Judges' Commentary: Migration to Mars

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Introduction

This year's policy problem was a new kind of problem for the ICM in that it required the teams to project into the future (the year 2100) and use their projection as the basis for solving a policy problem about the first large-scale colony on Mars.

There are many issues to consider for such a long-term projection, such as the complex model of the workforce and population and the myriad policies that could benefit and sustain a colony. This complexity resulted in many different kinds of models and policy recommendations in the 800 solution papers for the problem. The ultimate goal for the teams was to write a policy recommendation that explained the reasons for the recommendations and provided an analysis of the expected results. To accomplish this goal, the teams were tasked with building a model that evaluated elements of the colony related to income, education, and equality.

This topic has been in the news recently: After the contest, the data science website `fivethirtyeight.com` ran a series of articles about colonizing Mars [Aschwanden 2017; Boyle 2017; Hickey 2017; Koerth-Baker 2017]. In keeping with the nearly 100-year time-line of the problem, Steven Hawking recently made news with his prediction that humans need to colonize Mars within 100 years (see Fecht [2017] for a description of Hawking's rationale). Further back in time, Robert Zubrin [1996] made a strong case for Mars colonization.

The first wave of the colonization, called Population Zero, was to include 10,000 people with the goal of creating a workforce that would give citizens the greatest quality of life with policies that would provide for sustainabil-

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ity for over 100 years. The teams were challenged to model and recommend policies based on egalitarian principles in economics, government, workforce, and social systems. The mission of Population Zero would be to create a sustainable society by maximizing both economic output and happiness in the workplace for its citizens. Of course, these two goals could be in opposition, so the policy recommendations had to consider balancing factors, such as:

- **Income:** Ensure adequate compensation so that all people can afford fundamental necessities (shelter, food, clothes).
- **Education:** Provide appropriate, high-quality, education that prepares citizens for the needs and challenges of the 22nd century on Mars.
- **Equality:** Improve the retention of women in the workforce.

Some issues that were to be considered by the teams were

- minimum wage and salary distribution,
- skills required for an efficient workforce,
- types of education needed to obtain these skills,
- effective maternity / paternity-leave policies, and
- an affordable childcare system.

The teams were tasked to identify and analyze the demographic characteristics of their simulated Population Zero. Major challenges were to determine the main features of the population (e.g., demographics, occupations) that would contribute to the best outcomes, and to create metrics to evaluate whether the system is meeting its objectives. Many teams generated a sample population of the 10,000 people to emigrate to Mars by extracting data from a real census dataset. Other teams synthesized their selected or tailored population, from attributes that they considered desirable, to achieve special goals. Further tasks involved determining:

- the optimal minimum wage and salary distribution to best manage the tension between well-being (higher quality of life) and support for those less equipped to provide labor services,
- the best childcare and paternity / maternity leave strategies,
- the sensitivity of the model to the population selection for various migration phases, and
- the sustainability of the recruitment and selection processes.

The problem asked teams to modify their model to build a 100-year plan and see if it was substantially different from the 10-year plan. Another scenario tasked the team to investigate a maximum exodus of Earthlings to Mars.

Of course, the authors of the problem do not know if any kind of Mars colonization scenario will ever occur. Nor are they sure that society will develop the capability to successfully carry out such a major undertaking by the year 2100. However, modeling is a tool that enables analysis and policy recommendations for such intricate future plans.

Judges' Criteria

The main thrust of the judging criteria for Problem F was determining each team's performance of foundational modeling and analysis that used good science and led to a viable policy recommendation. The judges looked for analysis of the factors involved with facilitating the workforce operation and social cooperation of the colony. Often, the policy modeling for this problem was qualitative. Getting and using the right data were challenges for some teams. Issues that the judges considered included:

- the quality of the analysis in terms of work conditions and income, education, and social equality;
- the appropriate use of viable data;
- the quality of the explanations and visualizations of their model and framework;
- the fulfillment of the seven assigned tasks, by defining parameters and specific outcomes related to the three priority factors (income, education, and social equality); and
- the quality of metrics for determination or analysis of minimum wage, salary distribution, skills required for an efficient workforce, types of governance and infrastructure needed to obtain these skills, maternity and paternity leave, and an effective childcare system.

Judges looked carefully at how the teams generated the population of 10,000 people that would emigrate to Mars:

- From the data, did teams identify and analyze the demographic characteristics of this population and describe demographic distributions, such as gender, ethnicity, age, and education levels?
- What might be economic, social, cultural, and other global factors that might affect the viability of the model over that period?
- What are the best childcare and paternity/maternity-leave strategies?

Important for the policy recommendations were the policy incentives for future decision makers to consider.

Other factors considered by judges included identifying the major subgroups of the workforce and their associated priorities. The following general modeling elements were also expected by the judges:

- (**sensitivity**) How sensitive is their model to the population selection for various migration phases? Does the demographic distribution of this population significantly change the outcomes? Is this long-term plan substantially different than the 10-year plan?
- (**scalability**) Can the model adjust to move as many people as possible to Mars to live in enlarged manufactured cities? Is their model still functional?
- (**basics**) Does the team discuss assumptions, strengths, weaknesses, and sensitivity of their models?
- (**communication**) Does the team write a policy recommendation that includes the factors of income, education, equality policies based on their model?
- (**interdisciplinarity**) Do the team members discuss basic qualitative and quantitative elements of social science and policy modeling?

Modeling Techniques for the Problem

Many methods were used by teams to interpret, model, and analyze this problem. Myriad underlying theories used by the teams to measure or model factors included

- economic performance (such as GDP),
- education development (distribution of the academic degrees in the population or the availability of schooling),
- happiness (individual emotion or an aggregation for the entire population),
- political and social policies (a mix of democratic, crowdsourcing, and socialistic elements),
- equality and fairness policies (often a Gini coefficient or a demographic distribution plan with Leslie matrices), and
- workforce talent (job classification and distribution).

The mathematical techniques ranged from data simulations to the analytic hierarchy process. Some teams built simple data models and used classic programming solutions, principal component analysis, or regressions. Others built complex models based on relationships (networks), hierarchy of needs, individual trajectories (agent-based), genetic algorithms, or Cobb-Douglas differential equations. Many teams developed specialized measures for elements such as happiness and prosperity. The more practical recommendations focused on short-term survival, so their policies often included:

- recruit an initial population to work hard and do not consider happiness until later generations (the rugged pioneer approach);
- recruit farmers, mechanics, and industrial workers to produce the materials needed for day-to-day survival; and
- recruit a population without children, even though this could result in a chasm population that misses an entire age generation and causes demographic imbalance for a long time.

In any case, whether looking short-term or long-term, the better papers assumed a survival strategy for the colony and based their model format and analysis on their selected strategy.

Discussion of the Outstanding Papers

The best papers focused on the policies for the finances, education, and social equality of the future Mars colony. Doing so required a diverse set of skills including politics, government operations, data science, and data analysis in their modeling. The best teams found or generated pertinent data and included inherent needs on Mars along with human social attributes. The Outstanding teams developed creative and relevant solutions to the complex questions facing modern societies and workforces and built models to handle the specific tasks of the problem.

The four Outstanding papers showed a nice array of modeling techniques and analytic methods from the list above. New tools in network science, systems science, complex systems, data science, and other interdisciplinary fields provided the teams with the capabilities to understand the social and governmental systems needed on Mars. These modeling techniques also provided the capabilities to deal with issues of

- **scalability** (relevant for both small and large populations and effects),
- **modality** (multiple layers and subsets), and
- **dynamics** (changes over time).

Summaries for the four Outstanding team reports follow.

North Carolina School of Mathematics and Science

"To Infinity and Beyond: Agent-Based Modeling of 22nd Century Martian Civilization"[1]

Vilfredo Pareto Award

This paper, written by a team from a high school that annually competes favorably with the colleges and universities in the ICM, focused on the

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

socioeconomic structures and processes needed to establish and sustain a new Mars colony. The objective of the team was to recommend helpful governmental policies to provide for a population of 10,000 on Mars. The team sought to develop an egalitarian civilization that surpassed the current society on Earth. They built a model that evaluated properties associated with the income, education, and equality of the new population of 10,000 Mars citizens.

The team developed an agent-based model that simulated a population of 10,000 people, using U.S. Census data. In their dynamic model, each Martian citizen progresses through life stages with shifting demographics: increasing education, working at productive jobs, having and raising children, earning income, and retiring (see **Figure 1**). Their governmental model was built to protect the citizens from economic harm while calling for child subsidies and minimum wage. The team chose to calculate the community's well-being through economic-related metrics. Their three metrics were an income metric, an education metric, and an equality metric.

Their education metric is based on the amount of unemployment as an economic factor and the student-to-faculty ratio as a social welfare factor, so as to evaluate education through both productivity and well-being. The equality metric compares the proportion of women in occupations on Mars to their proportion in jobs on Earth. The income metric favors higher per capita income values on Mars and punishes a wage gap between the rich and the poor that is either too large or too small. The model includes several economic indicators and properties, such as the inflation rate, progressive tax system, total investment, and government debt.

Using their model, the team found that the most productive initial population had a mean age of 37 with a ratio of 1:10 of innovators to producers and that a minimum wage of $70,000 provided the greatest benefit to society. They determined a maternity-leave length of 10 Earth-months and a paternity-leave length of 3 Earth-months. Their progressive tax system provides for increased education, and infrastructure needs in the future.

This team's report was a pleasure to read. The policy letter for this team was simply the best that the judges read.

Shanghai Jiao Tong University

"Society Planning: Model, Simulation and Visualization"
INFORMS Award

This team's paper presents a model that attempts to maximize economic output and job satisfaction for the workforce while requiring long-term sustainability of the colony. The team ran simulations with their specific selected population together with simulations from random census data to compare outcomes. Based on their model, they proposed strategies to improve the living conditions on Mars. They reported suggestions to the Director of LIFE:

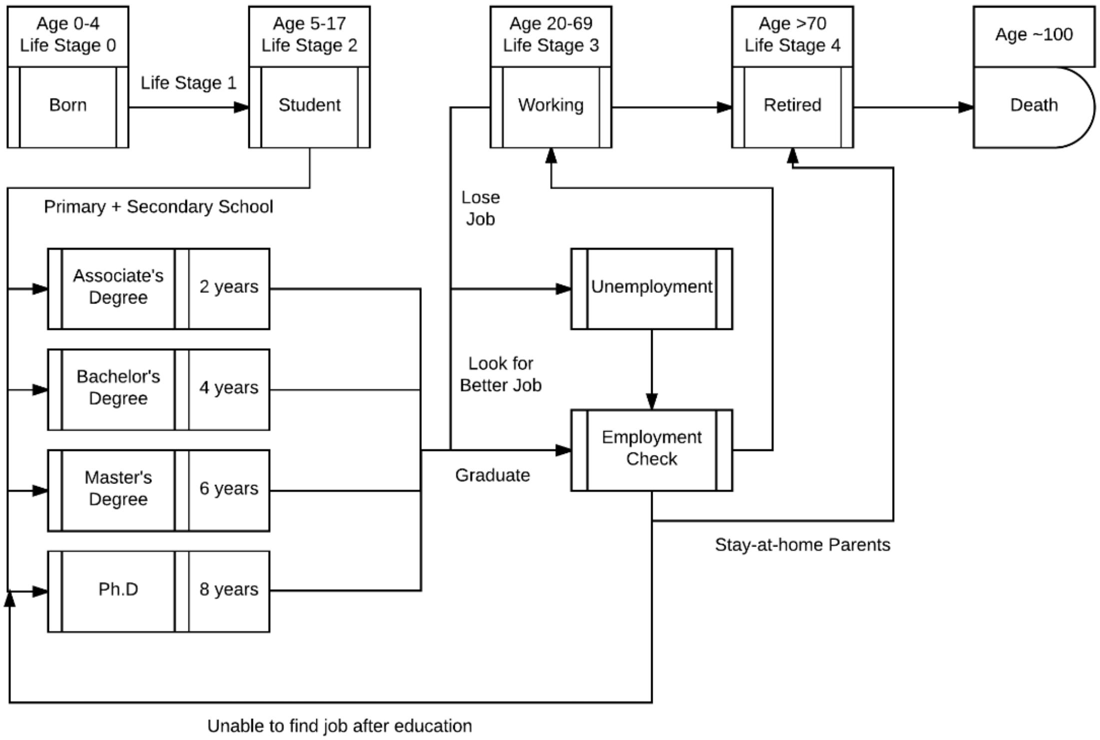

Figure 1. The life-cycle flow model of the team from North Carolina School of Mathematics and Science.

- **Select Educated Immigrants:** In terms of economic development, the team recommends recruiting more young immigrants with bachelor's degrees and high innovation abilities. Their model shows a higher ratio of innovators and that higher average education levels contribute to faster growth of GDP.
- **Maximize Minimum Wage:** Higher minimum wage results in lower standard deviation of income but lower average income.
- **Equalize Family Income:** Lower variance of family income leads to a higher Happiness Index but lower Net Domestic Product. The team balances the two factors and determines the minimum wage at $33,526.
- **Emphasize Education:** The significance of education is amplified by its correlation with economic development. Since a higher education level leads to higher income and better education of the children, emphasis on education creates a positive feedback loop.
- **Increase Parental Leave Pay:** The team recommends parental leave for both fathers and mothers to maintain equality and maximize the birthrate. Encouraging reproduction by implementing high parental leave pay is beneficial to long-term development on Mars.

- **Reduce Discrimination:** Cooperation among individuals contributes to higher economic growth rate.

This team decomposed their methodology into six sub-problems:

- They constructed a framework that integrates variables with the areas of income, education and social equality. They chose attributes from the census database and aggregated as possible to obtain properties such as Annual Family Expenditure, Annual Family Income, Number of Minimum Wage Workers, Personal Savings Rate, Weekly Working Hours, Education Budget, Childcare Budget, Gini Coefficient of Income Equality, and Unemployment Rate.
- They formulated specific criteria to select 10,000 immigrants for Population Zero and compared the demographics of the selected group with random samples. A simplified perspective of the population is shown in **Figure 2**.

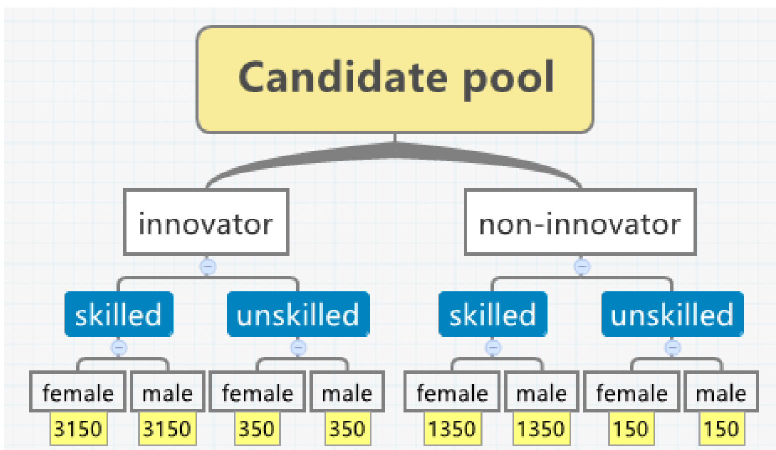

Figure 2. Description of basic demographics of the select population for Population Zero, by the team from Shanghai Jiao Tong University.

- They simulated the evolution of Population Zero from the dynamics of job formation, marriage, having children, education, and salary.
- Their model found the equilibrium point between the two contradictory goals of faster economic development and better social welfare. Through principal component analysis on the demographic data, they determined key elements of a successful society as high average family income, high minimum wage, and low deviation of income.
- They merged their models of income, education, and social equality into a global model. They built a nonlinear programming model to decide the strategy for resources allocation among different subgroups.
- They investigated the effect of new immigrants, using network theory. They represented the interpersonal relationships among individuals in-

cluding Mars residents and new immigrants. They concluded that 10,000 migrants every 10 years is sustainable.

United States Military Academy

"Social Equity and Human Capital in a Decentralized Martian Utopia"

This team set the stage for new opportunities on Mars where there would be equality and sustainment of both income and human well-being. They understood the qualitative and complex nature of the problem and focused on improving societal shortcomings in income equality, taxation fairness, education opportunity, and human rights. They developed a human capital measure where human capital is the level of skills, knowledge, and intelligence possessed by an individual that allows them to make significant contributions beyond the standard worker.

Throughout their model, the team assumed that people accumulate human capital through both work and traditional schooling. Their income model sought to reduce inequality by implementing a Nordic-like model of society. From that effort, they derived a minimum wage of $20,000 as well as progressive tax rates that increased with income up to a cap of 50%. They used a Gini coefficient to measure inequality and improved from .58 to .33, which approaches Nordic levels.

In the education model, the team used a weighted decision matrix, ranking different academic disciplines with how much they contribute towards values and fields of important economic application.

Their social equality model took advantage of opportunity cost analysis to simulate the retention rate of men and women in the workforce based on the cost of childcare and other demographic data. That model led to a childcare-cost model and a policy recommendation for equal lengths of maternity and paternity leave. Most importantly, they merged all their models together to verify that these policies and governmental systems were economically viable.

After establishing their models, they generated a representative sample population to study the long-term dynamics of the demographic composition of the Mars population. Through running their simulation, they discovered that:

- Human capital would initially decrease as Population Zero dies off, but then it would increase in the long run due to benefits initiated through the education system.
- The demographics of Population Zero and subsequent migrants affects the stability of the society, since undesired demographic distributions offset the benefits of the policies and systems.
- The simulation showed oscillations in the age distribution of the population due to the nature of various migrations from Earth to Mars.

As a consequence, the team considered the limitations of their model. They tried to take into account that the colony on Mars would probably exhibit different characteristics from the societies that we know on Earth. Even maintaining a stable equilibrium of the workforce in a small isolated economy would be a challenge. Their policies hoped that the organizers of LIFE could find migrants who were capable of setting aside their Earthly stereotypes and acting in the best long-term interests of preserving the new society. They used a strong social science flavor in their approach and modeling of this future isolated colony on the planet Mars.

Harvard University

"A Brave New World: A Quantitative Model of a Self-Sufficient Martian Society"

The Harvard team created a set of quantitatively-supported models to assess the various attributes and outcomes of Population Zero's colony on Mars. They carefully defined significant metrics and evaluation criteria for the three factors of income, education, and equality.

- They viewed income as economic efficiency and economic equality; and they used GDP, the Gini coefficient, and the minimum salary as this component's major measures.
- Education was evaluated in terms of student-teacher ratio and the contribution of education to the GDP.
- They modeled equality through gender and cultural perspectives, leading them to a metric they called dissimilarity.

Using dimensional analysis, the team analyzed the demographics and factors of Population Zero and determined that about 25% of Population Zero should be farmers. They also determined the best breakdown of other occupations in society, along with an optimal initial distribution of ages. They applied their metrics in the areas of income, education, and equality and developed a comprehensive model for each of these elements. They determined the optimal amount of education for a highly skilled, self-reliant community and established a governmental system with an economy mostly run by the government with salary tiers for workers. They built an economic system with very low income inequality (Gini = 0.034) and a GDP among the top 25% of national GDPs on Earth. Like most teams, this team simulated a population and produced charts and graphs of its demographics. See **Figure 3** for such an example. Dissimilarity-based simulations revealed a tradeoff between income equality and social equality.

The team consolidated their three models into one to assess the trajectories of different subgroups in society as a function of the priority areas. Their methodology applied weights on each critical parameter, such as GDP and dissimilarity, to determine functional system values. By analyzing the

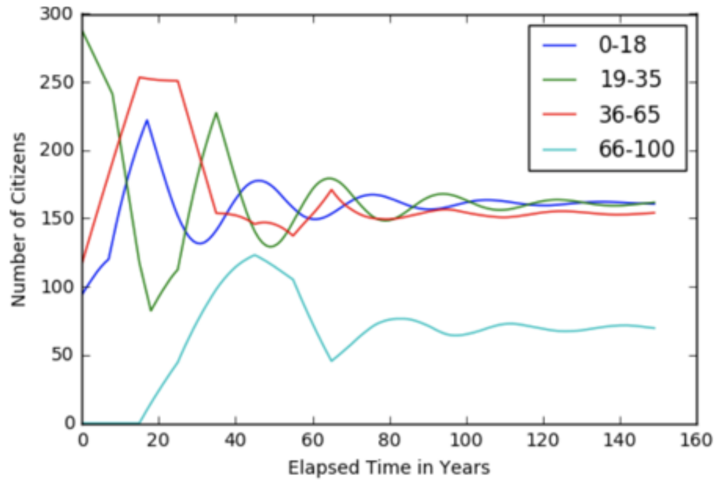

Figure 3. Age distribution demographic from a simulation from the Harvard team's paper.

tradeoff between social equality and income equality, they determined that a small amount of income inequality would be preferable to increases in social inequality. They applied their model to test the possibility of additional migrations to the colony from Earth. They monitored the effects on both age distribution and economic impact to see what kinds of migrations were sustainable. Gradual migration was the preferred form of introduction of migrants into the original colony, and they developed an estimate for the maximum rate of such a gradual, yet sustainable migration to Mars.

Conclusion

This problem presented challenges to teams in the form of understanding the scenario and its tasks, building viable models from very qualitative human-relevant concepts (e.g., happiness), and forming actionable recommendations for systems and policies based on their models. Many teams had innovative and useful ideas for some parts of the problem, but were unable to satisfy all the tasks required in the problem within the time constraints. The four outstanding teams seemed to fulfill those tasks the best and still write logical recommendations for the Population Zero leaders.

The judges see benefit to this kind of ICM problem, since time-constrained policy modeling is a demanding task that is performed by public and private analysts and modelers throughout the world.

The judges congratulate all the teams that selected and worked on this problem and wish those ICM modelers who will become real-life policy modelers well in analyzing issues and making valuable and acceptable recommendations to the decision makers.

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About the Author

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