment strategies on each light pollution risk level evaluation index. In this way, a **Light Pollution Treatment Optimization Model** is constructed to optimize the evaluation indexes that affect the light pollution risk level. Lastly, the potential impact of light pollution treatment is analyzed by combining the optimized light pollution risk values.

For problem 4, nature reserves and urban communities are selected for evaluation among four types of sites, and the optimization model of light pollution treatment is applied to analyze the effectiveness of three light pollution treatment strategies for these two sites. To determine the optimal improvement strategies for the evaluation sites in the short-term (0–10 years), medium-term (11–35 years), and long-term (36–50 years), respectively, this paper uses **Logistic** equations to predict the population data and also combines the predicted values of other factors by Arima time series method for the optimized light pollution score calculation. Comparing the risk levels before and after optimization, the results show that the optimal strategies for urban communities in the **short-term, interim, and long-term** are the strategies of raising residents' awareness of light pollution treatment, the strategies of regulating market standards, and the strategies of establishing a sound social monitoring mechanism, respectively; while in the next 50 years, the effects of the three optimal strategies on the treatment of protected land are not obvious, because the light pollution risk level in protected land itself is low and not easily influenced by external factors. For urban communities, crime rates increased by an average of **2.140%**, and traffic accident rates decreased by an average of **2.135%** in areas following light pollution treatment.

Finally, based on the results of solving the above mathematical model, we make flyers to advertise light pollution treatment measures in urban communities represented by Xi'an, China.

Keywords: light pollution risk level; EWM-TOPSIS evaluation; ARIMA; light pollution control

The Brighter the Light, the Deeper the Shadows

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Team members: Hao Li, Jiahui Yuan, and Shilin Luo
Advisor: Teachers Group

Light pollution is a new source of environmental pollution, which brings various adverse effects to society, human beings, and even the whole ecosystem. Thus, we established a broad light pollution risk assessment model and a flexible intervention strategy model to reduce the impact of light pollution.

Firstly, we build a risk assessment model based on a **GE matrix**. Our team select 10 indicators from social, economic, and ecological and health dimensions to establish a system (Figure 3). Then we re-divide the indicators into artificial light damage system (DS) and requirement system (RS). We get the weight of indicators by the projection pursuit method. Next, we define the scores of our two systems as DSI and RSI, respectively. Taking DSI and RSI as the horizontal and vertical coordinate axis of the GE matrix, the GE matrix can be divided into 9 regions (I to IX) and 3 levels (A,B,C). Levels A, B, and C are in descending order.

Secondly, ignoring intraregional differences, we apply our risk assessment model to four regions in China: Chengdu (urban), Jintang (suburban), Xingfu Vil (rural), Baishuihe Nature Reserve (protected). The results show that the risk level of light pollution in **Chengdu is level B. Jintang is level C. Xingfu Vil and Baishuihe Nature Reserve are level A.**

Thirdly, we establish a **goal programming model** for intervention strategy formulation. We introduce **priority factors** P_i and positive and negative bias variables (d_i^+, d_i^-) to implement region-specific flexible intervention strategies from three dimensions. We take the weighted sum of the (d_i^+, d_i^-) of all constraints as the objective function. Then establish the constraint conditions through the secondary indicators of three dimensions (equation 10). Furthermore, we discuss three targeted intervention strategies: **social, economic, and ecological and health strategies**. For example, social intervention strategies mainly control artificial light intensity and other actions at the social dimension, while intervention in the other two dimensions is secondary. The specific actions of each strategy and their impact on light pollution risk are detailed in 5.2.

Further, in order to select the most effective intervention strategy in a specific region, we introduce an **Intervention Optimization Index (IOI)**.

Based on the goal programming model, we select the strategy corresponding to the minimum value of IOI by changing the priority factor and adjusting the constraint conditions. We apply our intervention strategy model to Chengdu and Jintang. The optimal strategy in Chengdu is social intervention strategy while Jintang is economic intervention strategy. We use GE matrix to compare and analyze the light pollution risk level and various indicators before and after intervention. The light pollution risk level is increased from **B to A in Chengdu**, and **C to B in Jintang**. After intervention, IOI in Chengdu and Jintang decrease by 13.4% and 11.1%.

Finally, we analyze the sensitivity and robustness of four constraint parameters of objective programming of intervention strategy. It is worth mentioning that we introduced the **MAPE index** to test the robustness of our model. The results show that the MAPE of target planning in Chengdu and Jintang is 1.5% and 3.0%. Our model is very robust.

Keywords: light pollution; projection pursuit; GE matrix; priority factor; goal planning

Turn Out the Lights, Turn Up the Stars

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Team members: Tongtong Jia, Tao Yang, and Zixuan Shu
Advisor: Dehui Wang

Light pollution is a type of environmental pollution caused by human activities, which has negative impacts on wildlife, plants, and human health. With the continuous development of urbanization and industrialization, the problem of light pollution is becoming increasingly severe. Therefore, the evaluation and improvement of the risk level of light pollution is particularly important.

Firstly, we collected data on ten indicators from 55 regions and divided these ten indicators into three areas: Light, Society, and Nature. Then we combined the **analytic hierarchy process**, **entropy weight method**, and **coefficient of variation method** to calculate the combined weights of these indicators to construct the formula of light pollution index (LPI) and then build the **LSN evaluation model**. Finally, we use fuzzy cluster analysis to classify all locations into four categories, thus dividing the light pollution level into four classes.

Secondly, we choose New York City, Bellevue, Sedona and Yellowstone National Park as a representative of each location type. Using the **LSN**

evaluation model, their LPI were calculated to be 35.55, 41.33, 76.94, 84.18. Thus, their light pollution levels were obtained as Grade I, Grade II, Grade III, Grade IV, respectively.

Thirdly, we proposed three intervention strategies and their specific actions, constructed a **PIA-NN** model, and studied the potential effects of concrete actions on light pollution effects. The three intervention strategies are: reduce artificial light intensity and strengthen publicity and education and expand vegetation area. We quantitatively reflected the "potential impact" of the three intervention strategies on the light pollution effect by combining **Spearman's correlation coefficient** and the **BP neural network model**.

Next, we selected two representative regions, Sedona and New York City, to explore the effects of three intervention strategies on light pollution levels in the two regions using the **PIA-NN model** and the **LSN evaluation model**. The results show that for both areas, reducing the intensity of artificial light is the most effective intervention strategy to reduce the risk level of light pollution.

Finally, we will choose New York City as the location for the campaign and design a beautiful flyer around its corresponding most effective intervention strategy.

Keywords: LSN evaluation model; LPI; PIA-NN model; AHP

Recast Mystletainn to Fight the Artificial God of Light

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Advisor: Ye Jun

Bright windows, blazing streetlights, pulsating neon ... human beings are slowly being deprived of the dark night. Since the invention of artificial light, this artificial light has gradually started to affect animals, plants, and human health. It is sad that the technological light that should bring convenience has brought harm. To better measure and intervene in the effects of light pollution, we study light pollution to better enjoy this light.

Several models are established: Model I: Pollution Quantification Model; Model II: Risk Assessment Model; Model III: Intervention Strategy Model.

Prepare for establishing models, we analyzed the **composition and main impact aspects** of light pollution. By visualizing the results of a large number of data collected from official databases, we initially focused on areas worth studying.

For Model I: According to some literature and the results of similar natural system studies, we propose to use **human factors, social factors, and ecological factors**, a total of 13 indicators, combined with an **EWM-AHP algorithm** to obtain objective light pollution quantification results $Q_{\text{positive}}, Q_{\text{negative}}$. Then we randomly selected 10 areas of light intensity and our model calculation for comparison, the Pearson correlation coefficient is **0.8002**, which **verifies the validity** of our model.

For Model II: We defined a light pollution **risk indicator** Ω based on the **ALARP criterion and "Cost-Risk" analysis**, where the negative impact growth rate is assumed to be **normally distributed**. Based on the literature, we calculate the expectation of 6% and apply Ω to the four regions that we selected to evaluate the risk of light pollution after one year and analyze it to propose countermeasures. Theoretically, the model allows for medium- and long-term prediction of light pollution risk.

For Model III: We modeled three different strategies—"energy," "environment," "human security" and related factors respectively, and finally obtained the feasibility of intervention scenarios through coupling coordination analysis. The final evaluation value of the three aspects is calculated through the secondary indicators after the intervention. We selected two sites, Rutland and Westminster, with a **coordination index values of 5 and 3**, to study the impact of the three intervention strategies based on a coupled coordination analysis. The results showed that the best intervention strategy in rural Rutland was the "Human Friendly Strategy", which **improved the Human Health Index score by 10%**. The best intervention strategy for Westminster was the Resource Friendly Strategy, which improved the **overall score from 50.0080 to 59.6481**.

Finally, we evaluated the sensitivity analysis by adjusting the parameter r of the environmental part of the LPA model up or down by 5%, and the results showed that our pollution quantification model was **more resistant** to interference. Afterwards, we created a flyer to inform people in the Westminster area of the UK about the effects of light pollution and the options and benefits of implementing a lighting curfew.

Keywords: EWM-AHP algorithm, ALARP, risk indicator Ω, coupling coordination analysis

Local Light Pollution Analysis: A Multi-Layer Evaluation Model

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Light pollution is a growing concern for many communities and ecosystems around the world. In order to measure the level of light pollution in a region, this paper develops a Light Pollution System Model, which reflects the risk of light pollution in a region by selecting several relevant indicators. For four different regions, our **Light Pollution System Model** provides a good representation of their main characteristics, which makes it easy to propose targeted policies.

First, we identified four primary indicators: traffic, ecology, energy and society, and set several secondary indicators under each primary indicator to form the Light Pollution System Model. Finally, the entropy weighting method was used to determine the weights and establish the association between each indicator and the risk of light pollution.

Next, we used K**-means clustering algorithm** to divide the collected data into four classes and summarize the data distribution of indicators in four regions: Protected Land, Rural Community, Suburban Community and Urban Community. The **clustering centers** of the four classes were used as the data representatives of the four regions. Then, the data of the four regions were evaluated in the evaluation model, and the light pollution scores were calculated as Protected Land: **0.053**, Rural Community: **0.174**, Suburban Community: **0.359**, and Urban Community: **0.872**. Urban community has the highest level of light pollution. Finally, the light pollution of each of the four regions was analyzed by the scores of the minor indicators.

To identify three possible intervention strategies, we used the **top 10%** of each region as the ideal vision, compared it with the regional average, and identified strategies focused on one or two main targets for each strategy to reduce light pollution levels. We then **quantified** the impact of each strategy on the target using a scale, which was classified as **high (20%–50%), medium (10%–20%), and low (2%–10%)**. Finally, three feasible strategies were obtained: green infrastructure strategy (around ecology indicators), energy strategy (around energy indicators), and urban planning strategy (around traffic and social indicators).

Finally, we used the urban area of Tosca, Italy, and the suburb of Latsia, in Cyprus, as application targets. The three strategies that we designed

were substituted to calculate the minimum and maximum possible impact on the area. The effects of the three strategies were compared and we obtained that **energy strategy** were the most suitable strategy for the **urban area of Tosca**, with light pollution coefficient LPR reduction levels: **4.8%–11.65%**, while the **urban planning strategy** was the most suitable strategy for the **suburban area of Latsia**, with light pollution coefficient LPR reduction levels: **3.26%–7.51%**. Then we analyzed the impact of the strategies on the small indicators and summarized the reasons for the impact areas of these two strategies from a detailed perspective. Finally, we conducted a **sensitivity analysis** of the **Light Pollution System Model** proposed in this paper, and the results show that the model performs as expected in practice, proving that the proposed model is reliable.

Keywords: Light Pollution System Model, K-means clustering algorithm, entropy weight method

Turn Off the Lights, Turn On the Stars!

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> *"On the earth, even in the darkest night, the light never wholly abandons his rule."* Jules Verne, *Journey to the Center of the Earth*

With the rapid development of modern technology and excessive use of artificial lights, light pollution has resulted in increasingly severe problems. Therefore, the proper design and implementation of intervention strategies to address these problems deserve our attention. This report aims to build a **light pollution risk level evaluating model** and provide credible suggestions on how to effectively reduce the negative impacts of light pollution.

Three models are established: Model I: Ecologic-Social-Ecologic (**ESE**) Model; Model II: Light Pollution Risk Assessment (**LPRA**) Model and Model III: Interconnected-ESE Model (**I-ESE**) Model.

For the ESE Model (Model I), we first abstract the risk of light pollution into three subsystems: **Economic, Social, and Ecological Subsystems** and construct the ESE model. For the economic subsystem, we calculate the population growth by the **logistic equation** and measure the light pollution in economic systems. For the social subsystem, we take five types of land together with the brightness threshold into account and obtain the proportion of light-pollution-affected land. For the ecological subsystem, we set a formula with the number of organisms together with light intensity value to calculate the number of affected organisms.

For the LPRA Model (Model II), we use the **Analytic Hierarchy Process (AHP)** based on Google search index to quantify the light pollution risk level (RL) of a certain region, then apply our model to 284 regions. After that, we use the K**-means algorithm** to create a metric system for the risk levels and constructed four ranks: **Slight** (0.0443–0.1678), **Moderate** (0.1705–0.2542), **Serious** (0.2568–0.3698), and **Severe** (0.3976–0.6186). To apply our model to specific locations, we selected Ordos as **protected land**, Zhaotong as **rural community**, Qingyuan as **suburban community**, and Guangzhou as the **urban community** and obtained their RL scores: **0.1332, 0.1778, 0.2574, and 0.5154**, while their risk levels are slight, moderate, serious, and severe, respectively.

For the I-ESE Model (Model III), by establishing a link between every two subsystems, we constructed the **Interconnected (I)-ESE** Model on the basis of the ESE Model, and obtain quantitative relationships between ECL and SCL, ECL and ENL using nonlinear fitting. Based on I-ESE Model, we propose three effective intervention strategies to address the light situation: **I.** Reduce light intensity, **II.** Reduce the impact on society, and **III.** Delimit dark night protection areas and their actions correspondingly.

More specifically, we select Guangzhou and Zhaotong for further discussion and determine their **optimal strategies**: strategy I and II for Guangzhou and strategy II and III for Zhaotong. Then we measure the impacts of these strategies in general and particularly in Guangzhou and Zhaotong using I-ESE Model and visualize the impact with **GE cube**. The risk level in Guangzhou decreased from **0.5153 to 0.0309** while Zhaotong decreased from **0.1678 to 0.0885** after 20 years of implementing the optimal strategy.

Finally, the sensitivity and robustness of our model are tested. When we set the cost to be raw data, increase or reduce by 50%, the overall trend of risk level has little difference as the curve remains similar, verifying the sensitivity and robustness of our model.

Keywords: Light pollution, ESE Model, LPRA Model, AHP, K-means algorithm, GE Cube

Less Light Pollution and Brighter Starry Sky

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How long has it been since you saw a spectacular starry night sky? Nowadays, 80% of the world's population lives under skyglow. As light pollution continues to grow, more and more people are taking this issue seriously. In this paper, we established a light pollution assessment model and proposed three strategies to combat light pollution.

In task 1, we divided the area to be evaluated into eight grids according to the city plan map, and used the **entropy weight method (EWM)** to integrate three factors related to light pollution into a total attributional index. Then, considering the interaction of light pollution between adjacent areas, we innovatively use the **Raster method** and this index to introduce the concept of light pollution index (LPI). Light pollution index has a direct impact on the economy, ecology, and human health, leading to the light pollution risk. We use **AHP** to obtain the **light pollution risk level (LPRL)** and use it to identify the light pollution risk level of a location.

In task 2, we apply the model in task 1 to Saskatoon in Canada. By calculation, we obtained the average LPRI for a protected land location, a rural community, a suburban community, and an urban community. The result is 0.0665, 0.1529, 0.2726 and 0.3397, meaning that the suburban community and the urban community have a higher risk. Then we plotted the **heat map** of LPRI as shown in Figure 8 to accurately reflect the circumstances of each grid. Finally, we utilize K**-means algorithm** to classify the LPRI of each grid in the suburban community and the urban communities. We divide the grid into five groups and determine which grids are in extreme risk areas.

In task 3, we propose three possible intervention strategies to address light pollution. The grid movement strategy optimizes the layout of the city by moving the grid, thus reducing LPRI. The regulatory strategy eliminates light pollution at the source by reducing light luminance and illumination time. The compensation Strategy chooses to achieve LPRI decline through a certain economic cost.

In task 4, we applied three strategies to the suburban community and the urban community of Saskatoon. By calculation, the grid movement strategy can effectively reduce LPRL. However, we need to consider the high cost of city relocation. To compare compensation strategies with regulatory strategies, we introduce the concept of the **strategy intensity factor**. The level of LPRI reduction by the two policies for the same strategy intensity factor is shown in Figure 15. Ultimately, we conclude that the regulatory strategy is more effective for these two areas.

In addition, we conducted a sensitivity analysis of the model, adjusted the parameters of the constraint conditions with a fixed step length, evaluated the optimization effect. The advantages and disadvantages of the model are also analyzed. We also write a flyer to promote the regulatory strategy for Saskatoon.

Keywords: light pollution, raster method, K-means algorithm, Strategy Intensity Factor

Protect the Night, Control the Light!

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People generally are struck by the "beauty" of city lights without realizing that these are also images of pollution, like admiring the beauty of the rainbow colors that gasoline produces in water and not recognizing that it is chemical pollution. In this paper, we construct a broadly applicable Light Pollution Risk Assessment Model to assess the risk level of a given location, and propose an Intervention Strategy Model to mitigate the effects of light pollution in various locations.

For Task 1, we propose a **Light Pollution Risk Assessment Model**. The model integrates risks from **four dimensions**: humans, wildlife, plants, and energy waste caused by light pollution. Considering multiple related indicators, **EWM-TOPSIS** is applied to solve the overall **risk score**, which is divided into four levels: **fragile (0-1), poor (1-2), ordinary (2-3), and good (3-4)**.

For Task 2, the Light Pollution Risk Assessment Model is applied to **four typical regions in Shenzhen**, representing urban, suburban, rural, and protected areas. In the data preparation phase, we use nighttime remote sensing and multi-spectral remote sensing data to estimate the Normalized Difference Vegetation Index (NDVI), night-time radiance, and population density in the study areas. The protected area has a risk score of **0.357992**, while the rural community has a risk score of **1.859474**, the suburban community has a risk score of **2.114942**, and the urban community has a risk score of **3.19662**. These scores correspond to the fragile, poor, ordinary, and good levels, respectively.

For Task 3, we develop three intervention strategies including **improving the light source, lowering the lighting intensity, and optimizing regional light layouts**. Then we list multiple specific actions for each strategy. An **Intervention Strategy Model based on a differential equation** is established to quantify how three strategies impact the risk level.

For Task 4, we select urban and suburban communities to verify the effectiveness of the three intervention strategies. Over the next 50 years, the risk scores after the implementation of the three strategies are reduced by approximately **2%**, **6%**, and **3%**, respectively. It can be concluded that the second strategy, lowering the lighting intensity that aims to **reduce the total amount of light radiance, is the most effective intervention strategy for both urban and suburban areas**.

Finally, the sensitivity analysis of the risk assessment model shows that the fluctuation of a single evaluation indicator by -10% to $+10\%$ has a reasonable impact on the final risk score shown in Figure 16. Therefore, the model is robust to changes in a single indicator. Besides, the sensitivity analysis of the Strategy Model shown in Figure 17 means that our model is robust to the growth rate.

Keywords: light pollution, intervention strategies, EWM-TOPSIS, differential equation

Authors' Commentary: Light Pollution: Its Impact and Its Educational Opportunities

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Introduction

While not a new problem, light pollution is a serious pollutant that adversely impacts wildlife, entire ecosystems, and even the health and safety of humans. This important issue, which also allows us many conveniences, can also serve as an opportunity to engage students in meaningful and tangible data science activities. There are many educational levels that would be appropriate to tackle this question, but even more important is the ability to transform results into action through policy suggestions.

We discuss our approach to developing a datathon and the 2023 ICM Problem E around the topic of light pollution, before providing suggestions for educators (or students) wanting to get more involved in quantitative social justice. We also include information and resources for those specifically interested in light pollution.

The Issue Itself

Light pollution is defined as the brightening of the night sky by human light sources, such as streetlights, lights in residential and commercial

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buildings, and lights in factories. Like other kinds of pollution, light pollution is incredibly disruptive to surrounding environments and has negative environmental consequences, including for humans. Artificial lighting is now so powerful that it often overcomes the darkness of the night sky, interrupting the natural rhythms of day and night. The effects are vast, from the increase in our energy consumption [Gill 2020] to the deaths of newly hatched sea turtles [Florida Fish… n.d.] to the decline of mental and physical wellbeing and safety of people living in urban areas [Chepesiuk 2009; Staff 2023]. In recent years, the severity of light pollution has worsened on average at an alarming rate [Kyba et al. 2023], establishing light pollution as a relevant environmental issue.

Beyond the impacts on the natural environment and ecosystems, light pollution disrupts our circadian rhythms, which in turn reduces our production of melatonin. This decrease in naturally produced melatonin makes it difficult to maintain a normal sleep schedule, negatively impacting our mental and physical health in a variety of ways. In fact, sleep disorders have been linked to increased rates of cancer, obesity, diabetes, heart attacks, strokes, and depression [CDC 2022]. While these are things that can affect anyone exposed to light pollution, several recent studies have found that light pollution disproportionately impacts communities of color and low-income communities in both urban and more rural settings. According to one study by researchers from the University of Utah, "Americans of Asian, Hispanic or Black race/ethnicity had population-weighted mean exposures to light pollution in their neighborhoods that were approximately two times that of White Americans" [Nadybal et al. 2020]. They also found that an increase in renter population by 22% in a given area was accompanied by a 39% increase of light pollution [Nadybal et al. 2020]. Within these contexts, light pollution can further be posed as not only an environmental issue but an environmental justice issue, providing further motivation towards a solution.

Genesis of the Problem

While the problem was drafted a year before it was used in the competition, the idea had its roots about half a year earlier. At the time, Fall 2021, the Institute for the Quantitative Study of Inclusion, Diversity, and Equity (QSIDE) was organizing their first Datathon4Justice [Institute… 2022a]. This event centered around two data sets QSIDE had acquired and were interested in analyzing: one on judicial sentencings in Minnesota, and one on small-town police reports. Keynote speakers with experience on each topic gave talks, before teams (some in-person, some completely virtual, and many hybrid) had dedicated time to start exploring the data and highlighting any key insights they could. In particular, as the name implies, the focus of the event was justice. While patterns in data can be fun to find, the end goal was to (start to) transform data insights into action for the communities affected by the issues captured in each dataset. The Datathon4Justice provided a strong start to that effort, spawning two recurring research labs and another datathon aimed at high school students [Institute… 2022b].

The authors were present and active in the inaugural datathon, coordinating a team of undergraduate students, graduate students, and postdocs at the University of Utah (the U) in exploring the judicial sentencing data. For many of the students involved, this experience provided inspiration to consider thesis projects incorporating data science and social justice.

Wanting to provide a similar experience for more students at the U addressing justice-related issues in the Salt Lake area, the authors were part of a team to organize a similar datathon for Spring 2022. By leveraging expertise from faculty at the U, the theme of light pollution was selected. Moreover, the Utah Center for Data Science graciously provided support for the event through funding for food and coffee, securing rooms for participants to use, and providing website space to advertise the datathon. The main event was a 1.5 day (Friday night and all-day Saturday) datathon, featuring keynote speakers providing context for how to use data for social justice and social good, discussing why light pollution is a social justice issue from the lens of environmental and community activists, and finally discussing some more details about the provided data and goals for the datathon and beyond. Participants also had the opportunity to take pre-datathon workshops covering a variety of relevant computational topics, including an exploratory data analysis demo using data on mental health and depression and more advanced statistical and geospatial analysis tools. Finally, participants were invited to take part in a special symposium organized during the twice-a-year Undergraduate Research Symposium hosted by the U. More details about the organization and impact of the event are given in [DeGiovanni et al. 2022] by the organizers, though we revisit some of these later in this article when providing suggestions for activities that the community can organize.

With the success of (at least) two datathons focused on using data to inform policy and action in the community, the idea of a light pollution focused problem was pitched for an ICM problem in Spring 2022. While the core of the problem idea was to have teams develop models to quantify the effect of light pollution on communities (which was finalized as a metric or risk level for a community), a key component was that teams would also have to propose interventions to address these effects and measure the impact through their models. In other words, in designing the problem a non-negotiable requirement was having teams interpret their results in the context of the affected community, towards data-informed justice.

We are pleased to incorporate these key features in this year's ICM Problem E. The problem was written and refined over the next few months and resulted in almost 6,000 submissions. Another article in this volume goes in-depth with judges' commentary on the submissions and the outstanding papers. In the rest of this article, we propose activities that inspired or were inspired by this problem that educators can adapt for their students' needs and interests.

Pedagogical Activities

For those interested in incorporating questions of justice (social, health, environmental, etc.) into data-centric activities, here are a number of resources and activities the authors and their colleagues have implemented, utilized, and/or learned from:

- Lesson plans, including *High School Mathematics Lessons to Explore, Understand, and Respond to Social Injustice* [Berry et al. 2020] and *Mathematics for Social Justice: Resources for the College Classroom* [Karaali and Khadjavi 2019];
- Workshops, such as the recent ICERM (The Institute for Computational and Experimental Research in Mathematics) workshop on "Educating at the Intersection of Data Science and Social Justice" [ICERM 2023];
- Datathons, like those mentioned above and a similar one at Tufts [Lorch 2022];
- National Science Foundation Research Experiences for Undergraduates (REUs); and
- Thesis projects.

Of course, for each of these activities, timely questions and/or data are necessary. While there is no single strategy for identifying high-quality data and/or questions, here are a few approaches that we have used or seen colleagues effectively use:

- Use good data sources, such as
  - Kaggle https://www.kaggle.com/datasets.
  - Data.gov https://data.gov.
  - Our world in Data https://ourworldindata.org/.
  - Environmental Protection Agency https://edg.epa.gov/metadata/catalog/main/home.page.
  - World Bank https://data.worldbank.org/.
- Gain inspiration from previous competition questions, such as COMAP's MCM/ICM and HiMCM contests (see https://www.mathmodels.org), and SIAM's MathWorks Math Modeling (M3) Challenge contest (see https://m3challenge.siam.org);

- Form communities of practice/seminars and discuss with colleagues, either in-person or through online communities like QSIDE's Research Labs;
- See which questions students are interested in answering, and support their journey to answer those questions.

While these ideas and resources may provide a starting point for supporting students in exploring quantitative social justice, there is no single strategy that works for all educators, students, educational environments, etc. The key is having an open mind and being willing to learn about topics around social justice and inequity, and sometimes even being willing to have uncomfortable conversations about the subject matter.

Conclusion

While certainly not exhaustive, we hope that the story of writing the Light Pollution Problem, as well as the general resources for getting started with developing justice-oriented quantitative activities, hopefully provide a starting point for those interested in these areas. Moreover, both authors have relied heavily on the support of the quantitative social justice community, and educators interested in sharing ideas. We encourage anyone interested to learn from others and join the conversation.

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Judges' Commentary: Light Pollution

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Introduction

The invention of artificial lights changed the course of history, allowing for increased productive work time as well as safer outdoor areas. However, along with their many benefits, artificial lights also brought light pollution, which has environmental impacts and health risks to many species, including humans. In that, a problem of balance was created: What is at risk? What is an "acceptable" level of light pollution? What are "appropriate" steps to take to control light pollution? Are the answers to these questions the same everywhere or do they differ across communities and regions? This year's sustainability problem (Problem E) challenged teams to address these questions.

Teams were asked to develop a broadly applicable metric to identify the

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light pollution risk level of a location and to describe three possible intervention strategies. Once teams had developed their metric, they were asked to interpret its results after applying it to a protected land location, a rural community, a suburban community, and an urban community. In doing so, teams were testing their metric and learning more about the breadth of its applicability. This also served the purpose of providing teams with a base-line measure of the light pollution risk level for each of the four locations.

Teams were then asked to describe three intervention strategies. These strategies could have been of their own design, or ones that they found in their research of the problem. They were asked to specifically address actions to implement each strategy and the potential impacts that these strategies could have on light pollution. After exploring three intervention strategies in this way, they were asked to choose two of their four locations and to use their metric to determine which of the intervention strategies is most effective for each of them. The baseline measure that they had for each of the four locations then allowed teams to discuss how the chosen intervention strategy for each location impacts the light pollution risk level.

Finally, teams were asked to communicate their findings in a nontechnical way by developing a one-page flyer to promote the strategy that is most effective for one of their locations. In doing so, teams could inspire a community to take action to decrease the impacts of light pollution within their community.

Judges' Criteria

From this year's Successful Participants all the way up to this year's Outstanding papers, the judges saw evidence of teams engaging with this challenging problem. The judges applaud all participating teams for their ability to address this complex issue. The judges were happy to see teams making use of a variety of modeling techniques and approaches to the problem. The diversity in submissions is illustrated by the variety of approaches in this year's Outstanding papers. Here we provide commentary on components of the modeling process as well as a discussion of how strong papers demonstrated them.

Definitions

There are many forms of definitions throughout the modeling process. Teams must define:

- **the problem that the team addresses** with their models. Many teams just summarize the problem statement, but better teams realize they often answer a slightly modified version. They clearly state what the problem is so that their approach can be adequately contextualized.

- **all variables used**. Many teams have started creating a table with the symbols and their definitions early in the paper. While this is a helpful reference, it should be clear when those variables are used in the paper, what they mean, and why they are important.
- **formulas used**. Teams that use models from other papers often cite formulas, but they need also to explain why they are appropriate to solve this question.
- **terms or phrases used** in their paper. Some teams this year used definitions alternative to those provided in the problem statement. Such a decision can lead to confusion, so it is important that all relevant terms are clearly defined in the paper.

Judges appreciated it when teams clearly defined formulas and provided references if the formulas were adapted from elsewhere, as well as when teams included tables that defined each variable or term used in the paper. In preparing their models and reports, teams should ensure that all pieces of their model are clearly defined, and that they either use the definitions provided in the problem statement or pointedly and explicitly provide the alternative definitions that they are using. All definitions used by a team should be easy to find and be understood by the judges before used in context in the paper.

Choice of Locations

One of the requirements for this year's sustainability problem was to choose four diverse locations to apply the team's metric. These locations included a protected land location, a rural community, a suburban community, and an urban community. The problem statement provided definitions of each in terms of population density. Most teams chose real locations, rather than considering an abstracted version. However, there were teams that selected locations that did not match the given definitions; for example, all four locations contained within the same urban area, or a suburban location had a higher population density than the urban location. The judges expected to see clear distinctions between the types of locations, as defined in the problem statement. When a choice of location did not align with the given definitions, a team needed to explain their choices. An example of a justification for an alternative interpretation of the location definitions could be to look at the locations in terms of light pollution. For example, if someone were to travel five miles from the downtown area of a major urban community, would the light pollution level significantly change? Depending on many other factors, this may or may not be the case. Therefore, teams were welcome to provide justification for such choices. Unfortunately, this rarely happened.

Some teams chose to apply a light pollution metric to an entire country. While for some analyses this might make sense, judges were hoping that teams that did this would then focus on a smaller community level, explicitly discussing how interventions would affect two of the four specified types of communities. While defining the USA or China as an urban country can be effective as a coarse classification, judges were often concerned this approach ignored the diversity of communities within nations, and hence missed the target of the problem.

Assumptions

Models are a simplified version of reality; so to create a model, assumptions are necessary. When making assumptions, teams should address not only why they are reasonable but also *why they are needed to support their work*. Many teams create a list of assumptions with definitions, which is helpful to understand the basis of the modeling work. But it should also be clear in the report where and how these assumptions are used. Teams should also make sure they are stating all assumptions that they are making, both in the context of the problem and those underlying their choice of model.

Complexity

Light pollution is an inherently complex topic. Various human-made and environmental factors affect light pollution levels. In turn, light pollution directly and indirectly affects various health, social, and environmental factors. Many teams incorporated several factors into a single light pollution score and interpreted this score as it related to the diverse communities that they were asked to consider. Teams that stood out to the judges recognized that a single score may not capture the complexity in the problem and instead opted for multiple scores, or other creative metrics, that directly addressed one of the key aspects of the problem statement: What is at risk from light pollution? These teams connected factors affecting light pollution to the impact on human health, society, and the environment and were able to discuss the impact of their proposed interventions more effectively.

Choice of Intervention Strategies

Teams were asked to propose intervention strategies to address light pollution and measure the impact of each strategy using their model. Many teams addressed this aspect of the problem by essentially performing a kind of sensitivity analysis: the proposed intervention will change a variable by some percentage, and the light pollution metric will change by some corresponding amount. Judges noticed, and were particularly impressed, when teams were able to go a step further and connect their intervention to their model in a multi-faceted way.

One-Page Flyer

Teams were asked to choose one location and create a one-page flyer to promote its most effective intervention strategy. Judges were looking for teams to be creative and persuasive. This was an opportunity for teams to convince the judges that they understood their results and could summarize their work in a concise way. While the judges enjoyed the creativity of teams that used amusing graphics, it was when the creative flyer could be tied back to the team's work that the judges were truly impressed. Teams should keep in mind that including graphics not related to their modeling work adds no value to their report. In one page (of 25), teams should highlight the value of their work and how best to communicate it to a general audience.

Creativity

Judges saw many different approaches, but it was the ones that were unique in some way that stood out to the judges. Many teams chose to use Analytical Hierarchy Process (AHP) to address the problem. While this is a reasonable tool, unless done exceptionally it did not set them apart from other teams. This year's MAA Winner, Team 2309766 from Seattle Pacific University, differentiated themselves from other papers with their machine learning approach as well as their consideration of specific health factors. Overall, judges value creative approaches to modeling that incorporate the context of the problem rather than tools that don't provide insights into the problem.

The Modeling Process

It should come as no surprise that judges expect good mathematical modeling in each team's report. This includes clear model formlation, including any formulas, variables, and assumptions clearly defined and explained; model validation and verification; sensitivity analysis; discussion of strengths and weaknesses; and a strong presentation, both through the writing and visuals included in the report [Blyman et al. 2020].

- **Proper Documentation.** It is important for teams to identify and appropriately cite sources for their data or existing models used to develop their model. In particular, some teams that failed to adequately cite sources for formulas and approaches were disqualified.

- **Model Formulation.** As teams developed their model, judges expected them to include definitions of their variables, to state reasonable and necessary assumptions, and to include an explanation of the process of parameter estimations. The reasons for the selection of variables and how they are used are key features for the judges to understand the value of their work.

- **Model Validation and Verification.** Validation is an important part of the modeling process. Judges expect teams to validate their models to determine any weakness and provide confidence in the results. Teams would often accomplish this by connecting their light pollution metrics to their lived experience, such as interpreting their results in the context of residential and commercial development in communities they had lived in and/or visited.

- **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. Teams that attempted a sensitivity analysis to determine the robustness, flexibility, or accuracy of their model demonstrated to the judges a higher level of knowledge of the modeling process. Most teams incorporated their sensitivity analysis into the discussion of their interventions. While this could—and usually did—work in establishing a model's robustness, the judges were particularly impressed by teams that went beyond and were able to perform a sensitivity analysis independent of the discussion of possible interventions. These teams indicated a stronger understanding of the importance of sensitivity analysis in the mathematical modeling process.

- **Strengths and Weaknesses** The contest instructions specifically ask to "[d]iscuss any apparent strengths and weaknesses to your model or approach." Thus, after the modeling and analysis, judges expected discussions of the strengths and weaknesses of the model and some concluding thoughts.

- **Written Communication.** Judges were looking for a balance of sound mathematics with well-written justifications of each team's approach. Papers that clearly described the modeling approach and results stood out to the judges. Moreover, teams that incorporated effective visual aids, such as graphs, diagrams, and flowcharts, and described their value to the team's work, stood out to judges.

Recognition of the Outstanding Papers

We give below summaries for the eight Outstanding papers and the Finalist winner of the MAA Award.

Team 2320131: Tianjin University — COMAP Scholarship and SIAM Award

"Less Light Pollution and Brighter Starry Sky"

The team from Tianjin University impressed the judges with a highly unique approach to the problem. They included images throughout that supported their work in a way that greatly contributed to the reader's understanding. Among its many unique attributes was the choice to use Saskatoon, Canada as a case study. This allowed the team to focus on many nuances of this problem that teams looking at a more global selection of locations were unable to explore. On the other hand, this left the judges with a lingering question of how the team's approach would scale to a larger area.

For their approach, the team developed a grid system, identifying the area within each block as urban, suburban, rural, or protected; and also as commercial, residential, industrial, or depopulated (**Figure 1**).

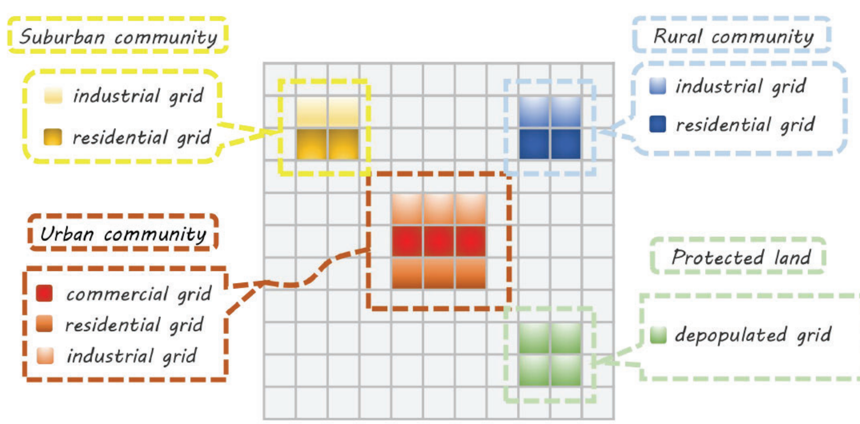


Figure 1. Four types of grids in different areas.

Applying this to Saskatoon and a nearby rural community and area of protected land, they arrived at **Figure 2**.

In building their model, the team developed a "Light Pollution Composite Index" that considered light damage, brightness balance, and illumination time. They used a convolution kernel to determine the influences of light pollution in one area on the index of its neighboring areas. To determine light pollution risk, they built a model that considered economic implications (both positive and negative), ecological diversity,

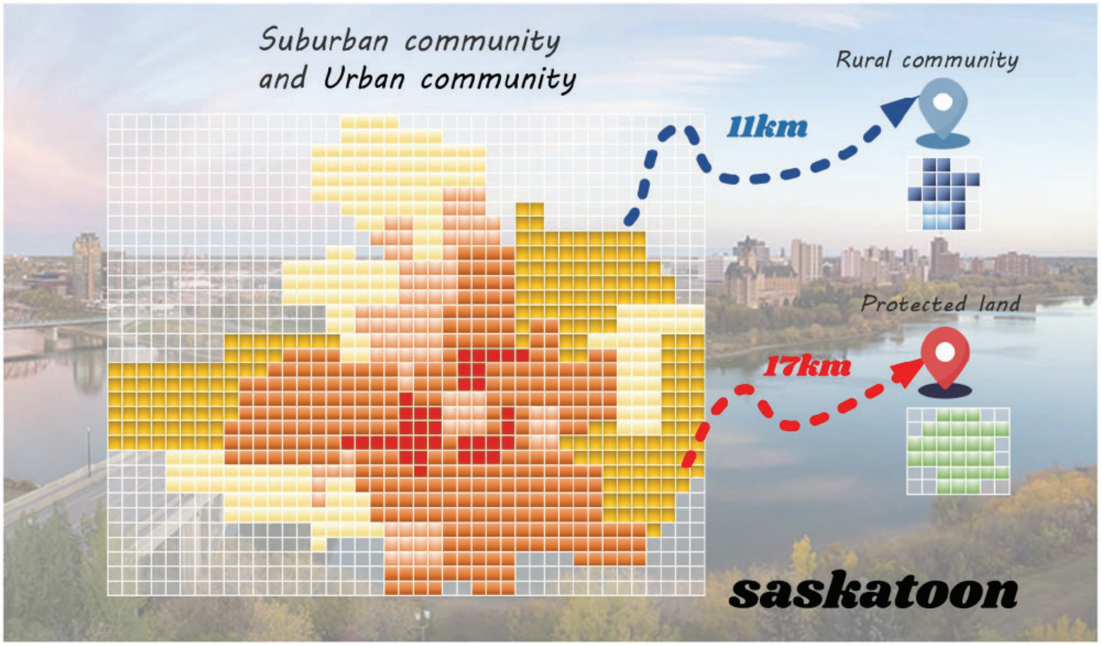


Figure 2. Gridding Saskatoon.

and human health. They also included a brief, researched, and thoughtful discussion about why they chose not to include social stability in their modeling. Rather than leaving their output as random decimal numbers with no meaning attached, they developed a classification system using K-means clustering to identify critical points (**Figure 3**). This approach allowed them to classify the risk for different types of areas in a meaningful way (**Figure 4**).

For intervention strategies, they suggested a diverse range of possibilities, including one about moving the grid. While this suggestion would be challenging, if not impossible, to implement in existing cities, it raised some interesting considerations for urban planning.

While the judges would have liked to see the team do a better job explaining their assumptions and some of their formulas, the apparent creativity and innovation in their thorough approach to this problem was refreshing.

Team 2312411: Chang'an University — Rachel Carson Award

"Evaluation and Optimization of Light Pollution Based on EWM-TOPSIS"

The submission by the team from Chang'an University stood out because of its inclusion of strong environmental considerations about the impact of light pollution. The judges appreciated that the paper included effects of light pollution on "plants, birds, beasts, amphibians, [and] reptiles" and not only on human populations.

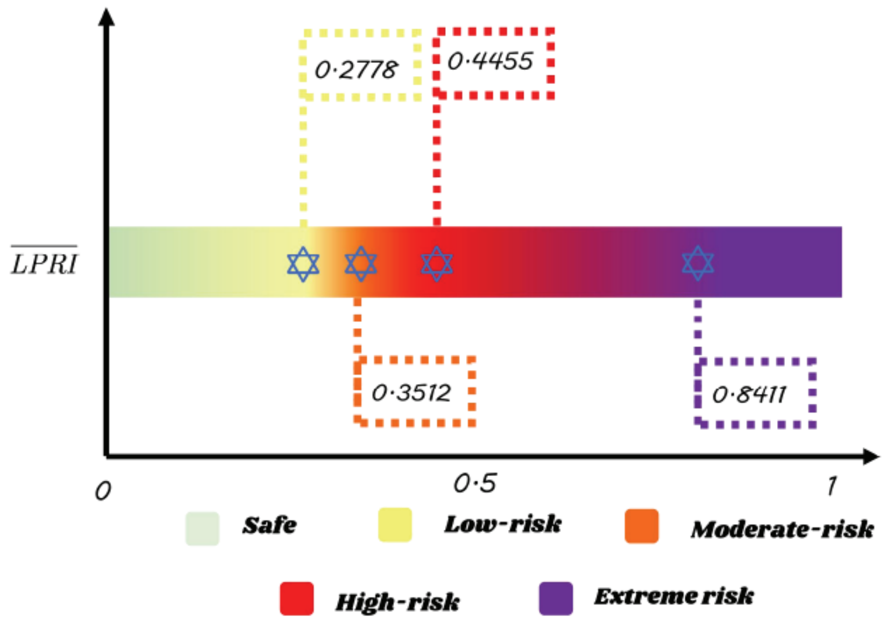


Figure 3. Classification standards and their respective critical points.

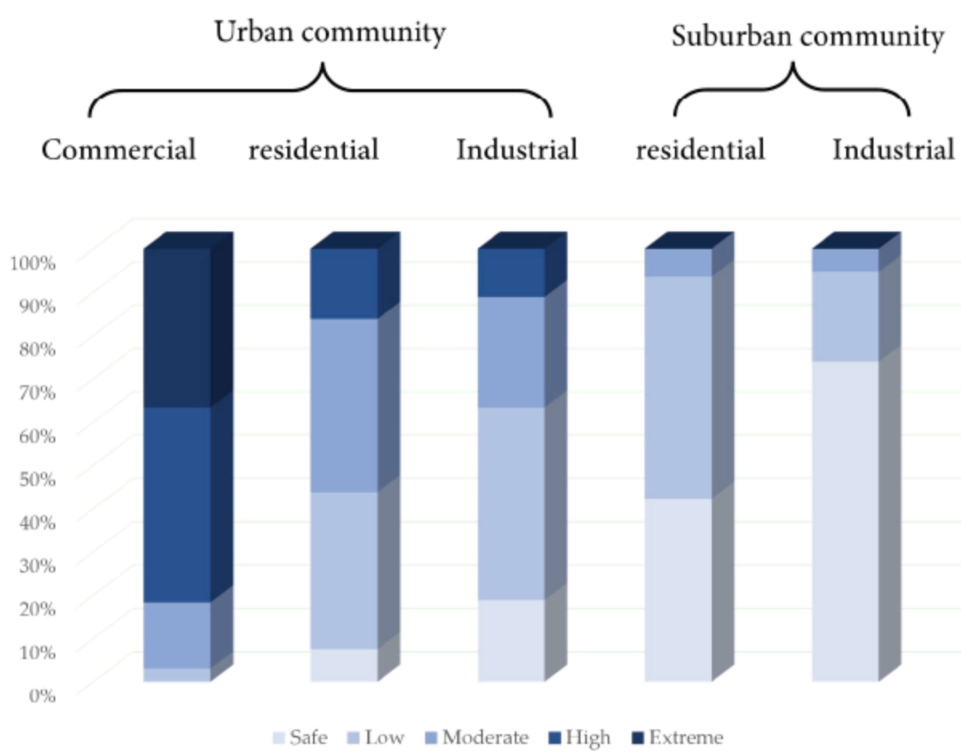


Figure 4. Percentage statistics of various types.

The paper started with a useful description of different types of light pollution, including light trespass, over-illumination, and light clutter. They then described their evaluation process.

The paper chose seven factors and used the Analytic Hierarchy Process to evaluate the regional light pollution in four locations in Shaanxi Province, China. This information was then used to establish an evaluation model of light pollution risk levels. Finally, a combination of the Entropy Weighting Method and TOPSIS was used to assess the risk of light pollution. The team did a nice job of explaining their model and approach. **Figure 5** was helpful in explaining how the overall evaluation system was constructed.

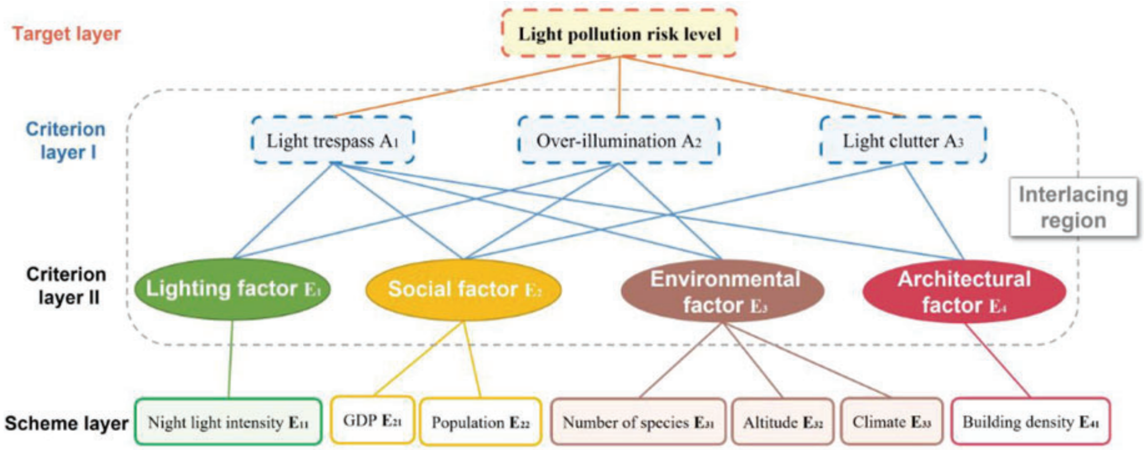


Figure 5. Hierarchical interactive evaluation index system.

Throughout the paper, the natural ecosystem, including plants and animals, was considered in the analysis of the detrimental effects of light pollution. It was clear the team was thinking beyond just a human perspective of the issue. The judges especially were impressed with the 10-, 35-, and 50-year projections of the treatment strategies on light pollution. This analysis was valuable and unique among the finalist papers. **Figure 6** shows the team's biodiversity projections for the next 50 years.

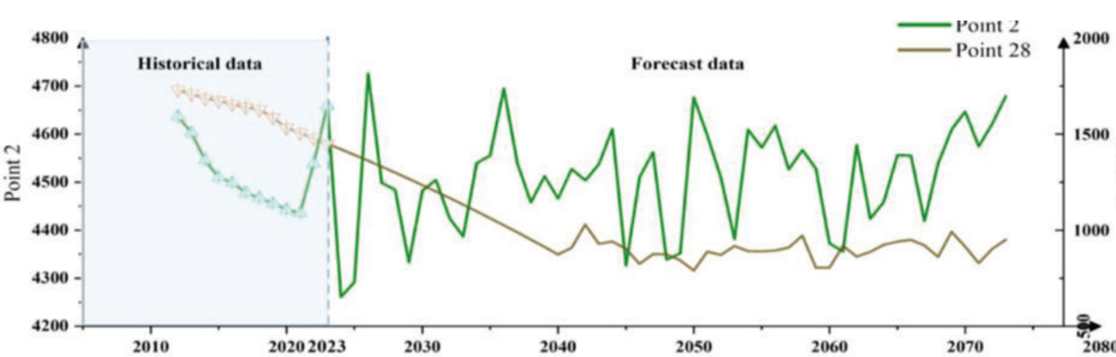


Figure 6. Biodiversity projections of the evaluation sites for the next 50 years.

The team provided a table of three light-pollution intervention strategies: increasing awareness of the light pollution problem, setting standards and norms, and establishing regulatory mechanisms to control and reduce the effects of light pollution. This table was useful in providing details of specific measures, since it was clear that the team recognized the issue and was suggesting addressing it in multiple ways.

In another table, the team sets an "environmental red line" at 50% of the median biodiversity data, in an attempt to prevent the ecosystem from collapsing. If the biodiversity drops below this "environmental red line," the government would need to act to increase biodiversity. A more detailed explanation of what is meant by "mandatory steps" that the government would take to increase biodiversity would strengthen this discussion.

The judges would have liked to see a more-thorough sensitivity analysis and specific measures of biodiversity, such as the Shannon or Simpson Diversity indices. However, the paper was prominent among the Finalist papers due to its description and concern for natural ecosystems and organisms, thus it was given the Rachel Carson Award, named after a woman who is credited for advancing the global environmental movement with her book *Silent Spring* [Carson 1962].

Team 2307336: Wuhan University — AMS Award

"Protect the Night, Control the Light!"

The team from Wuhan University submitted a well-rounded paper with attention to the various stages of the modeling process, from the initial assumptions to the sensitivity analysis. They made a comprehensive selection of indicators from their four chosen dimensions of risk levels, based on energy consumption and risk to humans, wildlife, and vegetation.

A unique aspect of their model was the distinction between risk from light intensity and from light spectrum. The judges particularly appreciated seeing how this distinction was incorporated into quantifying ecological risk from light pollution. The team used a combination of entropy weights and TOPSIS to build their light pollution risk model, which was a common approach this year, although they did stand out by quantifying the risk level of the four dimensions separately. That said, the judges would have liked to have seen more discussion of the formulas and why they are appropriate for this context. Some other teams achieve this by using references to relevant sources.

The team applied their model to four regions of Shenzhen and gave a good discussion of how the ecological and developmental differences between regions contributed to differences in risk levels, shown nicely in **Figure 7**.

The team proposed three strategies for reducing the effects of light pollution, which they broadly categorized as adjusting the light sources, the light intensity, and the layout. The judges were especially impressed with

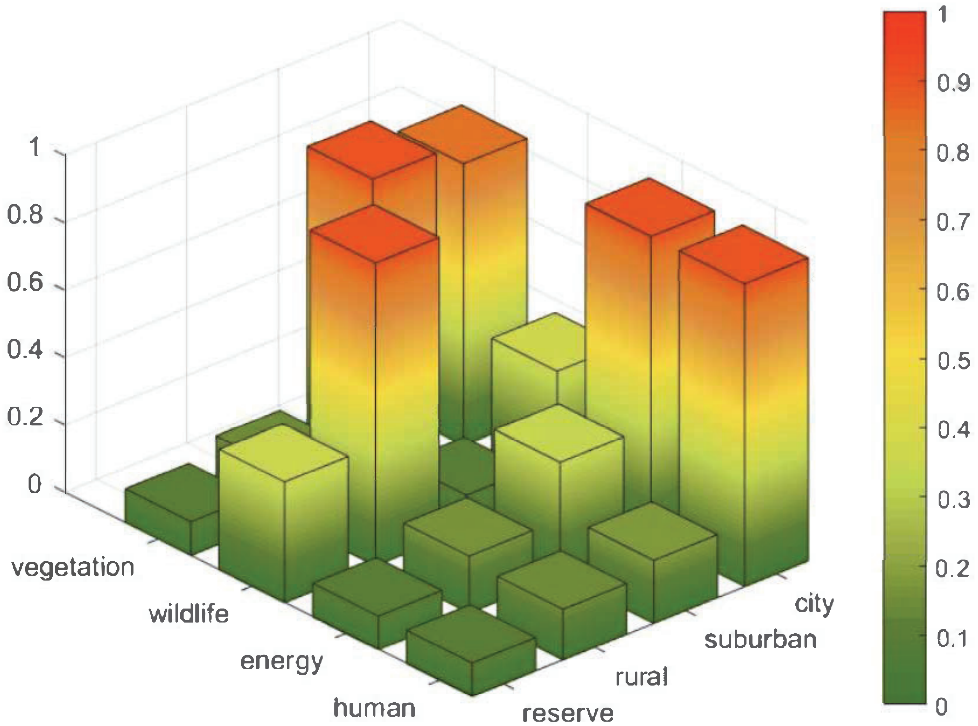


Figure 7. Risk scores of four locations in four dimensions.

the first strategy. The team used a competition model to describe the adoption of newer lamps over fluorescent lights and illustrated the benefits that this change can have on the radiance, based on its adoption in another location (**Figure 8**).

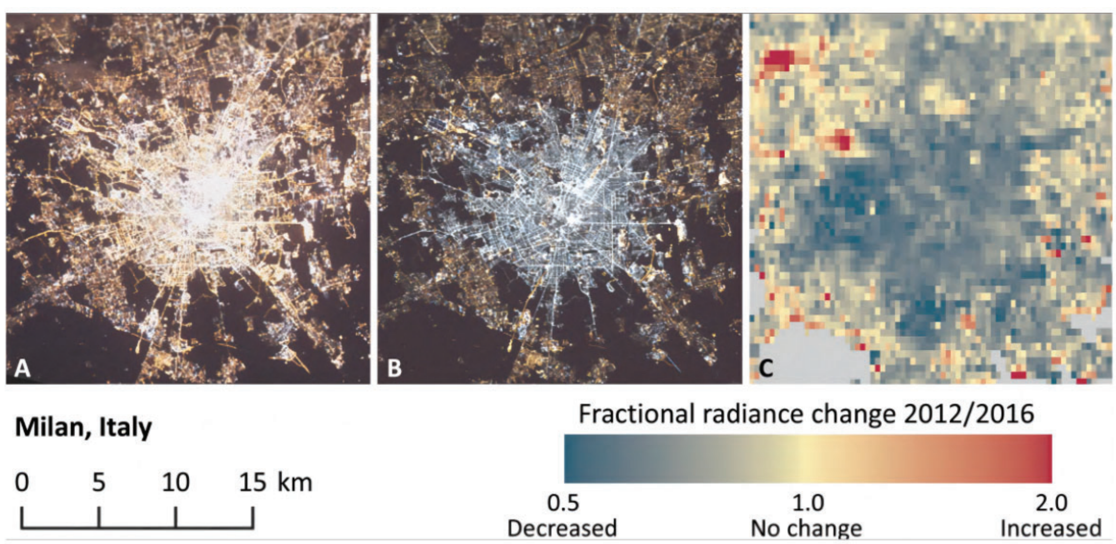


Figure 8. Change in lighting technology in Milan, Italy, observed from space.

Following the establishment of the strategies, the team projected how the risk scores for each region would change under each strategy over the next 50 years. Few teams made these forecasts, which distinguished this paper from others. However, the judges would have liked to see more of the details of how exactly the intervention strategies were implemented in the model and how the forecasting was conducted.

Additionally, the team included a discussion of the trade-offs between strategies, and compared future trends with, and without, interventions. The team tied together their discussion of strategies with their sensitivity analysis, noting that their light pollution risk metric is most sensitive to changes in radiance, which lines up with the strategy that they concluded was optimal, namely, the second strategy of adjusting light intensity. The sensitivity analysis was also well-done overall, and the judges appreciated how the team considered sensitivity in both their original metric and their strategy model.

Team 2308000: China University of Geosciences Beijing — INFORMS Award

"The Brighter the Light, the Deeper the Shadows"

The team from China University of Geosciences Beijing provided a logical and concise description of their method and modeling approach. The paper stood out to the judges for its unique goal-programming approach for developing intervention strategies. The intervention strategies were formulated based on priorities and the ability to achieve the goals that were specific to each of the regions.

The risk assessment model was based on the first indicators categorized by society, economy and ecology/health with a series of second indicators. The judges appreciated the identification of indicators based on advantages (called *requirement system*) and disadvantages (called *damage system*), as seen in **Figure 9**. The judges would have also valued a discussion about how the indicators were chosen.

The strength of this team's approach resulted from the development of intervention strategies based on the priorities of society, economics and ecology/health used in the risk assessment, and the optimization of the strategies based on the regional goals. This model allows for any region to determine intervention strategies based on local decision-makers' objectives. The team also recognized the need to introduce the cost of the strategies into future models. Overall, the team presented an organized and complete solution to the problem.

Team 2301428: Nanjing University of Posts and Telecommunications

"Recast Mystletainn to Fight the Artificial God of Light"

This team presented a clear modeling process and produced a strong model that incorporated light pollution impact as well as risk assessment

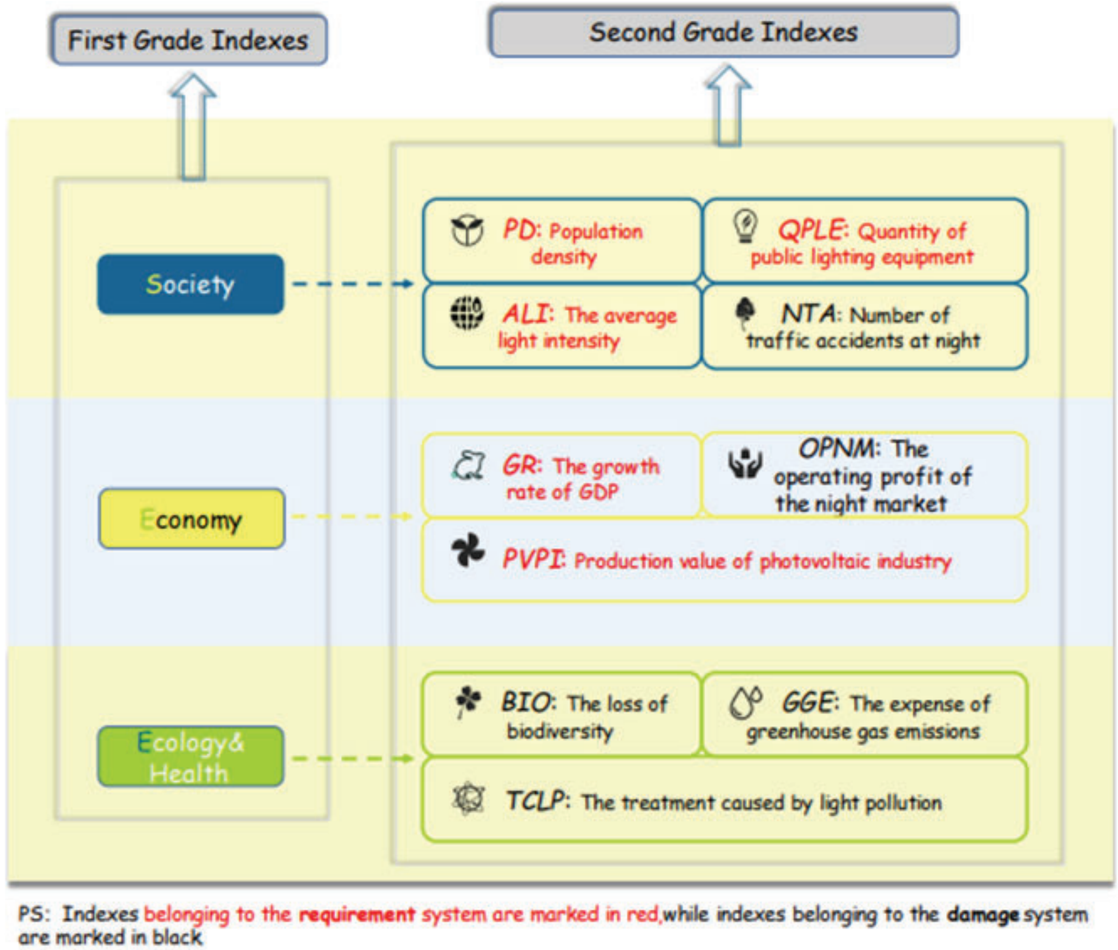


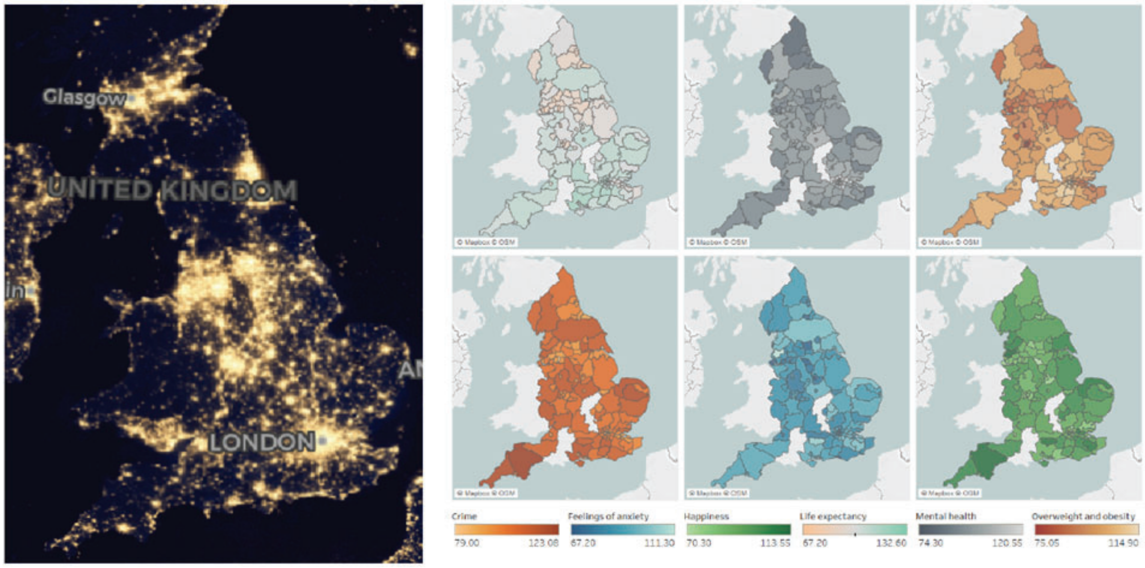
Figure 9. Light pollution risk level indicator system.

at both the micro and macro levels. The judges noted that the team acknowledged the benefits of artificial light when analyzing the impact of light pollution. The team's Light Pollution Assessment Model was strategically developed using data primarily from the UK, in order to minimize differences in geography and culture as it pertains to their selected indicators. This approach simplifies the complexity of the model and potentially reduces interference from other factors.

The judges appreciated that the indicators presented were clearly explained and justified; however, not all of the indicators seemed relevant. Some of the indicators presented are shown in **Figure 10**. This team verified their model and included a scale of risk that was applied to varying regions in the UK in their case study.

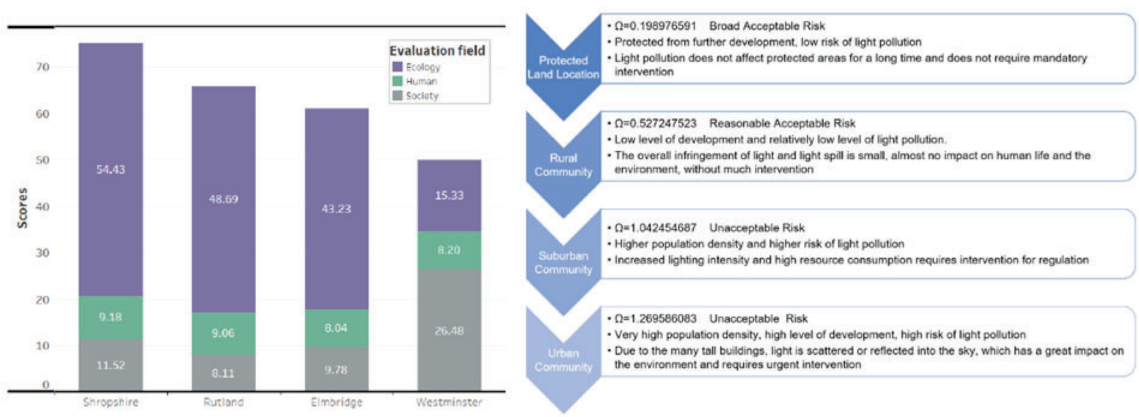
Another strength of this model is that the impact score for each region was subdivided into three scores according to human, society, and ecology aspects, as can be seen in **Figure 11**.

One area for improvement identified by the judges was the explanation and justification of the proposed intervention strategies. Overall, this team clearly addressed all parts of the problem in a well-organized paper that utilized reference material well throughout the report.



(a) UK Night Light Brightness (b) Some Indicators Related to Light Pollution in the UK

Figure 10. Some data visualization.



(a) Score of Three Security Levels in Four Community (b) Risk and Assessment Results of Four Community

Figure 11. Results of Light Pollution Assessment applications.

Team 205598: Liaoning University

"Turn out the Lights, Turn up the Stars"

The team from Liaoning University presented their work in a logical, well-organized paper. In particular, the judges were impressed with the clear exposition and easy-to-follow modeling explanations. The team began by giving detailed explanations to justify each of their indicators for the evaluation system. A pictorial representation, shown in **Figure 12**, helped to organize and clarify how each of the indicators related to the model.

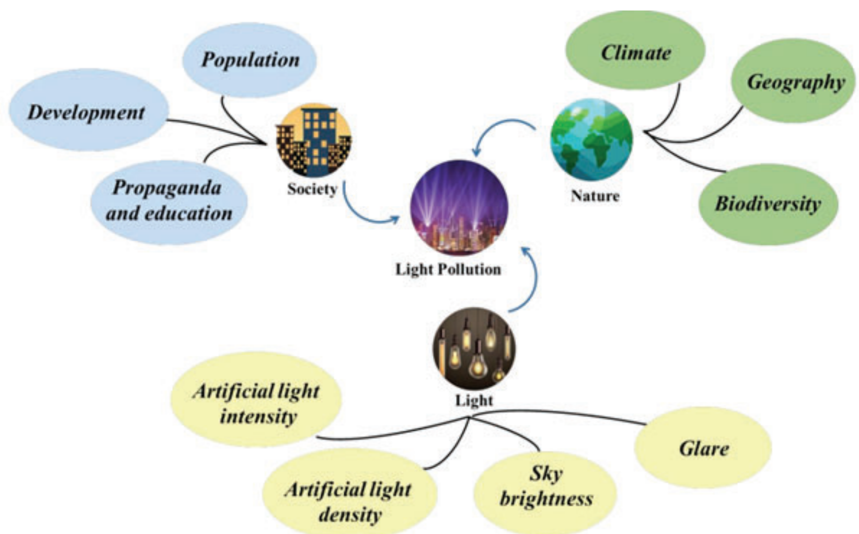


Figure 12. Evaluation system diagram.

The team gave good reasoning and descriptions of how the different types of regions were chosen. The location of each different type of region was reasonable, with a clear explanation of each of the 10 indicators for the region.

Another strength of this paper is the sensitivity analysis. The team tested the influence of different indicators on artificial light intensity to observe the relationship between the original model and the new model. The judges appreciated the detailed explanations throughout their intervention discussions for each of the three strategies.

One area that weakened the paper is the attempted use of neural networks to perform the impact analysis. The judges felt that there were not enough data used in the procedure to support this type of analysis. Despite this weakness, the team's strong communication and attention to detail made their work stand out among other papers.

Team 2314354: Southwest Jiaotong University

"Local Light Pollution Analysis: A Multi-layer Evaluation Model"

The team from Southwest Jiaotong University provided a well-organized presentation of their solution to all aspects of the problem. The provided images were especially useful in understanding the model and were visually pleasing. As can be seen in **Figure 13**, their Light Pollution System Model incorporated traffic through road density and type as an indicator, which stood out among other papers. In addition, all indicators and formulas were justified in the paper. The judges found the use of the K-means clustering approach to find representative values for each region well-explained and implemented in the case study, as can be seen in **Figure 14**. In addition to the visualizations, this teams utilized tables effectively to display relevant information for all indicators, making their values and use clear to the reader. One weakness that the judges noted was that the paper was lacking an interpretation of the model.

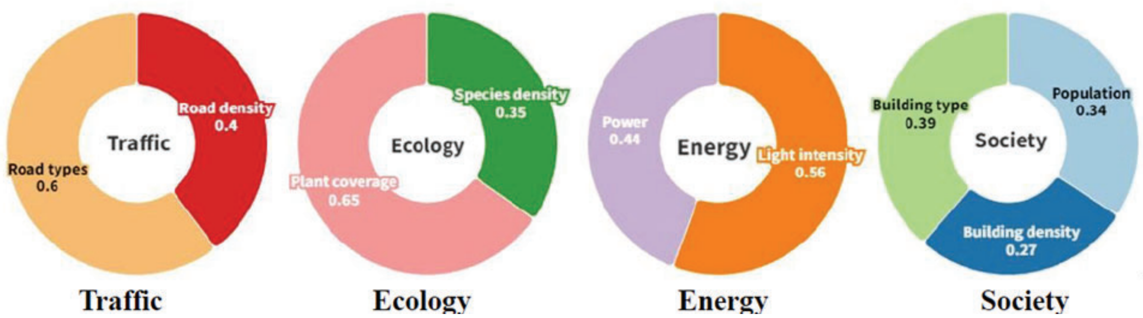


Figure 13. Indicator Ring Weights Chart.

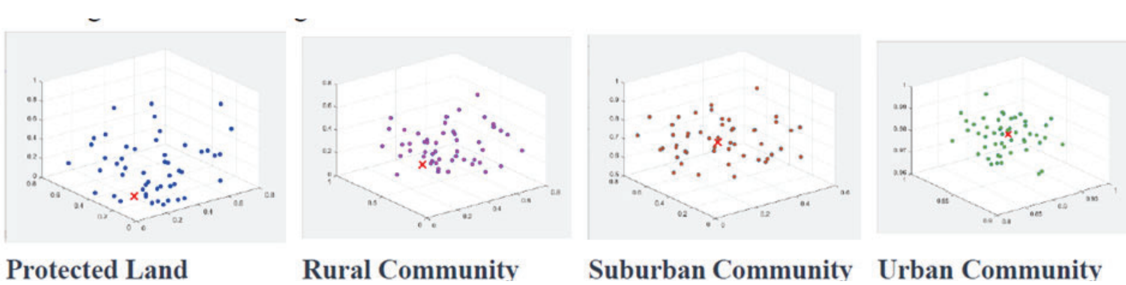


Figure 14. Cluster diagram by region.

The judges were impressed with the team's solution to the intervention part of the problem. The team proposed three intervention strategies that addressed their four main indicators. The intervention strategies were well-explained and connected with each indicator. Again, the judges appreciated the use of tables to clearly justify the impact level of each project according to the corresponding indicator. The team determined the optimal strategy for two regions and provided a thorough analysis of the impact. Another strength of this team is they provided scales for both the light pollution risk and the intervention strategy impact, which makes their model easily interpretable. Overall, this was an innovative and interesting paper to read.

Team 2314817: Sun Yat-Sen University

"Turn off the lights, Turn on the stars!"

The team from Sun Yat-Sen University began their submission with a strong executive summary that addresses both the team's approach to the problem and also briefly discusses results and recommendations. This paper approached light pollution risk level from three aspects, namely economic, social, and ecological (ESE) by developing light pollution scores for each of these subsystems. The ESE Model is a combination of the three submodels.

Population and proportion of different types of industries were used as indicators of the economic subsystem. For the social subsystem, the proportion of land used for (commercial, residential, administrative offices, green) was chosen as the indicator. For the evaluation of the ecological system, the target subjects were classified as aquatics, terrestrials, or humans. Using results from published studies, which the team cited, on the proportion of species in each category and illumination thresholds for the effect of light on animal and human rhythms, they calculated the total number of organisms affected by light pollution in an area. This analysis for the ecological subsystem was detailed and made this paper stand out.

For the light pollution risk assessment (LPRA) model, the team used the ESE model data and applied AHP to determine weights for the three aspects. The inputs for the AHP model were cleverly chosen to be the Google search index for the terms economy, society, and technology. The LPRA model was applied to 284 regions of China; results are shown in **Figure 15**, with a heat map of risk level at the province level given in **Figure 16**.

Four areas in China were selected for the analysis of protected land, rural community, suburban community, and urban community, using data from the ESE model and other data. This a good approach, though a more quantitative discussion of the indicators for the light pollution risk level would have strengthened the models and insights.

The team did a good job assessing the intervention strategies by evaluating the interdependencies among the three subsystems and presenting the results quantitatively in plots and equations. They applied the model to the Guangzhou and Zhaotong areas and determined the optimal strategy for each area. Evaluating the impacts of these strategies showed a significant decrease in the risk level after 20 years of implementing the optimal strategy. The optimal strategy in the form of GE Cubes was difficult for the judges to read and decipher, so this could be improved.

The sensitivity analysis focused on the impact of the change in light pollution investment cost on the light pollution risk over time. When the cost

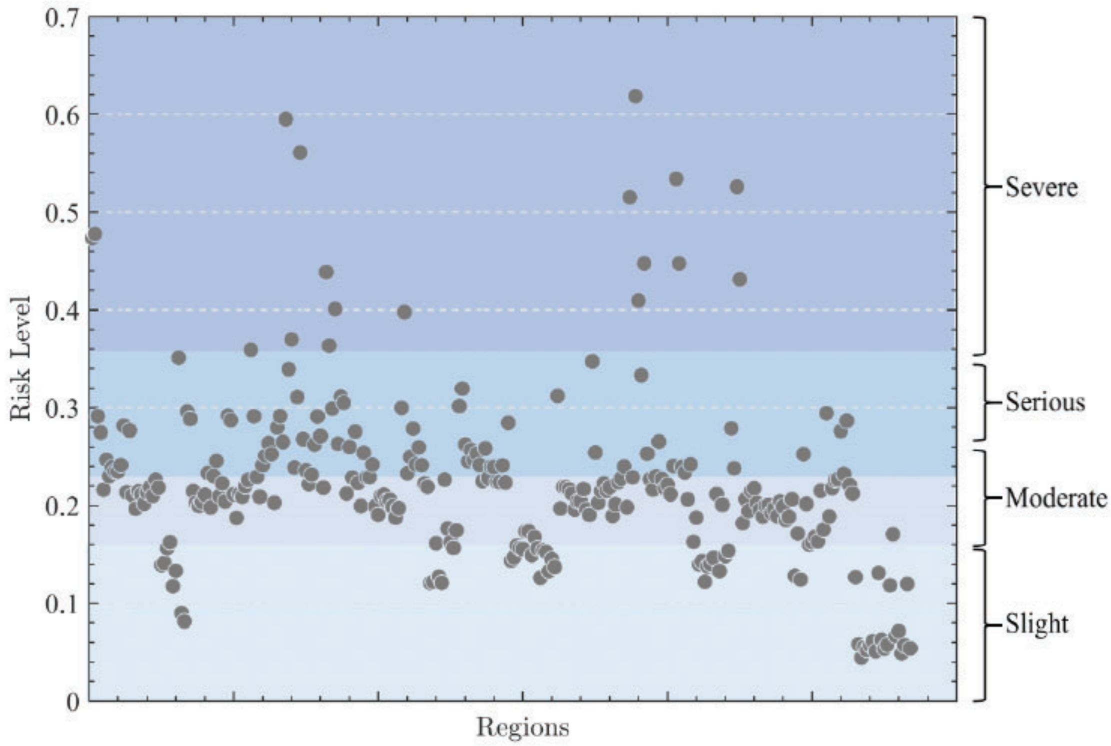


Figure 15. Risk level of light pollution in 284 regions.

Figure 16. Heat map of light pollution risk levels in mainland China.

is varied by ±50%, the trend of the risk level curve of the three strategies remains unchanged, as is shown in **Figure 17**.

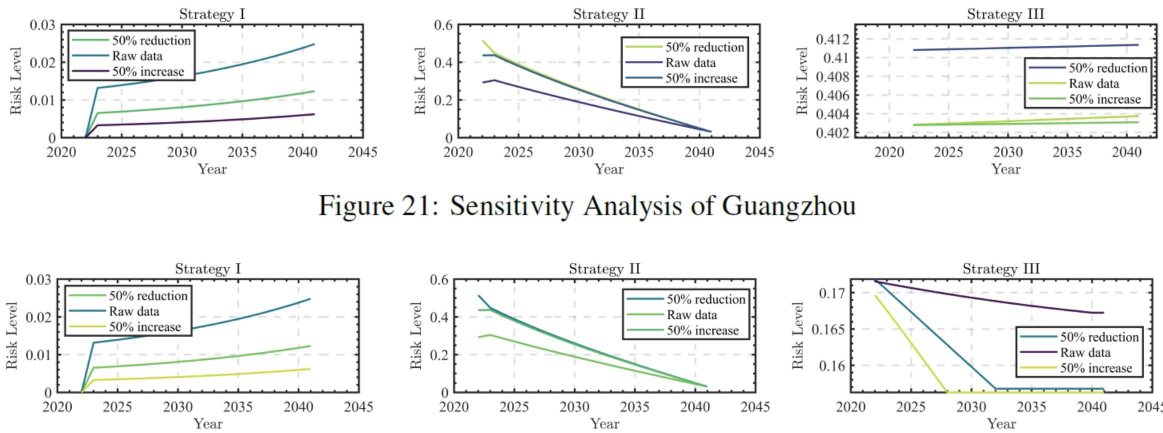


Figure 17. Sensitivity Analysis of Guangzhou and of Zhaotong.

Overall, the paper is well written and incorporated many figures to aid the reader's understanding of the models and results.

Team 2309766: Seattle Pacific University (Finalist) — MAA Award

"Light Pollution"

The team from Seattle Pacific University presented a well-organized and well-written paper including detailed consideration of light pollution on specific human health factors. They used a supervised machine learning model with multiple linear regression to predict a Bortle rating from county-level data on population density, median household income, and the protected status of the area. They trained their model on 70% of their 500 sample data points and tested the model on the remaining 30%. An analysis of their training is provided in **Figure 18**. They used the aggregated county level predicted Bortle rating from their machine learning model in a separate risk prediction model that they created to inform policy suggestions.

The judges appreciated the sustained elements of sensitivity analysis that were embedded throughout the paper. As a result, the final sensitivity analysis section was well-connected to the entire paper. There is always room for improvement however, and the discussion in the final sensitivity analysis section would have benefited from further details, including an appropriate graphical display.

Another area for improvement is the discussion of model fit for multiple linear regression, including an expanded treatment of residuals and the influence of outliers.

Overall, this paper stood out on the strengths of its writing and organization. Their risk prediction model combining economic, environmental, ecological, and humanitarian effects communicated a variety, and level of detail, of what was at risk that impressed the judges.

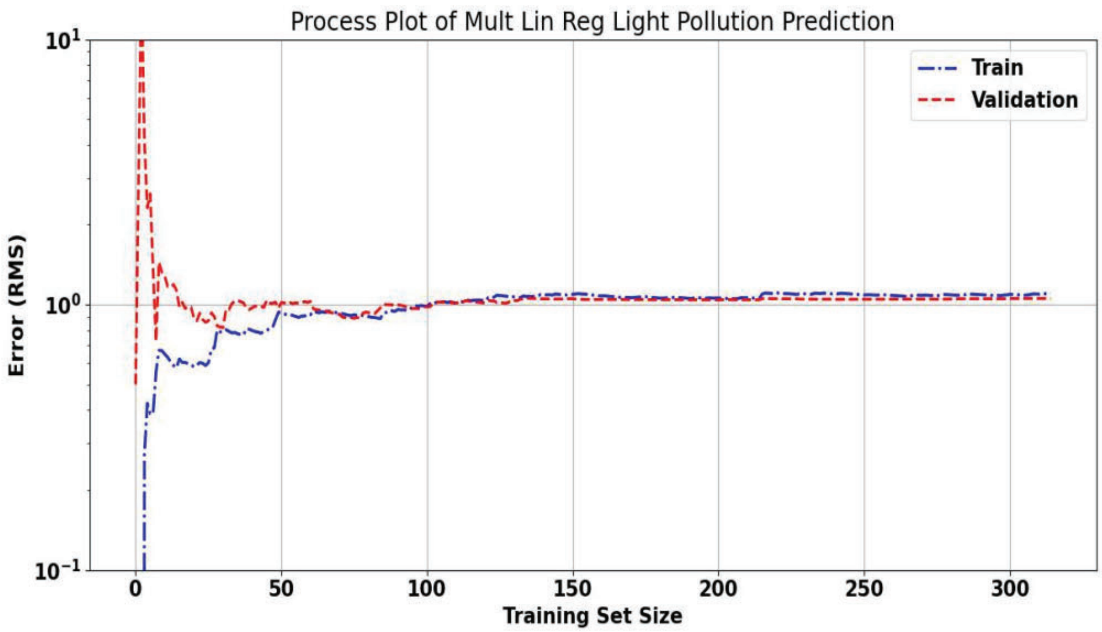


Figure 18. Validation by analyzing the error of data for different training set sizes.

Concluding Remarks

The judges continued to be impressed this year with the level of mathematical modeling that teams achieve. The judges applaud the diversity of considerations that teams included in their solutions when building their light pollution metrics, analysis, as well as the interventions. Judges also enjoyed the creativity displayed in the design of flyers. Moreover, teams are commended for incorporating an analysis in evaluating interventions to address societal and environmental issues. Papers that stood out were able to intertwine their modeling with their policy suggestions in ways that could feasibly be implemented in communities, while displaying strong core mathematical modeling skills. For many teams, this meant utilizing tools in meaningful ways, while for many other teams this meant thinking outside the box and tackling the problems in ways that pleasantly surprised the judges.

The eight Outstanding papers and the Finalist winner of the MAA Award all showcased best practices for interdisciplinary mathematical modeling that set them apart: keen understanding of the problem statement, solid modeling practices, effective communication, and creative approaches. The judges' decisions were difficult, due to the growing level of sophistication and abilities demonstrated by all participating teams around the world year after year. The judges are excited to see what teams will bring next year.

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About the Authors

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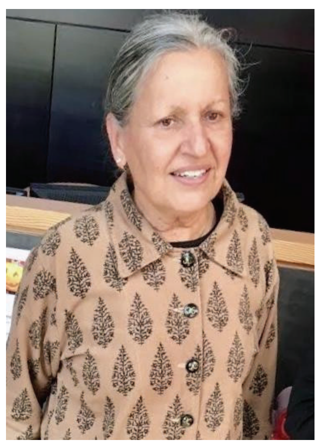

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2023 ICM Problem F: Green GDP

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Photo by Towfiqu Barbhuiya on Unsplash

Background

Gross Domestic Product (GDP) is arguably one of the most well-known and commonly used measures of the health of a nation's economy. It is often used in determining the purchasing power and access to loans for a country, providing motivation for nations to propose policies and projects that boost their GDPs. GDP "measures the monetary value of final goods and services produced in a country in a given time period; it counts all of the output generated within the borders of a country" [Callan 2023] This approach to calculating such an important and often quoted measure favors production today without any consideration about conserving resources for tomorrow. For example, a nation with rich forests could boost its current GDP by clear-cutting the trees and producing large amounts of wooden furniture. This nation could do so without penalty despite the loss of biodiversity and other negative environmental consequences. Similarly, a nation can boost its GDP by harvesting more fish now, without penalty for potentially irreversible harm to the fish stocks.

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Because GDP fails to give credit for natural resources, perhaps it is not a good measure of the true economic health of a nation. If nations change the ways they evaluate and compare their economies, national governments may change their behaviors, promoting policies and projects that are better for the environmental health of the planet. Could a "Green" GDP (GGDP), where "Green" refers to the inclusion of environmental and sustainability perspectives and factors, be a better measure than the current conventional GDP?

Multilateral changes are extremely challenging. Convincing nations to agree to this new GGDP over the conventional GDP as the primary measure of economic health would likely be very difficult. However, if making the shift initiates a global movement of national climate efforts that makes significant progress towards climate crisis mitigation, then perhaps it is worth the fight.

Requirement

Your task is to consider the world recognizing GGDP as the primary measure of the health of a nation's economy. What changes should we expect? What would the environmental impact of those changes be? Specifically:

- There are many proposed ways to calculate GGDP that have already been developed. Select one that your team believes could have a measurable impact on climate mitigation if it replaced GDP as the primary measure of economic health.
- Make a simple model that is easily defensible to estimate the expected global impact on climate mitigation if your selected GGDP is adopted as the primary measure of the economic health of a nation. It is up to you to decide how to measure global impact.
- Replacing GDP with GGDP could be met with resistance. Determine if your model indicates that the switch is worthwhile at a global scale, comparing both the potential upside of climate mitigation impact and the potential downside of the effort required to replace the status quo. Explain your reasoning and support your answer with your previous global impact analysis.
- Select a country and provide a more in-depth analysis of how this shift might impact it. For example, what specific changes would you expect in how its people use or save their natural resources between now (under the current GDP) and after the GGDP is adopted? Would those changes be beneficial to this specific country, considering both its current economic status and its ability to support future generations? Be

sure that your analysis is explicitly tied to the changes between how GDP and GGDP are calculated.

- Based on your country-specific analysis, write a one-page nontechnical report to the leaders of that country on whether to support a switch to GGDP or to reject a switch and maintain GDP as the primary measure of national economic health.

Your PDF solution of no more than 25 total pages should include:

- One-page Summary Sheet that clearly describes your approach to the problem and your most important conclusions from your analysis in the context of the problem.
- Table of contents.
- One-page nontechnical report.
- Your complete solution.
- Reference list.

Note: The ICM Contest has a 25-page limit. All aspects of your submission count toward the 25-page limit (Summary Sheet, table of contents, nontechnical report, solution, reference list, and any appendices). You must cite the sources for your ideas, images, and any other materials used in your report.

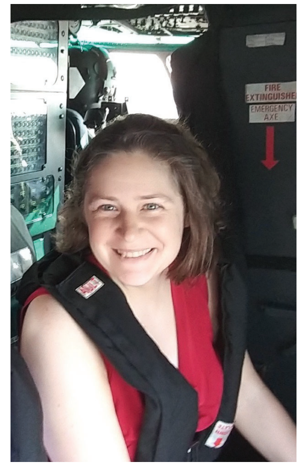
Glossary

- **Multilateral**: Having contributors, supporters, or participants from several groups, especially several different nations.

Reference

Callan, Tim. 2023. Gross Domestic Product: An economy's all. https://www.imf.org/-/media/Files/Publications/Fandd/Back-to-Basics/callen-gdp.ashx.

About the Author



Jessica Libertini is writing strictly in her personal capacity. Her career has spanned industry, academia, and government, with work in engineering, modeling, education, and science diplomacy. Her current research includes global social issues ranging from food security to human trafficking.

Summaries of Green GDP Outstanding Papers

Beyond GDP: Green GDP Revolution Leading the Way To a Sustainable Future

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Traditionally, GDP is used as the key indicator for measuring a country's economic health and guiding its development. However, the preservation of resources for future generations is also important besides current economic production. To address this need, the green GDP (GGDP) is introduced as a way to evaluate a country's potential for sustainable development. We explore the potential global impact of replacing GDP with GGDP as the primary economic indicator and utilize mathematical models.

For **task 1**, we suggest an accounting method for GGDP and forecast the global GGDP accordingly. Our method builds on **adjusting GDP for environmental damage approach**, improving it by subtracting environmental damage from the traditional GDP. Four main aspects of environmental damage are considered in our calculations for the estimation of GGDP. We also study the relationship between GGDP and GDP and derive the **Ratio Life Cycle Law**. Applying the ratio life cycle law and time series analysis, we forecast that the worldwide GGDP will reach $144 billion in 2050, with a GGDP-to-GDP ratio of 0.76.

For **task 2**, we first establish a **Comprehensive Evaluation Model of climate mitigation** to study the impact of the shift on climate mitigation. We build an indicator system by selecting six first-level indicators and 15 second-level indicators using **AHP**. We then use the **Group Decision Method** and the **Entropy Weight Method** to calculate weights. With the prediction results from task 1, we analyze the effect of the shift on each secondary indicator and evaluate the impact on various aspects of climate

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mitigation. The results indicate that greenhouse gas emissions will see the biggest improvement until 2050, with an expected reduction of **26.61%** in CO2 emissions and **49.71%** in NOx emissions.

For **task 3**, we measure the upsides and downsides of the shift. To analyze its impact on various industries worldwide, we establish a **Nonlinear Programming Model of Production Factors Flow** and examine the flow of capital and labor among the six industries most affected by the shift. Our analysis of the 10-year impact of the shift globally shows that the technology and service industries will benefit the most, while manufacturing, energy, and mining will be the hardest hit. We also examine the total value and find that, in the long run, the shift will increase global production, underscoring its worthiness.

For **task 4**, we analyze the impact of the shift on Peru. Based on our previous models, we conclude that Peru is still in the initial stages, with GGDP growing at a low speed and that the area that Peru needs to improve on the most is **energy efficiency**. Considering Peru's unique industrial structure and its competition with Chile in the South American copper market, we build a **Super-game Model**. After analysis, we recommend that Peru should shift after full development of the economy in the future.

Finally, **sensitivity analysis** is performed. We observe that the value of the objective function changes with parameter adjustments, and the changing trend is logical. This demonstrates the sensitivity and reliability of our model.

Keywords: Green GDP, climate nitigation, life cycle curve, AHP, EWM, nonlinear programming, super-game theory

Towards a Greener Climate-Analysis Based on 4M System

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With the continuous development of the world economy, humans' exploitation of resources, and the gradual intensification of environmental damage, the global climate situation is becoming increasingly severe. So it is urgent to strike a balance between economic development and environmental resource protection. In order to evaluate the turnaround and global impact brought by using GGDP instead of GDP as an indicator to measure economic health, we established a **4M System**: one Method, one Model, one Mould, and one Movement.

For the Method, we read considerable literature on different calculation methods, from which we selected a GGDP Calculation Method that considered multiple factors such as resource consumption and emissions, based on which we conducted a preliminary analysis on 40 years' data of 160 countries in the world. The results show that the unhealthy share of GDP (defined as %DIF) in countries around the world has declined by 5% in the past 50 years. Meanwhile, even some of the countries that cause a lot of emissions and pollution can do better while maintaining economic growth.

For the Model, we developed the **Climate Mitigation Impact Model**, which includes **3 levels of indicators** to describe the atmosphere, ocean, and land conditions. Among them, the **Entropy Weight Method (EWM)** was used to determine the weights of indicators. After that, we scored the past years and found a **consistent decline** from the 1970s to the present. Then, based on the results of **correlation analysis** and **regression analysis**, we found that the impact of %DIF on the world climate is up to **1/3 of climate change**, and its reduction can improve environmental deterioration.

For the Mould, we first ran a **cost-benefit analysis** of the replacement and applied **Ordinary Least Squares (OLS) regression**, analyzing different impacts on people's livelihood between GDP and GGDP. The result indicates that the replacement is friendly to **gender equality** and **human development**, though a slight increase in **income inequality**. Then we considered the future. In terms of economy, we combined ARIMA, GM(1,1), and SVG to predict the future, which shows that world GDP and GGDP will fully recover in 2052 and 2055 respectively, with rapid growth after that. In terms of climate, the scores normalized by a **logistic function** show that after 2075, the climate score will increase again.

For the Movement, we selected **Brunei** for specific analysis, and predicted whether it should accept GGPT or not. We concluded that if Brunei did not carry out reform, it would face resource exhaustion and economic collapse; while after the reform, it would completely recover the economy by 2077. In addition, we have also made several targeted policy suggestions for Brunei's reform, including industrial structure, economic structure, trading structure, etc.

Finally, we arranged the above analysis into a one-page nontechnical report to Brunei's leader, supporting Brunei's replacement of GDP with GGDP as the primary indicator of national economic health.

The sensitivity analysis at the end of the paper shows that no matter how large or small the short-term sacrifices that countries make to push forward reforms, they will ultimately reap substantial benefits commensurate with the costs. At the end, we had a further discussion of this system, hoping that it can be more useful and leading us to a greener future.

Keywords: climate mitigation; Green GDP; regression analysis; ARIMA

Green GDP: Unraveling the Diverse Challenges and Opportunities For a Sustainable Future

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In recent years, there has been growing speculation regarding the efficacy of GDP as a reliable indicator of a country's economic health, prompting the proposal of using Green GDP as a more appropriate alternative. Unlike GDP, GGDP factors in natural resources in its calculation, thus presenting far-reaching implications for sustainable development.This paper aims to examine the worldwide implications of transitioning from GDP to GGDP, assess the cost-benefit of this shift, and predict its specific impacts on China within the country's context.

First, we carefully selected a method to calculate GGDP, which involved monetizing the costs of natural resource damage (NRDC) and ecological damage (EDC) and subtracting them from the GDP. Using this method, we calculated GGDP and the GGDP-to-GDP ratio (GI) for over 90% of the world's countries. The resulting trends and global distribution of GGDP and GI were then visualized and analyzed.

Subsequently, we selected five climate change-related indicators: forest cover, share of renewable energy use, sea level, average surface temperature, and greenhouse gas emissions to form a climate index, CI, which can assess the global impact on climate mitigation. We fitted linear regression models to compare the relationship between GDP, GGDP, and CI. The GGDP was quantified by assuming that its annual growth rate after replacing GDP is the same as the historical growth rate of GDP. Our findings indicate that the adoption of GGDP will lead to a 31.57% reduction in the rate of environmental degradation, demonstrating its potential to be a powerful tool for climate protection.

In addition, a cost-benefit analysis is conducted to evaluate the switch from GDP to GGDP. This analysis considers not only the potential benefits of climate protection and the potential costs associated with the fluctuation of GDP, but also the resistance encountered during the multilateral change. To estimate the multilateral resistance, a clustering approach is creatively utilized to categorize more than 90% of countries worldwide according to their national conditions and predict their attitudes toward such a switch.

A unique algorithm is designed to monetize the cost of resistance for countries that oppose it. The results of the analysis indicate that the switch is worthwhile, and reflect a general trend as the world continues to evolve.

Furthermore, we selected China for in-depth analysis. Based on a sectoral perspective, we calculated the environmental costs of each sector and found that manufacturing, agriculture, residential, and transport accounted for 89.2% of the total environmental costs. For the different sectors in China, we gave a policy implementation schedule for each decade from 2020 to 2050. We then utilized EPS (Energy-Policy-Simulation) model to assess the potential impact of policies on emissions reductions, costs, and social benefits. The monetized benefits of avoided premature deaths and climate benefits could reach RMB 1.6 and RMB 2.9 trillion, respectively.

In the end, we conducted an objective analysis of the strengths and weaknesses of the aforementioned model and drafted a nontechnical report for Chinese leaders, leveraging the outcomes of our assessment while factoring in the prevailing national conditions in China.

"Green" GDP, Green Planet

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The concept of "green" GDP is an innovative one among many solutions to the growing impacts of climate change. GGDP successfully closely combines national sustainable development with global climate mitigation and environmental governance.

For Task 1: According to SEEA and related references, GGDP is defined as GDP **minus air pollution cost, waste utilization cost, and resource consumption cost**. Data of 46 countries are substituted into the calculation, and the ratio of GGDP to GDP (RGG) of all countries in 2020 is obtained. The larger the value, the greener the economy. We find that the RGG is generally higher in developed countries, followed by most developing countries, and lowest in resource-exporting countries.

For Task 2: Referring to the impact of major international events on carbon dioxide emissions in previous years, the impact of GGDP on pollution indicators was **estimated** and the results were calculated. It was found that the global average RGG in 2040 increased from **0.9784** to **0.9881**. Three climate indicators, namely, temperature, pollution, and ecosystem balance are considered in this paper. Then, the world's score on three indicators

is calculated by three-level fuzzy comprehensive evaluation. The results show scores in 2040 increased from (0.2534, 0.7591, 0.3802) under normal conditions to (0.7139, 1.2795, 0.3846) after the adoption of GGDP, indicating a positive impact on climate mitigation.

For Task 3: The feasibility of GGDP is analyzed from **two dimensions of space and time**. In the spatial dimension, **game theory** is used to simulate the profit distribution process in different countries. The results show that all countries which initially opposed to the GGDP *finally* **accepted** the standard within **15** years. Different development modes are quantitatively analyzed in time dimension. In the **20th** year, the adoption of GGDP generated more income than the conventional one; and in the following **40** years, an additional **$51.6** trillion of income was created globally.

For Task 4: We consider Australia as an **adopter** of GGDP. Firstly, **PVAR** is used to analyze the industrial structure of Australia. It is concluded that the contribution of the tertiary industry to the economy is about **47.27%**, higher than that of the secondary industry (**21.07%**), indicating that the industrial transformation in Australia will have a relatively **positive driving effect** on it. Then, comparing Australia with Germany, we found that Australia has a low waste utilization rate and a high landfill rate. Finally, we tailor-make policies for Australia to help the country's economic health improve rapidly.

For Task 5: From the above analysis, it is clear that the adoption of GGDP in Australia is **necessary**. Recommendations are made to the leaders from three perspectives: **economic development, environmental treatment, and waste utilization**.

Finally, the sensitivity analysis of the model is carried out to verify the stability of the model, and the strengths and weaknesses of the model are analyzed.

Keywords: fuzzy comprehensive evaluation, time-space analysis, game theory, PVAR

Judges' Commentary: Green GDP

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Introduction

This year is on track to be the hottest on record despite numerous global, national, and local efforts to combat climate change. Some economists argue that one reason these efforts are only able to make incremental impacts is because the gold standard for measuring a nation's economic well-being is the gross domestic product (GDP), a measure of economic output that currently does not account for conservation efforts. This widely-accepted indicator allows countries to compare their economic success relative to other countries and can influence global lending. Politicians are under constant pressure to increase their nation's GDP, and this can lead to short-sighted decisions that cash in on natural resources today at the expense of conserving them for future generations.

This year, the ICM Policy Problem, Problem F, asked students to consider a global pivot away from GDP as the primary indicator of national economic well-being, replacing this measure with a Green GDP that would also account for environmental impacts, such as protecting natural resources and investing in a green economy. If international organizations and the

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global community all agreed to recognize a Green GDP (GGDP) as the new standard to indicate national economic well-being, what would change, and what would the global impact of those changes be? And, given expected resistance to changing away from the status quo, would the global impact of the change be worth the effort of fighting for the change and the effort of implementing that change?

Judges' Criteria

Every year, the panel of final judges for Problem F is a mix of applied mathematicians, modelers, and political and social scientists, who are hoping to see papers that not only showcase excellent modeling of a complex social system, but also offer well-reasoned explanations intended for this diverse panel of experts in their respective fields. These experts always look for teams that

- make defensible modeling choices that are easily explained to nonmathematicians,
- base their work on strong linkages between the modeling and the policy discussion, and
- have internal consistency across the modeling, either by following a single model through the whole process or by building a cohesive system of models, as opposed to providing an unnecessarily large and disjointed collection of models.

The panel also looks for papers that

- start with a strong executive summary and
- offer a literature review that allows the team to build on existing work and/or ground their novel ideas in the literature.

In addition to the perennial considerations discussed above, this year, as the judges discussed the papers, there were a few themes that emerged:

- strong policy work tied to the modeling,
- visualizations that added value,
- adding a new angle,
- not assuming the conclusion, and
- selecting an appropriate model.

Each of these aspects is discussed in more detail below.

Strong Policy Work

The judges always want to see papers that connect the policy work and the modeling seamlessly. This year, judges expected to see the recommendations for switching (or not switching) from GDP to GGDP for a given country be grounded in results from the presented models. There were quite a few papers that had conclusions that might have been related to the findings, but some of these papers failed to make an explicit case of drawing the line from their model results to their findings. For example, if the model showed that it would take 20 years for a country to recover their international standing after the world adopted GGDP—but after those 20 years of recovery, their GGDP would be poised to skyrocket—then the team should include a results-based rationale for either switching (pointing back to the skyrocketing and what that could mean for the country) or not switching (pointing back to the 20 years and the strong domestic political pressures that would make such a switch unpopular at home).

The judges were impressed by teams that demonstrated thoughtful work around the challenge of implementing a transition from GDP to GGDP. This was perhaps the most nuanced aspect of the problem, since it pushed teams to move beyond making a model for the impact, and required them to consider the possible impediments to implementation as well as how to appropriately model the navigation of those impediments. While many teams focused their efforts on other parts of the problem, there were a few creative methods that emerged to address this part, and the judges were excited to see these.

Additionally, the judges appreciated when teams provided the rationale for the selection of the country for the in-depth analysis, particularly when this rationale was tied to data related to the preliminary analysis on the impact at the global level. In some cases, teams intentionally chose a country that seemed to sit in the middle, leveraging the country analysis to provide more insight into the global case, while other teams chose an outlier or a country with an unusual factor (polar, tropical, very high GDP, very low GDP, already implemented a strong green plan, etc.) to better understand what is happening at the extremes. When teams omitted any explanation for their choice of country, particularly if the country chosen was one that had not been included in any prior analysis, it left a distracting open question on the minds of the judges.

Visualizations that Added Value

Images are also something discussed by the judging panel each year, and the judges all agree that every image should

- be clearly and legibly labeled,
- be called out in the text,

- be accompanied by a reference to the source, and
- add value to the narrative.

Data visualization is a growing field with increasingly accessible tools, and many teams produced impressive maps and other creative visuals to help tell their data story.

In recent years, judges have noticed that many teams add a flowchart or concept map of their process, and these are even highlighted favorably in the Judges' Commentary. Some teams create excellent visualizations that guide readers through an otherwise complex process. However, this year, as with previous years, many teams added process diagrams that were not designed to offer additional insight. Some teams included images just for the sake of adding a picture, without providing good justification and context for that image's presence in the text. Quite simply, if a visualization does not add value to the paper, it should not be added. This is not to say that the paper should be all text; rather, investing in the skill of designing value-adding visualizations (infographics, process diagrams, tables, graphs, etc.) could improve the quality of a paper.

Adding a New Angle

The judges appreciated when teams identified important layers to the problem and explicitly explored them. For example, some teams divided countries into categories, based on size, latitude, or level of development, and successfully justified why their chosen categorization was important to their analysis. Other teams acknowledged that a Green GDP is not only about improving just the environment but also the health of people in that environment. Some teams even brought in game theory to address some of the political science and social aspects of the problem, like one of the Outstanding teams that used game theory to explore the geopolitical pressures of supporting or resisting the change from GDP to GGDP.

Not Assuming the Answer

Some teams assumed that there is a right answer to the problem: of course, the world needs to switch to GGDP, and doing so would result in climate mitigation. But a careful reading of the problem shows that teams were implicitly challenged to explore this assertion. The judges appreciated teams that didn't assume that conclusion—and it was great to see papers that

- challenged the premise of a GGDP,
- pulled reasonable and reliable data,
- selected an appropriate modeling approach,

- performed their analysis, and
- let the interpretation of their findings inform their decision.

The judges also appreciated those teams that looked into what factors might make it a worthwhile switch, a neutral switch, or a harmful switch for a given country under a given set of conditions.

Selecting Appropriate Models

Unfortunately, many teams misinterpreted this problem and attempted to apply models such as AHP (Analytical Hierarchy Process) and EWM (Entropy Weight Method) to develop a new Green Economy Index. However, just as GDP is an accounting method (not an index), Green GDP is also simply an accounting method. It was unfortunate to see so many teams fall back into comfortable models that were not always appropriately applied to the problem. Of course, there is no one right model that works for this type of problem, and there are some creative ways to apply AHP and/or EWM to this problem; but some models fit more naturally than others.

Discussion of the Outstanding Papers

This year, the final judges selected four papers as Outstanding. Each is extremely different, highlighting the value of creativity and showcasing how different tools, skills, and perspectives manifest in unique approaches to the same problem statement. While each was selected for its strengths, it also had some areas that the judges found lacking. Below we highlight both the strengths and the shortcomings of each Outstanding paper. It is important to remember that no modeling submission is ever "perfect"; all teams had up to three students working for about four days on an extremely complex problem. Therefore, the inclusion of the shortcomings is not intended to minimize the great work of these amazing teams; rather it intended to allow past and future participants to continue learning and growing.

Team 2315018 Soochow University — SIAM Award

"Green GDP: Unraveling the Diverse Challenges and Opportunities for a Sustainable Future"

The executive summary is a key aspect of any technical report. Regardless of the audience, if the executive summary does not clearly describe the contents and outcomes of the work, then the team did not do their job and the reader is less excited to continue reading. This team from Soochow University had a very good summary. They gave a short background/motivation to the problem, indicated the key factors of their GGDP metric selection, and for which countries they applied the method. Their outcomes were clear—a 31.57% reduction in environmental degradation and benefits to the climate and population health as measured in trillions of RMB. They also described challenges of the switch from GDP to GGDP as such a change can be met with much resistance and showed how to monetize it and give a long-term trend towards closing the gap. What they did not do was overwhelm the reader with a list of models as many teams did. The goal was to provide simplistic modeling that was well explained—this team did that well.

The first thing that judges do is to make sure that the team addressed the entirety of the problem. It seems like a simple idea, but many teams fell short. This team clearly outlined their work and then proceeded to properly select an existing measurement of GGDP, give a simple model for global impact using their selection, look at the resistance to the change from GDP to GGDP, give an in-depth study of a country (China in this case), and write a nontechnical document to those leaders. Their work was organized, and the writing flowed well.

To accompany the text, this team used visuals (tables and figures) to support their work. Many teams included figures that were not described in the text, were missing labels, and were shrunk so small that they were unreadable. However, this team had the perfect number of visuals to break up and support the text. The visuals were readable, well-labeled, and most importantly described in the text. Their figure on K-means clustering of the countries relating to their climate index was very nice (**Figure 1**). Their figure on policy implications was easy to read and supported their long-term plan for China's success towards carbon neutrality (**Figure 2**).

Regarding their work on China, it was very nice to see that they gave a long-term plan that was broken into decades, each focusing on different aspects of the implementation. For the final one-page report to the leaders, some teams seemed to think that "non-technical" meant that you couldn't include any data, but that was not the intent. This team repeated the quality from their executive summary in writing their one-page report. It gave a concise reason for a change from GDP to GGDP, listed clear benefits, and gave a roadmap with a 30-year timeline—all backed by their findings based on the modeling.

Overall, this paper certainly deserves the rating of Outstanding. It is also the winner of the SIAM Prize for "advancing the application of mathematics and computational science to problems from engineering, industry, science, and society." This problem included aspects of economics, climate change, public health, and the environment; and the team tackled all with quality modeling, discussion, and explanation.

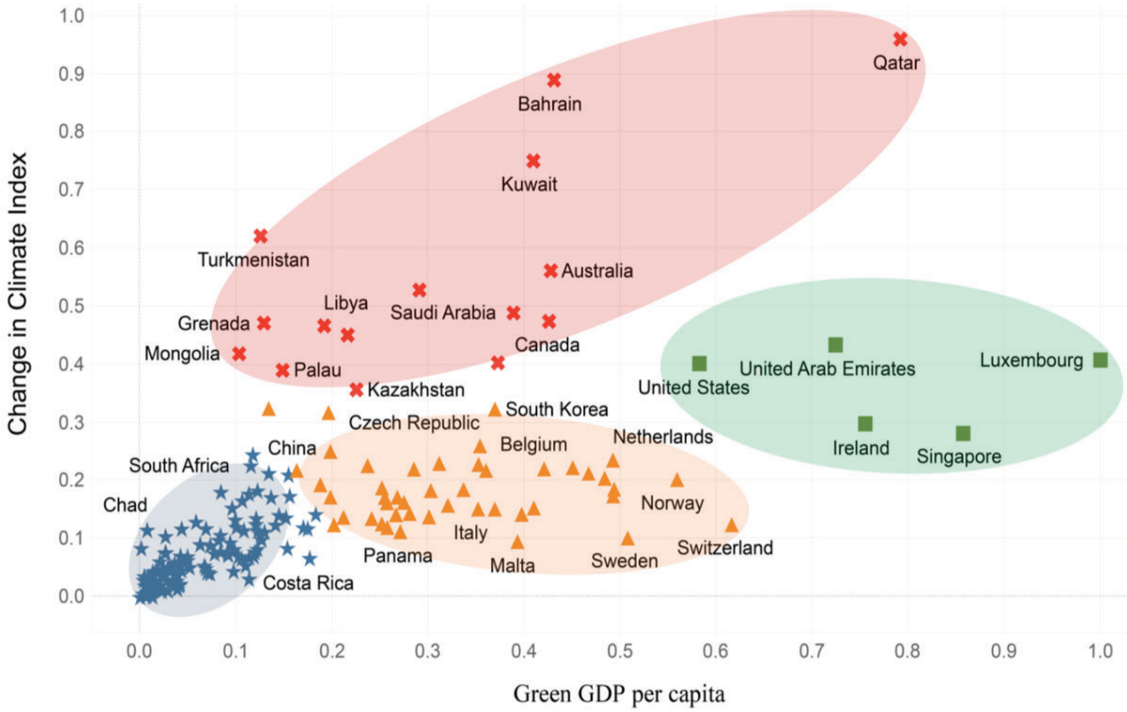


Figure 1. K-means results.

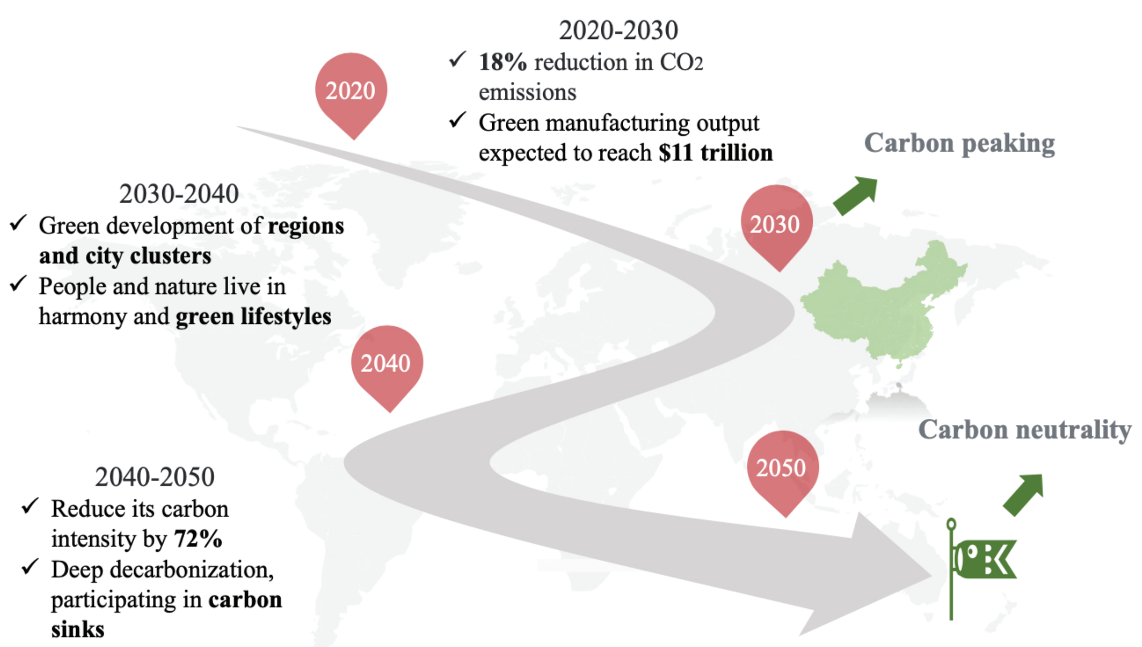


Figure 2. Policy implementation schedule.

Team 2311258 Xidian University — AMS Award

"'Green GDP, Green Planet"

The team from Xidian University wrote an Outstanding paper and was chosen for the AMS Award for their use of game theory in their transition model. The executive summary gave an easy to follow outline of how the entire problem was addressed. The team named methods that they used, provided information about when they made calculations from data, and summarized key results. The details in the executive summary made it easy to see that the team had completed substantive work on each piece of the problem. They incorporated data for 46 countries to evaluate the GGDP, estimated a global impact that such a change would bring, and created an explicit transition model to switch from GDP to GGDP. They chose Australia for a more in-depth analysis of the shift, with the selection of Australia framed in terms of data used earlier. The team provided a sufficient analysis for each component and it was complete.

Within the write-up of each section, the team provided a short introduction. These are very helpful for understanding how the team is thinking about the part of the problem. The information is potentially repetitive with earlier sections. However, including it makes it much easier for the judges to follow the team's reasoning and methods. The team provided a citation for the method that they chose for calculating Green GDP, explained their core calculations, and provided a map of the results.

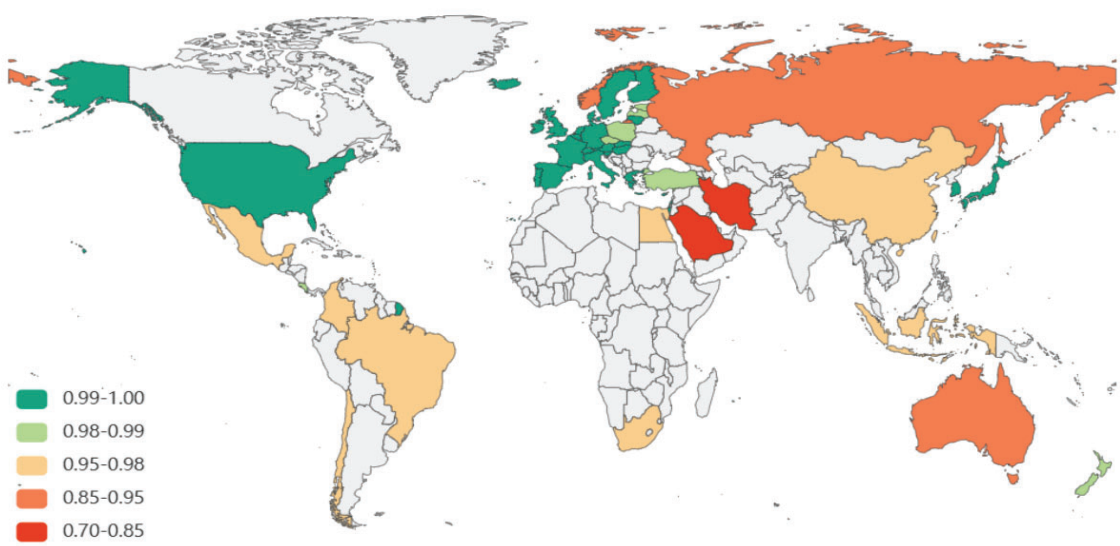


Figure 3. RGG of 46 countries.

The figures in this team's report, such as **Figure 3**, were helpful visualizations of their results and methods. Their diagrams were simple and used large enough fonts to be easily readable.

The team's transition model is particularly notable. They frame the transition from GDP to GGDP via a game. Using data used to compute GGDP with their selected model, they identify countries that might oppose GGDP and those that might support it. They create a mechanism for modeling losses due to climate impacts, and for supporting countries to subsidize opposing countries. They look at losses and gains to countries with and without GGDP and run a repeated game. This very explicit game-theory-based transition model creates a way to think about the costs and benefits of transition. There are some typographical errors in this part of the paper that make it a little harder to follow (including a copy-paste error that misidentified at least one of the countries in the game result table). Also, the explanation of their mathematical choices in building the game, including the loss-function exposition, could have been more thorough. Although the exposition had some room for improvement, the novelty of the transition model, along with the ways that they fully addressed each aspect of the problem, makes this paper Outstanding.

This team chose Australia for their in-depth analysis. In stronger papers, the choice of country was at least partially justified, and this team linked the choice of Australia to its pollution score in an earlier task. They used their data to choose Germany as a comparison country for Australia. To understand the importance of different sectors of the economy, the team used a panel vector auto regressive (PVAR) model. The model has a number of technical details, and not all of the abbreviations associated with the model were fully explained, but the basic stability checks and overall results were clear from the write-up. Some of the recommendations in the paper could have been more clearly linked to their modeling and modeling results (such as a discussion of waste incineration vs. landfilling). The description of recommendations for the country would also be strengthened by more direct references to the modeling. The modeling is present in this section, though, and it is relevant. For the nontechnical report, some of the information is linked to the modeling. Their report was closely tied to their analysis of Australia, which makes sense given the problem statement; however, the judges felt there was a missed opportunity to bring in Australia-relevant aspects of the team's transition model, since this was the most novel and note-worthy part of their analysis.

This team did an outstanding job in creating a relevant model for every piece of the problem, providing clear enough exposition that the judges could follow their work, and making use of relevant figures, tables, and diagrams. They were awarded the AMS Award for their thoughtful game-theory model of economic transition.

Team 2305794 Beijing Institute of Technology, School of Management and Economics — COMAP Scholarship Award and INFORMS Award

"Beyond GDP: Green GDP Revolution Leading the Way to a Sustainable Future"

The paper included many elements that made it Outstanding; the first being how easy it was to read, and the cohesiveness of the paper. Each part flowed from and built on the previous sections, creating cohesiveness that the judges look for and appreciate. The models referred to one another and created a modeling story, rather than having lots of unrelated models that feel disjointed. This team made excellent use of a flowchart explaining the content of their paper. It was instructive and added to the cohesiveness rather than being tacked on as an artificial figure. The clear communication of ideas in this paper really set it apart from others and made it an easy choice as an Outstanding paper.

Many papers assumed that a shift to GGDP would lead to climate mitigation, rather than demonstrating it. This paper first predicted GGDP values in the future and then used those projections to determine the effect that GGDP could have on climate mitigation. The judges appreciated that this team used a Ratio Life Cycle to predict future GGDP, an effective and elegant solution to this part of the modeling process. The team then extrapolated those results down to the climate indicators, using AHP and EWM to predict impact on climate mitigation. Their explanations of their Climate Mitigation Model and its results were clear and easy to understand. They were able to explain how GGDP impacts and improves each dimension of their climate model; and most importantly, they use the results from their model to support and illustrate their explanations.

Another unique aspect of this paper was the use of nonlinear programming to create their Production Factors Flow model. For this reason, the team was selected for the INFORMS Award. They used this model to investigate the impact of GGDP on various industries, which they broke down into the categories of Manufacturing, Transportation, Energy and Mining, Service, Technology, and New Energy. They were able to describe, using results from their model, how each of the six industries will experience setbacks and how the workforce may flow from one industry to another.

This team chose Peru for their in-depth exploration. While the judges appreciated the research and analysis of Peru's economy through the lens of its copper-mining industry, they would have appreciated seeing more than the game-theory approach of exploring how Chile's decisions could impact Peru's actions. The judges would have liked to see more done to investigate the impact of GGDP on Peru's climate and economy independent of Chile's actions.

Many teams found it difficult to include in their nontechnical report easy-to-understand graphs, charts, or figures to illustrate their points. Leaders want to know why recommendations are being given, the motivation and reasoning behind them. The team from Beijing Institute of Technology did an excellent job of creating a visually-convincing argument for Peru to make the shift to GGDP, as illustrated in **Figure 4**.

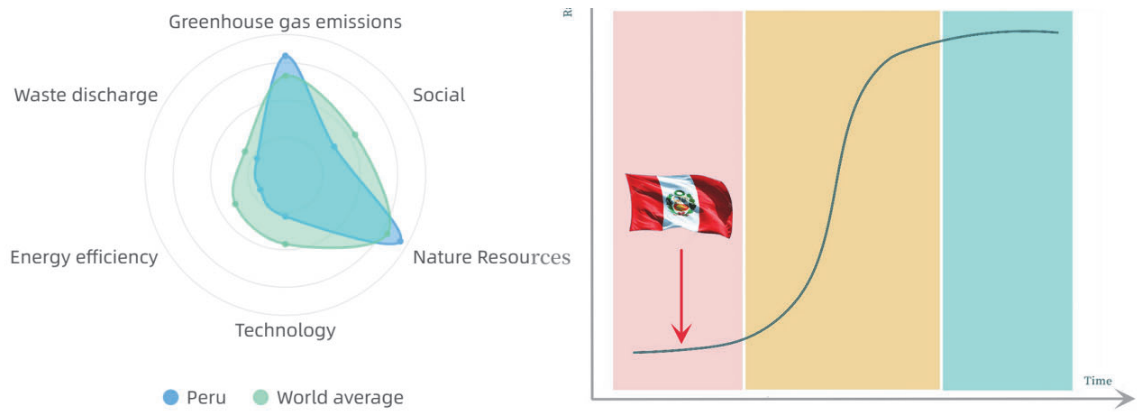


Figure 4. Comparison of indicators between Peru and the world, and Peru's position on the life cycle curve.

Overall, this team did an outstanding job in their choices of their models, the cohesiveness of their whole paper, and their clear communication of ideas and results.

Team 2311517 Renmin University of China — Pareto Award

"Towards a Greener Climate—Analysis Based on 4M System"

From the beginning, the judges enjoyed reading this paper. Starting with a clear and concise executive summary and literature review, the paper was strongly written. Overall, the paper was organized and engaging, the elements of the model were well explained, and the results were interpreted logically. The judges likewise appreciated that the models themselves were relatively simple, though they would have preferred that the models fit together in a more streamlined way. While many teams explored GGDP in relation to GDP through a percentage change, this team did a particularly nice job of explaining their rationale for using this approach. While some teams throw in a sensitivity analysis around model inputs without thinking about the contextual meaning or utility of that analysis, this team explored the impact of how long it would take to implement a transition, the results of which could be directly applied to show policy-makers the impact of their decision timelines.

The judges were particularly impressed by this team's thoughtful consideration of the complex human elements of adopting GGDP. The paper explored the reality of intergenerational and regional equity and how adopting GGDP may change the social dynamic. It also considered social welfare benefits, such as reduction of gender inequality and improved quality of life (from a health and social perspective), while also addressing a predicted increase in income inequality. The judges appreciated how the paper directly related these benefits and drawbacks to the model. The paper's interpretation of the results was well explained; however, the judges note that the conclusions that were reached risk reinforcing a social bias—namely, that while conditions in the global north may improve, conditions in the global south and in the overall globe may worsen, increasing global inequity and risking further harm to the planet.

Among the areas for improvement, the judges noted the introduction of several new models in the analysis of the long-term impact of adopting GGDP on a global scale. While each of these models connected back to the team's percentage difference metric, the inclusion of additional GGDP metrics felt superfluous. Additionally, the judges felt that some assumptions lacked sufficient explanation, and they would have preferred that the paper's exploration of Brunei was more explicitly tied to the model. Although the team did provide some policy recommendations, the judges noted that the policies were a bit vague. But despite these areas for improvement, the judges were still extremely impressed with the work of this team, particularly the way that they addressed some of the more-complex social aspects of this year's problem; and this is why this team is not only Outstanding but also winner of the Pareto Award.

Conclusion

The judges congratulate and thank all the teams who submitted a solution to this policy problem. The judges were truly impressed by those teams that explored the rich complexity of problem and selected models that were appropriate for exploring the pros and cons of migrating from GDP to GGDP.

An interdisciplinary problem is best addressed with an interdisciplinary team. The diversity of the four Outstanding papers beautifully illustrates the value of creativity in modeling, showcasing strengths in a range of subjects including economics, social sciences, computational modeling, game theory, data visualization, and more. At the same time, some aspects of modeling are universal, and each of these papers included clear summaries, appropriate model selections, and convincing explanations and justifications of the majority of their work. These four teams are to be commended on how they leveraged their individual strengths—as writers, as computational modelers, as social scientists and economists—and worked together as a team to explore the impact of a switch to GGDP in the 2023 ICM Policy Problem.

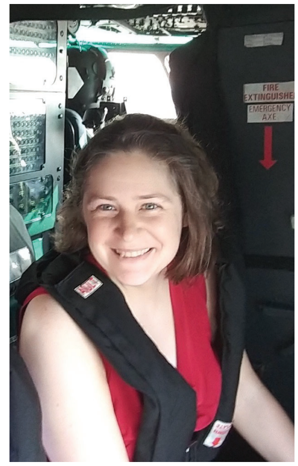
About the Authors

Heather Bloemhard earned a Ph.D. in physics from the New Mexico Institute of Mining and Technology and a B.S. in physics and astronomy from George Mason University. She is currently the Assistant Director of Federal Relations for Vanderbilt University; she has served as a Science & Technology Policy Fellow at the Dept. of Defense and the American Astronomical Society's John N. Bahcall Public Policy Fellow. She became involved with MCM/ICM in 2018 as a triage judge and has been a final judge since 2020.

Luke Castle earned his Ph.D. in mathematics from North Carolina State University, where he now is a teaching assistant professor. He first got involved in the ICM in 2019 as a postdoctoral fellow at Virginia Military Institute, when he served as triage judge, triage coordinator, and final judge for the competition. His current interests revolve around redesigning service courses to meaningfully showcase the broad applicability of mathematics.

Sarah Iams earned her Ph.D. in applied mathematics from Cornell University. She currently serves as the Co-Director of Undergraduate Studies in Applied Mathematics, and a Lecturer on Applied Mathematics at Harvard University. She has done ICM triage grading and served as a final judge for more than five years. Her research focuses on applied dynamical systems with biological applications.

Jessica Libertini is writing strictly in her personal capacity. Her career has spanned industry, academia, and government, with work in engineering, modeling, education, and science diplomacy. Her current research includes global social issues ranging from food security to human trafficking.



Eleanor Ollhoff studied at the University of Tennessee and has a background in undergraduate mathematics instruction and pedagogy and also in pure mathematics (low-dimensional topology and differential geometry). She has taught in the mathematics departments at Appalachian State University, the University of Tennessee, and the US Military Academy. Eleanor has been a triage judge for the ICM since 2014, and she has been on the final judging panel for several of the recent past years.

Troy Siemers has his Ph.D. in Mathematics from the University of Virginia. He has worked at the Virginia Military Institute (VMI) in Applied Mathematics since 1999 and since 2010 as department head. He has been a triage judge for ICM for several years and a finals judge for five years. He has taught applied mathematics majors in the VMI senior capstone course, which is based on preparing for the ICM competition. He has broad interests, having done research with colleagues in economics and business, physics, psychology, chemistry, and applied mathematics.

2023 ICM Problem Z: The Future of the Olympics

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Background

The International Olympic Committee (IOC) is facing a decreasing number of bids to host the Olympics—both Summer and Winter Games [Matheson and Zimbalist 2021]. In the past, hosting the Olympics was highly competitive and prestigious. More recently, however, host cities/nations have experienced a variety of short- and long-term negative impacts. To address these issues, innovative problem-solvers are considering various options and strategies. For example, perhaps the Summer and Winter Games should each have a permanent location. Another idea is to split the Olympic sports into four (instead of two) groups and hold four smaller Olympic Games (e.g., Winter, Spring, Summer, and Fall). This system might somewhat relieve the burden of hosting such a large event.

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Requirement

COMAP's **I**nterdisciplinary **C**ommittee on **M**odern **G**ames (ICMG) is interested in exploring creative options, strategies, and policies to ensure that the Olympics are successful and continue to bring the world together through sport. Your task is to make recommendations in support of the ICMG's work. The ICMG recommends building metrics for the impacts of hosting the games from various points of view: economic, land use, human satisfaction (athletes and spectators), travel, opportunity for future improvements, host city/nation prestige, and other criteria that your team identifies. Consider the feasibility, timeline to implement, and impact of potential strategies on your metrics. Write a one-page memorandum to the IOC describing your strategy and policy recommendations.

Your PDF solution of no more than 25 total pages should include:

- One-page Summary Sheet that clearly describes your approach to the problem and your most important conclusions from your analysis in the context of the problem.
- Table of contents.
- Your complete solution.
- One-page memorandum.
- Reference list.

Note: The ICM Contest has a 25-page limit. All aspects of your submission count toward the 25-page limit (Summary Sheet, table of contents, one-page memorandum, solution, reference list, and any appendices). You must cite the sources for your ideas, images, and any other materials used in your report.

Reference

Matheson, Victor, and Andrew Zimbalist. 2021. Why cities no longer clamor to host the Olympic Games. *Georgetown Journal of International Affairs* https://gjia.georgetown.edu/2021/04/19/why-cities-no-longer-clamor-to-host-the-olympic-games/.

About the Authors

Chris Arney is an Emeritus Professor at the US Military Academy. His Ph.D. is in mathematics from Rensselaer Polytechnic Institute. He served as a dean and acting Vice President for Academic Affairs at the College of Saint Rose in Albany and had various tenures as chief and program manager at the Army Research Office in Research Triangle Park, NC, where he performed and supported research in cooperative systems, information networks, and artificial intelligence. Chris is the founding Director of the ICM.

Kayla Blyman is Assistant Professor of Mathematics at Saint Martin's University in Lacey, Washington. She holds a Ph.D. in STEM Education and an M.A. in Mathematics, both from the University of Kentucky, as well as a B.A. in Mathematics from Messiah College (now Messiah University). She has taught at the US Military Academy at West Point, Berea College, Midway College (now Midway University), and the University of Kentucky. With COMAP, Kayla wears multiple hats: She is director of the Middle Mathematical Contest in Modeling (MidMCM); co-director, problem director, problem author, final judge, judges' commentary author, triage judge coordinator, and triage judge for the Interdisciplinary Contest in Modeling (ICM); associate editor for the Teaching Modeling Department of *The UMAP Journal*; and lead developer for the Introduction to Modeling course for the COMAP Certificate in Modeling (CiM). Kayla's research is focused on the development and implementation of new and creative ways to teach and assess undergraduate mathematics, with a goal of better developing creative problem solvers for our future. An avid explorer—both professionally and personally—Kayla loves spending time in the great outdoors, partaking in the arts, traveling to new places, and trying new food.

Summaries of Future of the Olympics Outstanding Papers

Save the Future of the Olympics

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School of Mathematics and Statistics
Team members: Jiamei Jiang, Xingyu Hao, and Xuhan Li /
Advisor: Haijuan Hu

Recently, due to COVID-19, there has been a decreasing number of regions applying to host the Olympic Games, which has drawn widespread attention. This article primarily focuses on how to quantify the impacts of hosting the Olympic Games and develop practical strategies and implementation timetables to alleviate its negative effects.

Firstly, based on the rich data collected, we conduct data preprocessing, including calculating cosine similarity to fill missing values, data normalization, and so on. Next, in order to measure the impact of hosting the Olympics, we select 18 secondary indicators, such as employment, from five aspects: **economy, society, politics, OFI,** and **environment**. Then, we combine **AHP** and **CRITIC** methods to calculate the weights of the relevant indices (see Figure 6) and the comprehensive scores. The results indicate that **Buenos Aires, Argentina** and **Vancouver, Canada** are the regions with the highest scores for the Summer and Winter Olympics, respectively, among the selected 35 regions.

Then, we evaluate the feasibility of the evaluation model from the perspectives of **discriminability** and **generalizability** by analyzing the impact of hosting the Olympic Games. To assess the discriminability, the K**-means clustering algorithm** is applied to partition the 35 regions into three clusters, where the threshold values of economic indicators are 0.26 and 0.63 (see Table 7 for other indicators). Furthermore, we consider not only the direct impact but also the potential long-term impact. Ultimately, we conclude that our model can effectively discriminate the impact of hosting the

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Olympic Games and can be used for the majority of regions around the world.

Next, we present the objectives of the strategy and propose four feasible strategies from the government's perspective: selecting permanent venues for sports with high environmental requirements; decentralizing the host region; arranging permanent locations for the Summer and Winter Olympics; hosting four small-scale Olympics. Subsequently, for each strategy, specific recommendations related to economics, environmental protection, and other relevant aspects are proposed, and a plan for the **next 50 years** is formulated with a corresponding timetable (see Figures 10 to 13). In addition, we select four regions, including Beijing and Sydney for analyzing the impact. With strategy implementation, the secondary indicators are obtained based on the quantified impact of policies. Without strategy implementation, the secondary indicators are predicted by the **GM(1,1)** model. The results show that Strategy 3 is most effective when Beijing hosts the Olympics, while Strategy 2 is more applicable to Sydney. Overall, Strategy 2 has stronger universality.

Finally, we evaluate the strengths and weaknesses of the model and extend it. We also analyze the **sensitivity** of parameters: land use, event revenue, and reputation, which shows the validity of the model assumptions. Furthermore, a one-page memorandum for IOC is prepared.

Keywords: Olympic Games, AHP-CRITIC, K-means, GM(1,1)

Rotate the Olympics into a Better Future

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Microelectronics, Physics

Team members: Lequan Wang, Yidi Wang, and Zihan Xie
Advisor: Zhenyu Wang

Facing the situation that fewer and fewer countries are bidding for the Olympic Games, it is of far-reaching significance to establish an effective and sustainable new Olympic system. In support of the work of the ICMG, we propose our recommendation: **Triple Olympic Circles (TOC)**. We address the following three questions: Is our pattern, TOC, better than the current pattern? How to implement TOC? And what benefits will TOC bring?

In Question 1, we establish the **Olympic Pattern Evaluation Model (OPEM)** to assess the costs and benefits to host the Olympic Games. A series of indicators are introduced to quantify multiple aspects of the Olympic Games. Accordingly, we establish 3 **primary indicators**, i.e., domestic pressure, degree of satisfaction, and opportunities for future improvements.

Each of them consists of 3 **secondary indicators**. Then we apply **EWM** and **AHP** to determine their weights. The results show that **TOC scores 1.31 times better than the current pattern**, proving the **feasibility** of our approach.

In Question 2, we use the **TOPSIS algorithm** to rate and select countries to join our TOC. In order to give developing countries equal chances to bid for the Olympics, we separate the current Summer Olympics into Summer (Aug. 10th to Aug. 27th) and Autumn (Oct. 16th to Oct. 30th) Olympics. After comprehensive scoring, Tokyo, Paris, and New York are the top three cities suitable for Summer Olympics, while Jakarta, Sao Paulo, and Peking are for Autumn Olympics.

For the Winter Olympics (Feb. 5th to Feb. 20th), we choose **K-Means and FCM algorithms**, introducing an "**ideal**" city for distance comparison. K-Means clustering sifts 12 candidates from 20 cities, after which the FCM selects Oslo, Stockholm, and Innsbruck as nominees of the Winter Olympic Circle.

In Question 3, we pick Paris to evaluate the **effectiveness** of our system. The **Grey Forecast Model** is applied to predict the GDP of Paris from the year 2023 to 2025, followed by a **Multiple Linear Regression Model** that predicts the GDP growth rate after Paris joins the TOC. The results show that joining the TOC boosts Paris' economy, with a **GDP growth rate of 1.154% higher**.

Finally, based on the models and conclusions above, we add a **timeline** of our proposal and propose a complementary method: the **Olympic Community** policy.

Moreover, the advice to IOC is elaborated in detail in the memorandum.

Keywords: TOC, OPEM model, EWM and AHP, TOPSIS, K-means, and FCM

Reviving Olympic Hosting Interest: A Sustainable Strategy

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Team members: Qiujing Wang, Luyao Li, and Jinyu Zhang
Advisor: Jian Zu

With the aim of analyzing the impact of hosting the Olympics on the hosts and rekindling interest in hosting, we undertake three main tasks: **task 1**, quantitatively analyze the effects on the host city and country of hosting the Olympics; **task 2**, propose and evaluate potential plans for site selection and time scheduling; **task 3**, select the optimal plan and further elucidate its feasibility.

For task 1, we focus on the sustainability of the host country and construct the Olympic sustainability index **(OSI)**. The OSI incorporates 9 second-level indicators from the economic, social, and ecological perspectives and quantifies both short-term impacts such as direct costs and revenues, as well as the long-term viability of venue usage and national prestige measured through media influence. We use a Vector Autoregression time series model **(VAR)** to forecast these indicators' values in the absence of hosting the Olympics. We then employ the Difference-in-Differences model **(DID)**, an effective method for inferring causal effects of hosting the Olympics on various indicators, to estimate the impact. Finally, we give the changes of OSI in the 2012 London Olympic Games.

For task 2, firstly, for each plan, we conduct a preliminary screening of **candidate cities** based on their environmental and socioeconomic conditions, and split the Olympic **events** based on their climate requirements and venue costs. We construct an optimization model with Olympic Game Scale Indicator **(OGSI)** as the decision variable and maximizing OSI and its changes as the objective function. The evaluation scores for each plan are determined using Kernel Ridge Regression **(KRR)** and Analytic Hierarchy Process and Entropy Weight Methods **(AHP-EWM)**. We then utilize the Augmented Lagrangian Method and Alternating Direction Method of Multipliers **(ALM-ADMM)** to solve the model and obtain the optimal OGSI for each plan. Finally, based on the optimal scores of each plan, we determine that **Plan 3, a hybrid method of fixed and rotating venues**, with the highest score of **72.71**, is the optimal plan.

For task 3, we further elaborate on the content and feasibility of the optimal plan. Firstly, we combine the results of the ALM-ADMM model to present the specific timeline and project arrangement of plan 3. The Olympic Games still follow a **four-year cycle**, with the **Winter Olympics fixed in Vancouver or Sochi** in February of the first year, **key events fixed**

in Sydney or Los Angeles in October of the third year, and other **events held in different cities** in August of the second and fourth years. And "Key events" include **marathon, cycling, swimming, tennis, and gymnastics**. Then, we analyze the feasibility of the plan from five perspectives: **economy, ecology, safety and fairness, humanization, and society**. Finally, we use Sydney as one of the locations for the Summer Olympics to implement plan 3, predict the changes in OSI in Sydney and Vancouver, and compare them with the traditional hosting model. We found that the economic pressure on Sydney was significantly **reduced** (with PG and GG scores increasing by **3** and **13**, respectively); and although Vancouver's PG score slightly decreased, its GG score increased by **4**, showing a clear upward trend for the future.

Keywords: Olympics, sustainability, fixed and rotating, DID, KRR, ALM-ADMM

Judges' Commentary: The Future of the Olympics

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Editor's Note

When available, this commentary will be posted at the COMAP website https://www.mcmcontest.com, and the electronic edition of this issue of *The UMAP Journal* will be amended to include the commentary.

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