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Published, sold and distributed by:
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PO Box 1024
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Outside North America:
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The preferred citation for this publication is

C. L. Munson *et al.*. *Predictive Global Sensitivity Analysis: Foundational Concepts, Tools, and Applications*. Foundations and Trends® in Technology, Information and Operations Management, vol. 17, no. 4, pp. 235–339, 2024.

ISBN: 978-1-63828-339-3

Foundations and Trends® in Technology, Information and Operations Management
Volume 17, Issue 4, 2024

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Foundations and Trends® in Technology, Information and Operations Management, 2024, Volume 17, 4 issues. ISSN paper version 1571-9545. ISSN online version 1571-9553. Also available as a combined paper and online subscription.

Contents

Predictive Global Sensitivity Analysis: Foundational Concepts, Tools, and Applications

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ABSTRACT

Modern managers must sift through huge data overload to make quick decisions in dynamic environments. Predictive Global Sensitivity Analysis (PGSA) represents a statistical approach to simplifying a complicated mathematical optimization model into a straightforward set of predictive equations by summarizing numerous complexities into a few highly explanatory variables. Managers can use such equations to make swift decisions with colleagues or customers in real time, or the equations can be used as a monitoring tool to verify current decisions as external conditions change.

In this monograph, the authors review the published applications of PGSA that have emerged over the past two decades. Differences in the published works illustrate the underlying flexible nature of the method. Modelers get to practice significant judgement all throughout the process, from application selection through model validation. Section 3 provides a step-by-step tutorial of the full PGSA process. The authors

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Charles L. Munson, Lan Luo and Xiaohui Huang (2024), “Predictive Global Sensitivity Analysis: Foundational Concepts, Tools, and Applications”, Foundations and Trends® in Technology, Information and Operations Management: Vol. 17, No. 4, pp 235–339.
DOI: 10.1561/0200000113.

describe how each step has been addressed in the literature to date, and they illustrate each step in detail using two new applications of classic problems in operations research. Section 4 introduces a brand-new application of PGSA that predicts which among three centralized purchasing scenarios that a newly introduced product purchased at a local site should adopt.

1

Introduction to Predictive Global Sensitivity Analysis

1.1 A Tool for Quick Decision Making

Operations researchers have developed a plethora of increasingly complicated mathematical models over the years, covering a myriad of topics ranging from logistics to scheduling to inventory control. Many such models provide optimal solutions to the problems at hand; however, they may be onerous to populate and/or time-consuming to solve. They also may lack robust what-if-analysis capabilities. Such models may contain thousands of variables and constraints. While these models work perfectly well given enough time to populate and solve, it may be difficult to answer questions from customers or other managers in real time.

Long before *machine learning* and *AI* entered mainstream conversation, Harvey Wagner introduced the concept of global sensitivity analysis as a way to identify factors that appear to be the main drivers of mathematical models (Wagner, 1995). The idea is to generate one or more equations that can estimate model outputs by inserting a limited number of explanatorily powerful inputs. Charles Munson and colleagues have coined the term "Predictive Global Sensitivity Analysis" (PGSA) as a proactive approach based on Wagner's technique to create real-time tools needed for optimization-challenged managers who may handle Excel well but might have difficulty dealing with sophisticated optimization software. The PGSA approach generates equations that represent a bridge between the underlying mathematical model and the technical capabilities of the practicing management team. At a minimum, such equations can perform instantaneous "back-of-the-envelope" calculations during company meetings or client interactions.

With PGSA, the researcher analyzes a large-scale math program to seek a way to avoid numerous details and extract the most important factors that drive model results. This is accomplished by solving the underlying model many times using a wide variety of input values. The researcher creates a list of potential summary independent variables that he or she believes may have significant explanatory power. Linear regressions are run to identify the most important independent variables. After those are identified, the researcher creates a new regression model that includes interaction terms of the chosen independent variables, e.g., AB, A/B, A^2/B, etc. In other words, the researcher attempts to predict model outputs using linear equations containing nonlinear terms. A final stepwise regression produces the finalized explanatory equation that summarizes the underlying model with a few key independent variables. This is essentially a data mining approach with the goal of creating a practical tool for managers to be able to use in real time.

A major challenge with PGSA is identifying a few key summary independent variables that should be relatively easy for practicing managers to calculate. Validation represents an important step in the process. Not only should the adjusted R^2 from the stepwise regression be high, but the researcher should test the model in some other way to compare the prescribed decisions from PGSA to the prescribed decisions from the underlying math model. As PGSA is an estimation, the match does not have to be perfect, but it needs to be "good enough" to provide practical insight and to avoid catastrophic decisions.

Potential applications include anything using an underlying mathematical model, especially ones with any of the following characteristics:

- Is difficult or time-consuming to solve.
- Addresses a problem requiring constant monitoring.

- Addresses a problem necessitating on-the-spot sensitivity analysis or decision making.
- May be divided into strategic and tactical parts.
- Involves multi-level decisions.
- Accesses large data sets (i.e., makes use of "big data").
- Introduces marginal decisions.

We see *marginal decision making* as a particularly valuable benefit of PSGA. It may help answer such questions as: Would the addition of a new product be profitable? Should we add this new supplier? How would adding this job impact our schedule? What might be the impact of cutting safety stock in half? Should we enter this new market? How would output change if we sold this machine?

Furthermore, PGSA can be used as a monitoring tool, akin to the concept of statistical process control. As external conditions change (e.g., oil prices, inflation rates, the competitive environment, tax rates, or shipping routes), managers can insert new values of key inputs into the PGSA equations to gauge whether current strategies or tactics may need to be altered. Even if the PGSA estimates are not exact, a positive signal would direct the management team to go back and revisit the large-scale optimization model for guidance on precise changes needed.

1.2 Aim and Structure of This Monograph

While the PGSA approach has appeared in the literature to a limited extent, its use is still not widespread or particularly well-known. This monograph provides a detailed tutorial as a guide for both researchers and practitioners to understand how and when to implement PGSA. While the technique involves a fair amount of "number crunching," it also requires a significant subjective cognitive component. The researcher must consider how to define potential summary variables and subsequently use judgement to determine which to keep and which interaction terms to include. If initial results underperform, the researcher must rethink initial approaches and try again. Sometimes, better variables could be defined. Other times, initial equations may have attempted to cover too wide of an input space. In those cases, the researcher may choose to divide the input space into sections and generate separate sets of predictive equations for each. These types of judgement calls add interest and challenge to the technique.

The tutorial section follows two examples through each step of the process. For illustration purposes, we chose both examples to be relatively simple models themselves. Nevertheless, applying PGSA to those models creates some unexpected complications. In the following section, a more realistic application of PGSA to a complicated centralized purchasing model illustrates the full process from beginning to end. We hope that these three examples provide enough detail to be able to be implemented by researchers and managers alike while providing a flavor of the variety and complexity of using PGSA.

The rest of the monograph is organized as follows. Section 2 describes the PGSA applications that appear in the literature. Section 3 represents the "tutorial" section, which describes each step in the process and illustrates how each step is applied to two examples: (1) a safety stock model using the fill rate criterion, and (2) a classic linear programming transportation problem. We also briefly describe how the different published papers address each step. It becomes clear that modelers have a lot of flexibility in deciding how to apply each step to their situation. Different approaches can all produce quality results under the right circumstances. Section 4 presents a full PGSA application for a model used by firms with multiple facilities purchasing many different component parts. The model determines which parts should be purchased locally, which should be purchased centrally, and which should be partially centralized. The PGSA predictive equations do an excellent job at placing parts into the three categories. Section 5 concludes by describing challenges and limitations of PGSA, along with providing several recommendations for future research.

Appendix

A

Spreadsheet Implementation of the Section 3 Models

This appendix provides screenshots to illustrate how to implement the two base models from Section 3 in Microsoft Excel. Appendix A.1 covers the safety stock with fill rate criterion model, and Appendix A.2 covers the transportation problem.

A.1 Excel Implementation of the Safety Stock with Fill Rate Model

Figure A.1 illustrates how to use Microsoft Excel to calculate the safety stock necessary to achieve a desired fill rate, given a lot size Q and standard deviation of lead time demand σ_L.

For modelers who know VBA for Excel, the Goal Seek process can be automated by using the following VBA subroutine. A command button could be linked to run the subroutine when clicked.

```
Public Sub SAFETY()
    Range("A8").GoalSeek Goal: =Range("B8").Value, _
    ChangingCell:=Range("D5")
End Sub
```

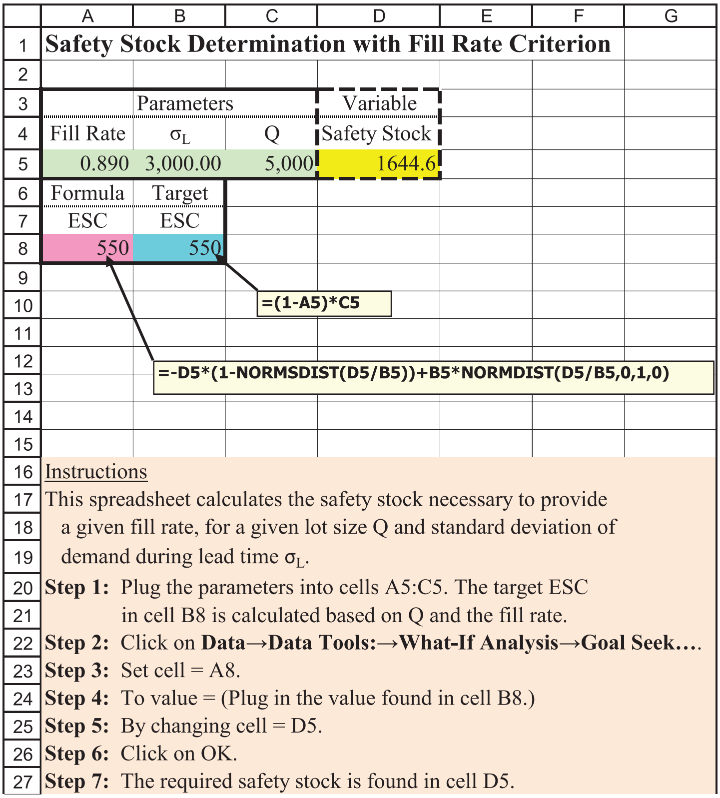

Figure A.1: Excel implementation for determining the safety stock needed to achieve a desired fill rate.

A.2 Excel Implementation of a 3 × 4 Transportation Problem

Figure A.2 illustrates a Microsoft Excel template that can be used to solve a transportation problem with three origins and four destinations.

Figure A.3 shows the completed Solver box for the 3 × 4 transportation problem template. The user simply needs to select **Data→Solver** and click **OK** in the box to find the optimal solution.

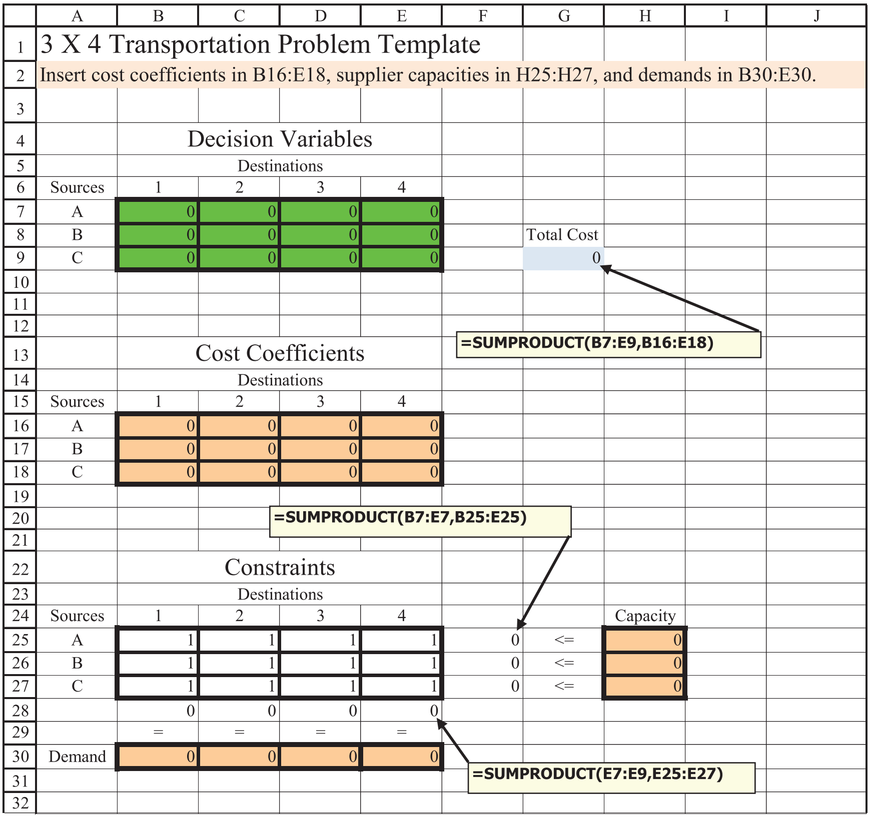

Figure A.2: Excel template for a 3×4 transportation problem

For modelers who know VBA for Excel, the Solver process can be automated by first setting a reference to the Solver add-in within Visual Basic:

Tools→References (and check "Solver")

The simple code is contained in the following VBA subroutine. A command button could be linked to run the subroutine when clicked.

```
Public Sub Solutions()
    SolverSolve
End Sub
```

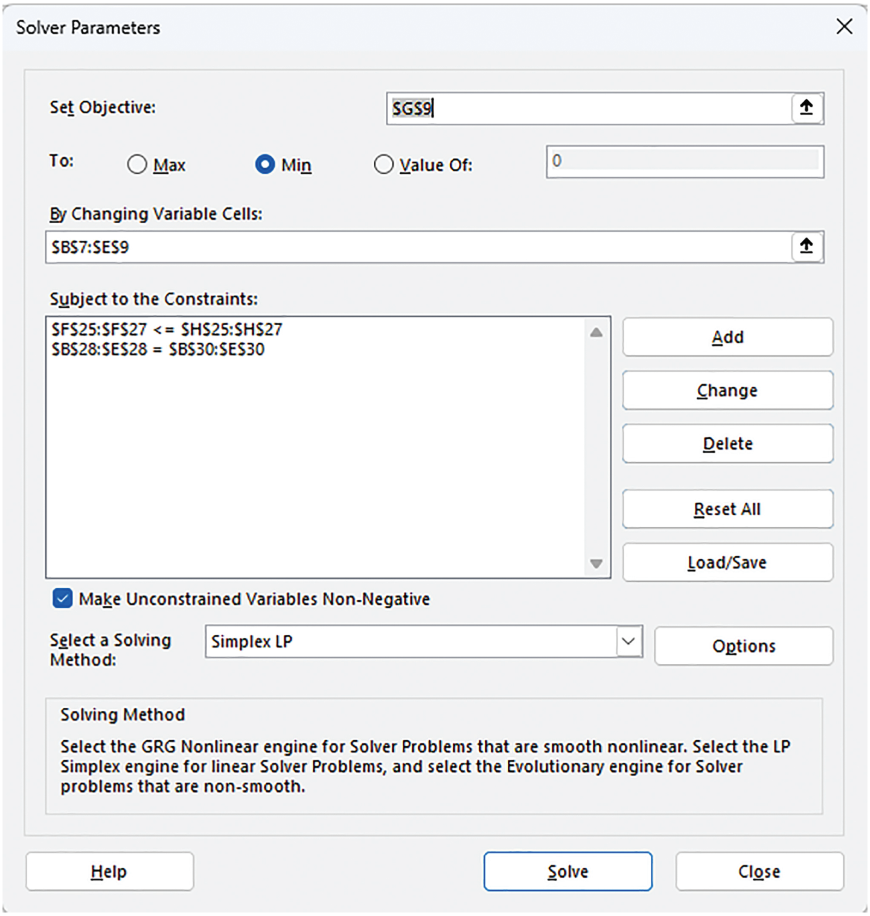

Figure A.3: Completed Solver Box for the 3×4 transportation problem template

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