STRUCTURAL CHANGES IN NORTH AMERICAN FERTILIZER LOGISTICS

A Dissertation
Submitted to the Graduate Faculty
of the
North Dakota State University
of Agriculture and Applied Science

By

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In Partial Fulfillment
for the Degree of
DOCTOR OF PHILOSOPHY

Major Program:
Transportation and Logistics

June 2014

Fargo, North Dakota

North Dakota State University
Graduate School

Title

Structural Changes in North American Fertilizer Logistics

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The Supervisory Committee certifies that this ***disquisition*** complies with North Dakota State University's regulations and meets the accepted standards for the degree of

DOCTOR OF PHILOSOPHY

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ABSTRACT

Nitrogen-based fertilizer industry in United States is undergoing major structural changes, the demand for which is primarily driven by agriculture. Traditionally, this industry sources anhydrous ammonia through imports from Canada and U.S.-Gulf, the latter comprises bulk of imports. The anhydrous ammonia produced domestically or imported is consumed as is or converted into urea, UAN or other variations of nitrogen-based fertilizer in combination with other minerals.

Changes in composition of crops mix and increasing acreage of fertilizer intensive crops have led to an increased demand for nitrogen-based fertilizer in order to promote foliar growth; as a standalone form, for example urea, or in combination, for example Di-ammonium phosphate (DAP). Contributing to change in industry is reduction in prices of natural-gas, in part due to oil exploration, making it cheaper to produce anhydrous ammonia domestically. Anhydrous ammonia is perquisite for making other types of nitrogen-based fertilizer and the process is highly energy-intensive. Lower natural-gas prices provide incentive for domestic firms to either expand existing fertilizer plants or construct new. Recent expansion or construction plans by companies/firms increases competitive pressure on an industry that already has surplus capacity, highly competitive production costs, and technology. Natural-gas prices are volatile; therefore, any commitment to expand or open new plant is subject to volatility in demand, natural-gas prices, and imported price of fertilizers.

The purpose of this dissertation is to analyze spatial competition among U.S. nitrogen-based fertilizer plants and their respective market boundaries. This dissertation also derives the structure of the supply chain for nitrogen-based fertilizer in the United States (at macro level); and the stochastic spatial-optimization model to account for risk in random variables. Locational information is used to account for spatial nature of problem, and linear and mixed-integer based optimization techniques are applied to arrive at current and most likely future cases.

Combination of linear optimization, and mixed-integer, and geographical information systems helps in determining regional areas where competition is expected to be ruinous and most intense; and provide insights on viability of newly announced fertilizer plants that are most likely to be successful and significantly impact the structure of overall supply chain.

ACKNOWLEDGEMENTS

Special appreciation is due to several individuals who contributed to the successful completion of this dissertation. Dr. William W. Wilson provided valuable guidance and advice as my major academic adviser. I will always be indebted to his timely motivation and encouragement; his constant push to experiment, and his priority-driven, yet patient, approach to multitasking. My sincerest gratitude goes to Dr. Denver Tolliver for serving as a co-adviser; as the director of the program, he was instrumental in providing an excellent atmosphere at Upper Great Plains Transportation Institute (UGPTI) during my time pursuing the Ph.D. program. The UGPTI experience helped me tremendously not only with research assistantships, but also with full-time internship. I feel honored to be part of the research projects with which the UGPTI has been involved and will forever be thankful for the financial support and professional growth that the institution provided. I would also like to thank Dr. Saleem Shaik, a committee member, for his unfaltering support in solving a problem such that it is statistically correct. Dr. Shaik's "Analytical Methods and Applied Econometrics" class ignited my curiosity with statistical coding; his sense of humor and calming approach helped me enormously during my lows. I would also like to thank Dr. Joseph Szmerekovsky, whose timely suggestions, tips and guidance helped me gain irreplaceable professional opportunities; I will forever be in debt to him.

My special thanks go to Bruce Dahl for his practical, valuable insights about programming and for sharing interesting experiences related to the software's updated versions. Special thanks go to Dr. Robert Herren, then interim chair for the Department of Agribusiness and Applied Economics, for providing me with the opportunity to teach a large class during my Ph.D. program; it was an invaluable experience. I would like to thank Jody Bohn at UGPTI for the incredible support. Numerous thanks go to Mitchel Hoffart for helping me with the computer crisis as well as all the UGPTI staff members and my colleagues in the Transportation and Logistics program for making the program a memorable one. I am also thankful to Shelly Swandal, Joan Peterson, Norma Eckerson, Eddie Nelson and Judy Moe, from the Department of Agribusiness and Applied Economics for their countless favors and kind words to me.

I am deeply indebted to my parents for their unconditional love and support towards me. Special thanks go to my brother Subodh Shakya, who provided me with personal, professional and emotional support all the time. My journey would be incomplete without thanks to my special friends who have cherished my silly moments and encouraged me with their lighthearted comments about the most serious troubles of day-to-day life. A well deserving thanks to Lee Thomas, and his family, for treating me as member of their family.

DEDICATION

I dedicate this dissertation to my father Dr. S. K. Shakya, a retired professor and national award winner, who inspires me to be the best in my field and to strive for a national award like him; my mother, Mrs. S. M. Shakya, a retired government teacher, who always knows that things will turn out just fine; and my elder brother Subodh Shakya, who is the most brilliant, perfectionist, hardworking person I have ever known. I look forward to him as a role model, and be as smart as him. I would also like to dedicate this dissertation to my sister-in-law, Vasudha Shakya, for her charming support as well as my niece, Niru Shakya, and nephew, Shrinand Shakya, for brightening my day with their giggles and smiles. I thank Niru and Shrinand for being the stars of my life. My deepest thanks go to Kailash Yadav for his continuous love and support.

Thank you, from the bottom of my heart.

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1. INTRODUCTION

Major changes are evolving in the United States' fertilizer sector. Traditionally, this industry provided a product to meet the demands from both, the domestic production and the imports from Canada, as well as a multitude of sources, primarily through the U.S. Gulf. There are at least a couple of major factors that are creating changes. One is the change in the composition of crops within the United States, as well as the more robust commodity market, the effect of which is an increase in the demand for fertilizer. The second one is the dramatic reduction in natural-gas prices, a primary input for fertilizer manufacturing. This change is spatially heterogeneous across regions and has a distinct impact of creating spatial advantages for plants located in lower-cost natural-gas states. The third factor is competitive pressures. A number of new entrants are looking to enter and expand in this sector. Traditionally, the industry was dominated by a few major firms which will have to confront a number of new entrants in the future. The combined impact of these exogenous factors is that there are numerous proposed plants looking to expand or enter this sector. Indeed, as noted below, there are at least 12 to 15 plants being proposed for the United States, each at costs of about $1.5 billion or more. If all the reports are to be believed, this number is claimed to be 25, which is unlikely without credible confirmation; in the absence of which, 13 new plants are considered in this dissertation. This industry has a number of important structural characteristics that impact competition and conduct. Specifically, domestic manufacturers have to compete with imports; demand is volatile; and firm-processing functions have high fixed and low marginal costs. The combination of these factors, ultimately, means that, if and as excess capacity emerges, the industry would likely evolve toward ruinous competition.

The purpose of this study is to analyze spatial competition among nitrogen-based fertilizer plants and their respective market boundaries in the United States. This study also derives the structure of the supply chain for nitrogen-based fertilizer in the United States and a stochastic spatial optimization model to account for risk in random variables.

1.1. Industry Background

Fertilizer is one of the important inputs that impact crop productivity. Over time, fertilizer use has risen substantially, increasing from 2 t/sq km in 1961 to 11 t/sq km in 2010 (Parker, 2011). The United States is one of the major users of nitrogen-based fertilizer and growth in other countries is accelerating. Fertilizer demand varies across crops and regionally. The most nitrogen-fertilizer intensive crops are corn, potatoes, and rice, with moderate use in sorghum, canola, wheat, cotton, and barley, while crops such as peanuts and soybeans use substantially less or no added nitrogen fertilizer. Thus, changes in the crop composition have an important impact on demand. Indeed, expanded corn production in the northern plains is a major source of new demand for this input.

Fertilizer use varies geographically and has important implications for spatial competition. For example, recent fertilizer use for corn varied from 87 lbs/a in Pennsylvania to 178 lbs/a in Indiana. Hard red spring wheat application varied from 54 lbs/a in Montana to 115 lbs/a in Minnesota (ERS, 2013; USDA-ERS, 2013b). Fertilizer use by type also varies substantially across states (AAPFCO Publications & Programs, 2013; The Fertilizer Institute, 2013). There are three primary types of nitrogen: anhydrous ammonia (Anhy), urea (urea), and UAN (UAN).[1] There are substantial differences in demand for each type across states. Some states make extensive use of urea (e.g., New Jersey, Maine, Connecticut, Arkansas, Montana,

[1] In addition, other sources of nutrients include phosphorus, potassium, and micronutrients. None of these sources are included in this study.

Massachusetts, Minnesota, North Dakota, Oregon, South Dakota, Utah, and Vermont); some states use more UAN (e.g., Delaware, Arizona, Alabama, Florida, Georgia, Hawaii, Louisiana, Maryland, Michigan, Mississippi, Nebraska, Nevada, New Mexico, New York, North Carolina, Ohio, South Carolina, Texas, Virginia, Washington, and Wisconsin); and others make more predominate use of anhydrous (Wyoming, North Dakota, Illinois, Iowa, and Missouri). These data (comparing 2006 and 2007, and 2011) do not suggest that fertilizer use by type changes between years, although variations in future cropping patterns and production practices may induce changes.

Traditionally, this industry has been dominated by a few large firms, and processing was largely done in Oklahoma, Louisiana, Texas, and a few plants scattered throughout the Midwest. In addition, the industry imported significant amounts of fertilizer to meet its needs, with nitrogen fertilizer imports in the area of 57% of the consumption. U.S. Gulf imports are in the area of 13 million U.S. tons, mostly in the form of urea and anhydrous ammonia primarily through Louisiana and Texas. A large amount of urea is imported through Galveston. The dominant origins for these imports were Trinidad/Tobago, Russia, and Venezuela for ammonia; Oman, Saudi Arabia, Kuwait, Egypt, Qatar, Bahrain, and Russia for urea; and Trinidad/Tobago, Estonia, Russia, Lithuania, and Egypt for UAN. These shipments are then distributed predominantly by rail and barge throughout the United States. Indeed, shipments from the U.S. Gulf ports to the upper Midwest are some of the dominant flows for this sector. Imports are also made from Canada. Urea is the largest volume type, and import peaked at 1.9 mmt in 2010/11; it has since declined.

Imports and domestic prices are extremely volatile, impacting domestic-plant utilization. Urea prices at the U.S. Gulf have ranged from $100-200/U.S. ton in the early 2000s to a peak of over $800 in 2008 and nearly that level again in 2012; since then, prices have declined to the $300 level. Since 2007, there have been few instances where the U.S. Gulf is less than $300, and the average from 2010 to the present has been $413/U.S. ton. It is important that, in contrast to price relationships within the United States, import prices seem to have little relationship to U.S. or international natural-gas prices. Also, the correlation between prices at the U.S. Gulf and those at export origins (e.g., Trinidad, Russian Black Sea ports, etc.) is very low.

Fertilizer manufacturing has tremendous economies of scale. Fixed costs are high, and marginal costs low, and marginal costs declines with increase in output. The dominant input cost is natural gas which comprises 50% or more of the manufacturing costs. Thus, access to low-cost natural gas provides an important competitive advantage. Indeed, competitive advantage is partly the escalation in U.S. domestic oil output that results in increased spatial heterogeneity for natural-gas prices. Prices are lower in states such as Louisiana, Texas, Oklahoma, and North Dakota. The impacts of low priced natural gas on U.S. production may potentially adverse effect on the exports from Trinidad (SuperUser, 2013). Indeed, a recent article providing an explanation for fertilizer-plant location decisions indicated:

Those price declines have been seen across the board, even though the average commercial price still varies among states. The cost of 1,000 cubic feet of natural gas in Arizona, for instance, was $10.49 in 2007 and was down to $6.36 in 2012. Likewise, Texans paid an average of $6.76 in 2007 and last year paid $3.05. The nationwide industrial average for 1,000 cubic feet of natural gas in 2007 was $7.68 and by 2012 fell to $3.87 (Wiser, 2013).

Finally, the breadth and scope of the new entrants in this industry are important. Since 2011, there have been many announcements about new plants. In total, about 25 new plants have been proposed throughout the United States; each one proposed production in the area of 1.1 to

3.7 million tons/year and costing $1.5 billion or more. Some announcements to open new plants have reportedly been put on hold. Characteristics of the new entrants are important.[2] Some companies are incumbents that are expanding (CF Industries, Agrium, and Koch);[3] some are established cooperatives (e.g., CHS), or, newly formed cooperatives (e.g., Northern Plains Nitrogen); some are regional energy firms (Dakota Gasification or Mississippi Power); and some are off-shore firms expanding into the U.S. market (e.g., Eurochem). Aside from the structural changes giving rise to opportunities for new plants, each has differing goals. Incumbents would seek to expand and pre-empt new entrants. The cooperatives, no doubt, view this as a means to better serve their grower customers in a more vertically integrated system. Energy companies are looking to use their outputs. Off-shore entrants are looking for opportunity, and several are looking for exports, potentially to China.

1.2. Problem Statement

In an industry that has that has a high fixed cost, as well as low and declining marginal cost with increasing output, there is increased competition with the announcement about expanding existing fertilizer plants or opening completely new plants. Natural-gas prices comprise more than 50% of the input cost for nitrogen-based fertilizer production, with availability and volatility in the natural-gas price being a big factor affecting expansion/new plants. This decision to expand or to construct is despite the fact that there is already surplus capacity in the industry and that most fertilizer plants are under-utilized because of competition

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[2] Report titled “Overview of Key Markets” (Greenmarkets, 2013) provides a current indicator of each proposed plant’s status.

[3] See “The New Koch” (Leonard, 2014) for a recent description of Koch in the fertilizer industry and Kelleher (Kelleher, 2013) for a similar interpretation of the industry evolution by CF Industries.

with cheaper import prices from the U.S.-Gulf (USG) and Canada. High production costs are subject to the price of natural gas, the electricity cost (varies by state) economies of scale (operational costs), and surplus capacity in the industry overall with fertilizer plants built at different time periods with various technological advantages. On the demand side, there is uncertainty of not only change in existing crop-acreage patterns, but also change in the crop planted with respect to geography, thereby leading to different quantities of demand per county for various types of nitrogen fertilizer.

New entrants to the industry are confident about gaining from technological advantages coupled with recent reductions in the price of natural gas. Natural-gas prices have fallen drastically with a surge in oil production from states such as Texas and western part of North Dakota, the two largest oil-producing regions in the United States. The main problem is to analyze how viable the recently announced expansion plans or new fertilizer plants are, and if it would make the United States a potential net exporter of nitrogen-based fertilizers. In order to determine the viability of new plants, it is necessary to take into account the randomness and volatility factor of inputs such as natural-gas prices and import prices at the USG in addition to changes in demand by quantity and type. It is also important to know how the existing fertilizer plants change their output (utilization rate) under stochastic optimization, which is imperative to address price volatility for domestic natural gas and fertilizer at import points (price of imported fertilizer as quoted for delivery at the U.S.-Gulf region). Plant-utilization rate changes will indicate how things are likely to change in the future. Given the regional effect of plant expansion at the county or state level, it is necessary to build a model that reflects spatial price competition among fertilizer plants. Because only the locations of production and consumption points are known with some certainty, parameters such as the distance traversed by fertilizer from the origin to destination should be considered. Other intermediate nodes, such as fertilizer warehouse or distribution centers, may be ignored because they are subject to the forces of supply and demand.

The elements of the problem described above are important to participants throughout the industry as well as for a better understanding of the overall market conditions and competition in this sector; by governmental agencies and academia. Growth in the demand for new fertilizer capacity is both a challenge and opportunity for investors and promoters of industry expansion. Dynamic changes with the elements impacting fertilizer demand and competition are important. However, they are highly uncertain, notably in terms of demand, import competition, and natural-gas prices. Each of these factors are not only uncertain, but also has important impacts on spatial competition. Hence, for developers of expanded capacity, having a better understanding about how these uncertainties impact the viability of new plants is important. Such knowledge is crucial for shipping industry (railroads, barges, and distributors). Finally, an enhanced grasp of future competitive behavior is important for inter-firm and spatial competition. Fertilizer use directly impacts agriculture and the food industry, thereby directly affecting the economy. Growing surplus capacity worldwide has the potential to change the viability of both old and new plants. Traffic patterns and the general supply chain structure are likely to change geographically, warranting policy and regulation changes. These adjustments can help make new plants competitive with the local and global supply chain of nitrogen-based fertilizer.

1.3. Objective

A spatial-competition model is developed that represents the current structure of the nitrogen-based fertilizer industry in the United States. The purpose of this dissertation is to analyze spatial competition among U.S. nitrogen-based fertilizer plants and their respective market boundaries. This dissertation also derives the structure of the supply chain for nitrogen-based fertilizer in the United States and the stochastic spatial-optimization model to account for risk in random variables. Specific objectives for the model include that it should account for risk associated with stochastic random variables to best address the expected changes in the fertilizer industry (for example, volatility in the price of natural gas). Such a spatial model for fertilizer should account for following conditions:

1. The spatial and geographical location-related nature of problem elements, especially the location of fertilizer plants, the demand points, and the proximity between them.
2. Fertilizer plants' market boundaries to analyze the impacts of current and potential fertilizer plants in a geographic region.
3. Risk associated with the stochastic nature of random variables, including demand at the county level, international prices for importing fertilizer, and the price of natural gas, to best address uncertainties in the future state of the fertilizer industry.
4. Flexibility to analyze the feasibility or viability of recently announced expansion for current U.S. fertilizer plants or construction of new plants.

Addressing the uncertainty associated with the future state of the fertilizer industry also requires the ability to derive changes in market boundaries when the model is subjected to stochastic spatial optimization and to derive distribution of production for each fertilizer plant. Stochastic spatial optimization is critical because, in its absence, a static spatial-competition model cannot account for the uncertain, random nature of variables such as natural-gas prices as well as the international prices of importing Anhy, urea, and UAN.

Last, it is important to know if the new plants will, indeed, be used in the most likely future state of the fertilizer industry: how much of the plant-production capacity is expected to be utilized? The utilization rates for current state of the industry are also warranted so that the utilization of the current and future industry can be compared. Utilization rates for production at fertilizer plants should also give readers a better idea about the industry's total surplus capacity and if a possibility exists to export nitrogen-based fertilizer from the United States.

The nature of the nitrogen-based fertilizer industry requires that the model should ensure there is a way to convert anhydrous ammonia to either urea or UAN. Fertilizer plants can produce anhydrous ammonia and ship it out as is, or they can convert the anhydrous ammonia produced into urea or UAN, if warranted (and if plants have the capacity), at an additional cost for conversion. The conversion ability significantly differentiates this model from traditional, multi-commodity flow spatial models and is an important addition to a normal cost-minimization model that allows the flexibility to meet all demand types at the county level without getting an infeasibility condition. Therefore, it is the cumulative quantities of anhydrous ammonia, urea, and UAN on production side that matters when balancing the total supply and demand constraints, whereas the individual type of demand has to be met at the county level.

1.4. Approach to Solving the Problem

The current scenario (Section 4.4.1) for the 2012 year is a static linear-optimization model that allocates flows of fertilizer from production to origin via transshipment points (if applicable) along the supply chains such that the total distribution cost in a model network is minimized. Production costs are known with certainty and treated as discrete values, along with the capacity at each node (plant) by type (Anhy, urea, or UAN). Demand, by type, is also known at the county level. During optimization, least-cost flows are distributed among the supply and demand nodes, while taking care of conservation of flows, supply and demand constraints, additional constraints to address specific limits of conversion, and capacity constraints, such as maximum import by type, by location, etc.

In practice, a static, linear, optimized model may best represent the current structure of the fertilizer industry under the assumptions made in this dissertation. However, such assumptions would be limited to address the volatility and randomness of the input variables if only discrete known values are considered. Stochastic spatial optimization is, therefore, used to address the randomness for input variables such as the volatility of natural-gas prices, thereby affecting the fertilizer plant's cost of production. Two approaches for implementing the stochastic nature of variables are used: linear and mixed integer. A linear, spatial, stochastic model helps address the randomness of input variables based on the historic fit of distribution for, say, fertilizer import prices at USG. Linear stochastic optimization allows all plants to work if and when required to meet the demand. There is no lower limit for plants to work, the fertilizer plant can work anywhere between zero and its production capacity. There is no minimum operating constraint for current and new plants either. In the mixed-integer model, selected plants that are the most important from an industry expert's point of view are allowed to have a binary variable for decisions. In this case, a binary variable is introduced as a decision variable to decide if the plant should be built or not, and if it is built, then it has to operate in excess of 70 percent of production capacity.

Transportation-network or spatial optimization involves the distances between nodes. In this dissertation, network distances are derived for road, railroad, and barge as reported by public agencies (U.S. Department of Transportation, 2013). Geographical information systems (GIS) are used to determine the distance between origin and destination nodes. The distance can then be used to better determine the counties (demand nodes) that fall within the market boundary of a production (fertilizer plant) node. Fertilizer can travel via different modes, thus different origination-destination matrices, by mode, are calculated along with the corresponding distances for any “origination–destination” (OD) pair. Each OD pair uniquely identifies an origin identification number and a destination identification number. The OD pair has a distance for each type of mode that may exist. The OD pair is further classified as the type of fertilizer carried (for example, anhydrous ammonia [Anhy], Urea [urea], or ammonium solutions such as UAN [UAN]). The transportation modes considered are railroad (Rail), truck (Truck), pipeline (Pipe), and barge (Barge).

The analytical framework developed in this study is a spatial-network flow model for the U.S. fertilizer industry. The model is calibrated and used to analyze production, imports, and fertilizer flows from origins to destinations. Primary activities include producing nitrogen fertilizer at existing and proposed plants, importing fertilizer, and shipping from origins to demand. Costs are derived for each activity. Fertilizer plants are represented by point locations corresponding to actual geographic locations (if address was known) to the level of zipcode or county (locations for proposed new plants). Imports are through the U.S. Gulf (Louisiana and Texas) and from Canada. Demand is modeled at the county level. Each activity is modeled for the three types of nitrogen fertilizer: anhydrous ammonia, urea, and UAN.

Demand is determined at the county level for each crop and is then aggregated by type of fertilizer. The model includes production at 29 existing plants, and 11 proposed plants or plant expansions. Each fertilizer plant produces different types of fertilizer and has capacity restrictions. Imports from Canada are modeled similar to U.S. production. Fertilizer imports, by type, at the U.S. Gulf are based on import prices and shipping costs to destinations.

The model is calibrated and solved for the base-case period which is 2010-2012. Projections are made to the year 2018 for the important exogenous variables. These values are used in the model to derive the stochastic spatial equilibrium for 2018. Comparisons are then made to outputs of interest between the base case and projection period. The variables of particular interest are demand; production of fertilizer, by type, at each plant; imports; and shipments, by model, from origins to destinations.

1.5. Dissertation Organization

The dissertation is organized as follows. Chapter 2 provides background and industry-related information. This chapter provides a "LITERATURE REVIEW" about the techniques of geographical information systems, transportation, and spatial competition: three major, broad areas that this dissertation utilized.

Chapter 3 presents the theoretical concepts and models required to understand the model established in this dissertation and to understand the approach taken to addressing the problems in the model. Chapter 4 establishes the mathematical explanation of the model used to address the problem and the major input parameters. Some methodological concepts are also discussed. The empirical model is discussed in Section 4.4.1 (Base Case Current), which best represents the current scenario that illustrates the structure of the nitrogen-based fertilizer industry. In section 4.4.2, a linear, stochastic, spatial, optimized model is presented for the 2018 year when most of the currently announced fertilizer plants are expected to reach completion and start production; randomness in demand, natural-gas prices, and import prices at the USG are addressed in this scenario. Mixed-integer optimization for 2018 is presented in Section 4.4.3. Mixed-integer case, wherein the plant either works or not, and if it works, then it works at least 70 percent of its production capacity. There is not a lower limit of production for linear optimization. Last, the sensitivity for linear and mixed optimization of the future case for 2018 is presented.

A description of each scenario and its model specification is discussed in Sections 4.3 and 4.4; the results are presented in the corresponding sections of Chapter 5. Due to the data-intensive nature of model and, subsequently, the results, most graphical results are presented in the appendix to maintain continuity for readers. “Appendix A” provides most of the tables and figures related to the inputs that are used in the model. “Appendix B” has results and graphs for static base case scenario for 2012. “Stochastic Linear Future Case 2018” has results for the stochastic linear future case for 2018; “Stochastic Mixed-Integer Future Case 2018” has results for the stochastic, mixed-integer future case for 2018; “Stochastic Linear Future Case 2018 Sensitivity” has results for the sensitivity of a future linear case for 2018; and “Stochastic Mixed-Integer Future Case 2018 Sensitivity” has results for the sensitivity of a future mixed-integer case for 2018. All the results are categorized into the respective scenarios as mentioned. Last, all the cumulative distribution functions across scenarios are presented in the “Summary Results Across Scenarios.”

2. LITERATURE REVIEW

2.1. Overview

Ammonia production capacity is expected to increase not only in United States but also in East Asia and Africa (Heffer & Prud'homme, 2014). Global ammonia capacity is expected to grow 16 percent over 2013. Major additions are expected in East Asia (China, Indonesia), Africa (Algeria, Egypt, Nigeria), West Asia (Saudi Arabia, Iran, Bahrain), and Latin America (Venezuela, Brazil). Moderate growth in seaborne ammonia supply is expected in year 2018, an increase of 3-4 percent over that in year 2013 to reach 19 million metric tons (Mt). In addition to increasing demand from agriculture, industrial demand is expected to steadily increase in East Asia and Latin America. Global industrial demand is expected to grow by 30 percent between year 2013 and year 2018, with 7.4 percent in fertilizer sector alone. Around the world, about 60 new urea plants are planned to start operating between year 2014 and 2018, with 25 being in China alone. This dissertation considers 12 new fertilizer plants (expansion of existing plants or new plants) planned to operational by year 2018 in United States. North America is expected to contribute 13 percent to net increase global urea capacity while 36 percent from East Asia. East Asia, South Asia, and Latin America together account for 80 percent of growth in global demand between years 2014 and 2018. Major part of demand from East Asia is from industrial sector.

This chapter describes studies as related to fertilizer industry and spatial equilibrium model. In today's world of transportation and commodity trading, price volatility of commodity in majority is affected by cost of transportation. Cost of transportation from place A to place B is determined by not only cost of fuel, but also by economics of competing modes of transportation available in region. For example, if place A happens to be close to river, grain can be transported to place B downstream, either by truck or by barge over short to medium distance.

It may be more economical to transport same or more quantity of grain over larger distance by train and barge but not by truck. This extent of transportation within economic and profitable extent of distance changes with change in transportation costs. Changes in transportation costs, changes the destination of commodity transport as well as “market boundary”. Such changes in market boundary are not static, but rather dynamic. Since a change in fuel cost is stochastic, so is the transportation cost. The stochastic nature of transportation costs causes the market boundaries to be random in nature. Although, the commodity markets are integrated, they are traded at different prices with higher price differentials, yet volatile and correlated.

2.2. Fertilizer

There have been a number of recent industry studies that provide perspective on these emerging changes.[4] Prud’homme (Prud’homme, 2005) discusses trends and outlooks for nitrogen fertilizer production, use and trade. He notes recent increases in ammonia and urea production capacity and groups urea producers into three categories 1) producers serving maturing domestic markets (accounting for 28% of supply), 2) Export oriented producers (16% of supply), and 3) emerging producers catering to domestic markets (56% of supply). Prud’homme indicates that the export producers and emerging producers are likely to be able to expand capacity, with export producers taking advantage of large cost-competitive reserves of natural-gas.

Yara handbooks (Yara, 2010, 2012) provides a fairly detailed description of the underlying demand, pricing and costs for nitrogen fertilizer. Debertin (2012) and Lamp (2013) explained the logic of the proposed plant to be built by CHS. A recent presentation by CF

[4] In addition to these, there are many non-public industry studies on pricing (e.g. Greenmarket (Greenmarkets, 2013), International Fertilizer Industry Association (IFA)) (Heffer & Prud’homme, 2014) and industry developments. However, these are typically only available with subscriptions and as such are note reviewed here.

Industries outlook (Kelleher, 2013) indicated returns to their new plants ranged from 14-20% depending on natural-gas and urea prices. The World Bank (Baffes & Ćosić, 2013, p. 12)pointed to the easing of world fertilizer prices in part due to the expansion of production in regions with lower natural-gas prices.

There have been a few studies on the fertilizer industry and logistics and even fewer academic or public studies. Huang (2007) analyzed the impacts of rising natural-gas prices (at that time) on fertilizer price and described the structure of the industry and geography of production. Casavant et al., (2010) reviews the fertilizer industry and the importance of transportation. While the focus of the study is on rural agricultural transportation issues, a segment reviews issues relevant to fertilizer transportation. They indicate three issues facing the U.S. fertilizer industry, 1) volatility of U.S. fertilizer prices, 2) transportation policies and procedures and 3) long-term increases in fertilizer use.

Zilberman et al (2013) analyzed the future demand for food and point to the need for increased fertilizer requirements. For varying reasons it is important to have a better understanding of the factors influencing future fertilizer nutrient requirements and availability. Rosas, (2011) developed model of world fertilizer demand, tied into the world FAPRI projections model. Olson, Rahm and Swanson (2010) examined factors affecting plant input supply industries. They indicate that for the fertilizer industry, important market forces include effect of high fixed-costs, market segmentation, the presence of low cost natural-gas supplies, etc. Key producers and exporters of nitrogen have low cost natural-gas such as the Mideast, Russia and Caribbean Basin. Global industry concentration for nitrogen producers remains low with Herfindahl-Herschman Index scores of less than 400. They note that capacity of U.S. production of nitrogen is down about 40% from 15 years ago due largely to increased competition from foreign producers and high U.S. natural-gas prices. Recent decreases in natural-gas prices due to development of shale gas reserves have potential to slow or reverse this trend.

2.3. Previous Studies in Spatial Competition

Location of plants was first focused studies suggesting that consumers do not always buy from the least expensive supplier for the reason that firms are differentiated by their geographic locations or characteristics associated with product (Hotelling, 1929). Hotelling described that disutility of travel to make a purchase is different from simply a disparity of transportation costs. Thus consumers are likely to pay different prices for same good at different locations. Transportation costs and downward sloping average costs curves over a range of quantity sold was considered in a study much later (Capozza & Order, 1978). There are two conditions have to be met for any spatial model. The first one is nonzero positive transportation costs and second condition to be met is that average cost curves must be downward sloping over some range. If the transportation costs were to be zero, a firm 100 mile away would just as competitive as one less than mile away. Consequently, spatial separation would have no effect and perfect competition would exist among firms. Transportation costs thus in general, give an advantage to firm that is close to its customers. In light of second condition, if average cost curves were to be non-negatively slopped throughout the range, no advantage would exist for concentrating production at specific geographic location. Each customer could make their product as per their required quantities, just like any other concentrated firm. In such case, spatial competition would not exist. The average cost curve may be negative in case there are fixed-costs or due to economies of scale.

There are two basic forces that are frequently mentioned in literature of spatial microeconomics. The first one is called ‘market share effect’ (Pinkse & Slade, 1998) which motivates firms to locate near competitors in order capture, more customers or steal from competitors. The second one works against the first one and is referred to as ‘market power effect” due to which firms tend locate farther away to avoid competition and capture customers within specific geographic area. In a review of empirical literature (Borenstein & Netz, 1999), its was found that ‘market share effect’ tends to dominate over ‘market power effect’ and thus firms tends to cluster.

Three main theoretical variations considered in spatial economic theory analysis are Löschian competition, Hotelling-Smithies competition, and Greenhut-Ohta competition (Greenhut, Norman, & Hung, 1987). Löschian competition is applicable when firms tend to believe that competitors will match any price changes by pursuing price strategies to maintain fixed market area. Löschian competition contradicts nonspatial competitive theory, and results in high short-run benefits, effects of which are lowered entry in the long-run (Fik, 1988). Löschian competition predicts:

1. With transport costs and/or fixed-costs approaching zero, the firm’s price will approach the nonspatial monopoly price.
2. With increase in fixed-costs and transport costs, the price falls, whereas increase in marginal-costs leads to ambiguous results.
3. Firm’s Price increases with entry of new firms (with increase in competition).
4. Firm’s Price increases with increase in population density of consumers.

Hotelling-Smithies competition and Greenhut-Ohta competition are similar in predicting pricing behavior. Greenhut-Ohta assumes that at the edge of its market are, each firm tends to maximize profits subject to given price constraint. Hotelling-Smithies and Greenhut-Ohta provide following theoretical variations:

1. With transport costs and/or fixed-costs approaching zero, the firm's price will approaches marginal-costs and results in nonspatial perfect competition.
2. Increase in all fixed-costs, marginal-costs, and transport costs lead to increase in firm's price, a classical theory result.
3. With entry of more firms in industry or market, firm's price is lowered due to increased competition.
4. Firm's price reduces with increase in population density in the long-run.

Spatial competition studies done in agribusiness sector are very few. Spatial competition in food markets or supermarkets (Fik, 1988) theorized that price competition in retail food markets is highly dependent on location and distance to competitor firms. The results this study established strong link between firm's price, space, and intensity of price reaction as inverse distance. The role of spatial pricing in allocation of tomatoes from farms to processing facilities was determined for state of California (Durham, Sexton, & Song, 1996). The analysis found modest inefficiency in allocation of processing tomatoes from farm to processing plants. A simulated entry of competitor at either of the geographic end of producing region caused competitive impacts affecting whole industry (approximately 500 growers and 32 processor considered). Authors mentioned that standard spatial competition models do not capture such type of indirect competitive linkage among even between firms that were spatially distant.

Spatial competition among fertilizer plants in United States and their respective market boundaries has not been done before. Studies related to fertilizer production are focused on products manufactured, and their composition. Shaw (1982) analyzed economic aspects of product strategy based on three aspects, namely (a) the size of product range, (b) the extent and type of product differentiation and product matching, and (c) the role of new product innovation in firm's competitive strategies in United Kingdom (UK). Shaw's research focused on firm's competitive behavior between size of product range offered and size of firm. Study concluded three major results. First, no significant correlation was found between size of product range offered and the size of firm. Secondly, despite the effort of oligopolist's (three major firms) to differentiate their products, the style of competition edge was similar to product of their respective firms. Thirdly, despite the requirement of competition edge to stimulate some developments, new product competition was a persistent feature of oligopolistic rivalry.

Another spatial competition study was conducted in context of pricing in context of agricultural chemical industry (Hall, Dorfman, & Gunter, 2003).in this study, three spatial competition models were tested on retail price data for agricultural chemical industry that included insecticides, pesticides and herbicides. Agricultural chemicals and fertilizers were analyzed for surveyed expenses in Georgia and treated as representative of national average. Survey was conducted via telephone and fax to determine dealers that sell pesticides. Study was based on 552 prices from 65 dealers. The authors collected the data for distance between closest competitor and number of competitors using 'Microsoft Map Quest' and the firm as listed with Georgia Department of Agriculture. The fifteen mile radius was chosen as approximate distance farmer was willing to travel to purchase chemicals. The distance more than 15 miles was deemed too far to expect a farmer to travel, that too as direct (euclidean) distance and not the distance travelled on road. Authors considered this distance reasonable based on demands of farm labor time and the transportation costs associated with bulky chemicals. Average distance between competitors was assumed as average of 5.83 miles, with the longest distance between competitors being 18.7, and the shortest distance as 0.3 miles. Such approximation was only good for s smaller model as applicable to Georgia.

This dissertation uses actual geographic location of fertilizer plants and actual road and rail distances travelled. Model applied in this dissertation deals with supply chain at much large scale (complete transportation geography of United States and Canada). Results of Hall et al found no evidence of any spatial competition using data from 65 retailers and twelve chemicals. Demand and supply-side variables were statistically significant. The results pointed to virtually complete control of retail prices by chemical manufacturers, which was attributed to rebate programs offered by retailers. The results also suggested retailers or distributors do not have anti-competitive effects since price competition was essentially found to be absent.

Other studies have been grouped in smaller subtopics to account for overlapping nature of topical sciences. There is high correlation between terms used in different areas of study, but still different.

2.3.1. GIS in Transportation and Spatial Analysis

With increase in digital information processing and hardware capabilities, the fields of geographic information systems (GIS), transportation, and spatial analysis are intertwined to an extent of being inseparable. With the development of several software packages that help in capturing, storing, analyzing, and filtering geo-referenced information, the use of GIS has increased to many fields and is not limited to the subfield of spatial analysis of geography (Miller 1999). It specifically helps in visualization of spatial information and viewing of distribution of various parameters. It helps in efficient and equitable distribution of scarce resources along with routing and shortest path distance generation.

GIS has significant potential for spatial analysis and advantage over traditional aspatial techniques that cannot capture minor relationships between spatial variables most of which are left to researcher's imagination. Ignoring these subtle but critical relationships is not just loss of information, but also it may have non trivial impacts on research conclusions and policy decisions (Fotheringham and Rogerson 1993). GIS is being used as "front end" and "back end" to geo-referenced databases, specifically as spatial database management system (SDBMS) for managing geo-referenced data and a spatial decision support system (SDSS) for mapping and visualization by researchers and policy makers alike. This assumes more importance in field of transportation analysis where users are a diverse group of transportation service providers, commuters, freight providers and industries that directly depend on transportation.

GIS in agricultural transportation has been applied since late 1980s, specifically in commodity movement and mode of transportation. Studies for optimal flows of commodities and alternate mode of transportation were done using ArcGIS starting mid 1990s (Ellis 1996). Data collection for transportation analysis includes both spatial and non-spatial data samples. non spatial data may include fright rate or waybills for carloads whereas spatial data may include price information for a commodity at various geographic markets. Trade flow between two distinct geographic markets will be based on price difference between them and cost of transportation between the respective markets. The distribution of flows can also be determined based on capacity or routes and mode of transportation chosen, which would be normally ignored, if traditional spatial techniques were to be used.

2.3.2. Transportation and Spatial Arbitrage

Transportation cost is indispensable for any spatial arbitrage to exist. The process of spatial arbitrage was formalized in nineteen fifties (Enke 1951; Samuelson 1957; Samuelson

1952). The main problem that was targeted was to solve the generalization of standard "back to back" graphical construction to more than two markets. Enke's solution relied on nonlinear electric network analogue. Later on Samuelson was able to reduce it to so called transportation problem in linear programming. In decades thereafter, a standard form of spatial price equilibrium model has been used for many commodity markets; the livestock-feed market(Bates and Schmitz 1969), international trade (Bawden 1966), world sugar market (Bates and Schmitz 1969), spatial price fluctuations (Granger and Elliott 1967), two spatial random markets model from perspective of describing at retail outlets . Work related with spatial fluctuations was highlighted for commodities in ninety seventies and eighties (Bressler and King 1970; Bronars and Jansen 1987).

The assumption of perfect competition is difficult in analysis of movement of commodities. Problem concerning spatially separated markets in case of linear market functions was suggested to be possibly solved by electric analogue (Enke, 1951). Proceeding from purely descriptive problem in non-normative economics of spatially separated segregated markets, was translated into mathematical maximization problem (Samuelson, 1952). Samuelson also presented duality and maximizing net social pay off and duality. The problem concerning competitive equilibrium among spatially separated markets was reformulated under the assumption of linear regional demand and supply relations, which allowed for problem's conversion into quadratic programing. Computational algorithm was specified that could be used to directly and efficiently derive optimum solution (T. Takayama & Judge, 1964). The paper also provided an example to indicate structure of programing tableau to discuss the existence, uniqueness and regularity of the solution. A simple network model for monopolistic spatial price equilibrium was later developed in mathematical form (Takashi Takayama & Judge, 1971).

Spatial price methodology based on maximum likelihood estimation of mixture distribution model incorporating price, transfer cost, and trade flow data was used to distinguish between equilibrium and integration in spatial price analysis (Barrett and Li 2002). This was expansion of a widely used model of switching regime model that estimated the distribution of transport prices from spatial price differences under assumptions that arbitrage takes place instantaneously and the transport prices follow a parametric distribution such as truncated normal or a gamma distribution. Recently, parity bound models that incorporate transport price information into estimation procedure have been developed (Baulch 1997; Barrett and Li 2002).

Transfer costs comprises of transportation, loading and unloading costs, and trader's normal profit. These determine parity bounds within which the prices of a homogenous commodity in two geographically distinct markets can vary independently (Baulch 1997). When transfer costs equal the inter-market price differential (or spread) and there is nothing to hinder the free trade between markets, then the trade will cause prices to simultaneously towards equilibrium price and spatial arbitrage conditions are binding. However when the transfer costs exceed inter-market price, the trade will not occur and spatial arbitrage conditions will not be binding. .this methodology has limitations that transfer costs should be as accurate as possible.

Most of the studies, either recently or decades earlier, focus on integration of spatial markets, equilibrium or both. They have considered transportation costs in some of and ignored in others. One that has been consistent is that they have highlighted the importance of volatility of prices, correlation between prices at two or more different markets, and how they affect spatial arbitrage. While analyzing spatial arbitrage, with or without considering transportation cost, their focus has been on methodology, their advantages and disadvantages. Most of these studies use discrete values for price of commodities. Simulation of prices has been limited to reaching of equilibrium price under continuous or discontinuous flows. None of these studies use the transportation cost that is based on distance between the markets as they have relied on freight rates only.

This paper contributes in the fact that actual distance between markets as well as freight rates at markets under consideration are used therefore more reliable analysis can be done with respect to results. Moreover, instead of treating the prices as discrete, they are treated as random, with certain distribution based on historic prices, so as to capture the temporal aspect of price movement.

3. THEORETICAL MODEL

Nitrogen based fertilizers are extensively used in agriculture. Natural-gas comprises majority of input costs associated with production of anhydrous ammonia (Anhy), which can be shipped out as is, or converted into Urea (urea) or UAN solution (UAN). Anhydrous ammonia is the most concentrated form of nitrogen with 82 percent available nitrogen. Urea is granular form of nitrogen fertilizer, usually coated for controlled release of nitrogen, with 42 percent nitrogen content. UAN is a solution of urea and ammonium nitrate in water applied as fertilizer with a nitrogen percentage of 30 percent. Variation of different grades of Anhy, urea, and UAN exist with slight variation in available percentage of nitrogen. Continuous effort is made regarding timely application of nitrogen-based fertilizer in sufficient quantities to support vegetative growth of crops in agriculture sector. Newer varieties are even more fertilizer demanding for crops like corn and soybeans. Various stress tolerant crops varieties allows for farming in drought prone areas, leading to potential increase in crop acreage.

Reduced natural-gas prices as a result of shale oil drilling in parts like western North Dakota and others in United States, provides increased incentive for fertilizer plant firms to take advantage by producing anhydrous ammonia domestically. Traditionally, anhydrous ammonia is mostly imported from countries like Trinidad and Tobago, and other gulf countries which have lower natural-gas prices. This anhydrous ammonia is then shipped from U.S.-Gulf (USG) to various fertilizer plants in United States (USPlants) for conversion to either urea or UAN or consumed as is (anhydrous ammonia).

Fertilizer industry is an industry with high fixed-costs associated with construction of fertilizer plants, high volume and low marginal-costs. Until recently, there has been no reported construction of new fertilizer plants in last two decades. There are many risks associated before construction phase due large investment and regulatory approvals involved, during the construction phase (market conditions like price of natural-gas and price of importing anhydrous ammonia can vary) as well as after the fertilizer plant reaches operational phase.

This chapter presents theoretical concepts used in empirical model used in this dissertation. The approach taken in mapping out the supply chain of nitrogen-based fertilizer industry is based on combination of key concepts of market boundaries for firms and market competition, network modelling in transportation, stochastic optimization using distribution for random input variables. . In literature, some of terms are used interchangeably with stark contrast in their referred meaning. Some of these key concepts are defined as required for use in this dissertation.

3.1. Elements of Problem

In order to narrow down the scope of analyzing impact of recent reduction of natural-gas prices on nitrogen-based fertilizer industry in North America, key features were identified that have significant impact on industry. Some of these key features of problem are explained below.

3.1.1. Demand

Demand is an important variable that affects the overall big question of impact of addition of new fertilizer plants to the industry. Demand of nitrogen fertilizers may be governed by changes in crop varieties, change in acreage of crop types/varieties as well as crop pattern in any geographical area. Demand at geographical area of county level is considered appropriate to account for impact of fertilizer plants within states. Demand at county level is derived by summing up all the nitrogen-based fertilizer requirements for all the crops are reported to be grown per county across United States (USDA-NASS, 2013b). Demand is treated as discrete initially to arrive at current structure of nitrogen-based fertilizer supply chain in United States, and later treated as random distribution to account for expected change in future. Since demand at county level changes by type of fertilizer, demand is treated separately for anhydrous ammonia, urea and UAN for each county and needs to be met independently. Increased pressure on yields further adds to increase in fertilizer demand for nitrogen-based fertilizer; exacerbated by changes in cropping patterns.

3.1.2. Fertilizer Plant Capacities and Costs

Fertilizer plant capacities at each specific location are necessary to account for supply of nitrogen-based fertilizer at regional level. In absence of geographic location of fertilizer plant, it is difficult to assert and analyze the impact of supply from fertilizer plant in meeting the demand at county level. For example, a fertilizer plant on eastern part of a state like North Dakota may have significant impact on Minnesota and little to no effect on western part of North Dakota. Beside location, existing and future fertilizer plant capacities are used to account for upper limit of supply at each of fertilizer plant by type of fertilizer produced. Since, anhydrous ammonia is a precursor to producing urea and UAN (ammonia based solutions), the plants may produce the anhydrous ammonia on their own and buy from nearby plant (from same or different firm) for conversion, but the final product shipped is limited by the respective type of capacity for fertilizer plant. This conversion from anhydrous ammonia to urea or UAN has to be accounted for better representation of actual flow in supply chain. Plant capacities for current and future year are treated separately and reflected in model.

Cost of production at fertilizer plant is different at various locations for a variety of reasons. Beside technology, other factors influencing cost of production are size of plant, cost of inputs such as electricity, natural-gas price, labor costs and land costs. Natural-gas being a major input, is treated as significant input variable along with electricity cost which differs by state. To account for natural-gas price, Henry-Hub, an index for natural-gas price, is used. Nitrogen-based fertilizer plants of various sizes enjoy different economies of scale. Recent reports clearly indicate that ammonia production costs vary by plant size (Maung, Ripplinger, McKee, & Saxowsky, 2012). There is an initial sharp decline in anhydrous ammonia production costs with increase in plant size. When plant size reaches 516,000 tons/year, the rate of cost decline flattens. Cost of ammonia is reported to be $325/ton, for the plant size of 516,000 tons/year (Table 3.1). Levelized[5] cost for ammonia production estimated by plant size show tremendous economies of scale with increase in plat size. Storage and transportation costs were excluded in in estimating costs. The share of capital cost, when considered as percent of total cost, declines with increase in size of fertilizer plant. The share of natural-gas cost increases as a percent of total cost with increase in size of plant. The natural-gas cost accounts for 50 percent of total cost as the plant size of 516,000 tons/year of production capacity is reached (Table 3.2). Cost of natural-gas has substantial impact on production of ammonia (Figure 3.1). With increase in price of natural-gas from $5/MMBtu to $12/MMBtu, the production cost of ammonia increases significantly from $325/ton to $556/ton for a plant with production capacity of 516,000 tons/year. Economies of scale play significant role in production of ammonia. When price of natural-gas is held constant, the total production cost of ammonia declines with increase in plant size from 3,400 tons per year to 516,000 tons per year. Effect of economies of scale is reduced beyond the plant size of 516,000 tons. The proposed new plants with higher production capacity are likely to realize better economies of scale compared to fertilizer plants with lower production capacity. Proposed

[5] *levelized cost represents the present value of the total cost of building and operating a generating plant over an assumed financial life and duty cycle, converted to equal annual payments and expressed in terms of real dollars to remove the impact of inflation.*(USEIA, 2010)

plants are also likely to operate at higher production capacity during initial operating period to better distribute their total costs over more of the net-output produced.

Table 3.1. Levelized cost of production by size of fertilizer plant (Maung et al., 2012, p. 12).

	Ammonia Plant Size (tons per year)				
	3,400	50,000	516,000	1 Million	1.5 Million
	$/ton of ammonia				
Capital Cost	721	281	124	99	86
Natural Gas Cost	165	165	165	165	165
Electricity Cost	57	57	6	6	6
O & M Cost	40	40	30	30	30
Total Ammonia Cost	983	543	325	300	287

Table 3.2. Share of costs as percent of total levelized cost (Maung et al., 2012, p. 12).

	Ammonia Plant Size (tons per year)				
	3,400	50,000	516,000	1 Million	1.5 Million
	Percent of total cost				
Capital Cost	72	52	38	33	30
Natural Gas Cost	17	30	51	55	58
Electricity Cost	6	10	2	2	2
O & M Cost	4	7	9	10	10
Total Ammonia Cost	100	100	100	100	100

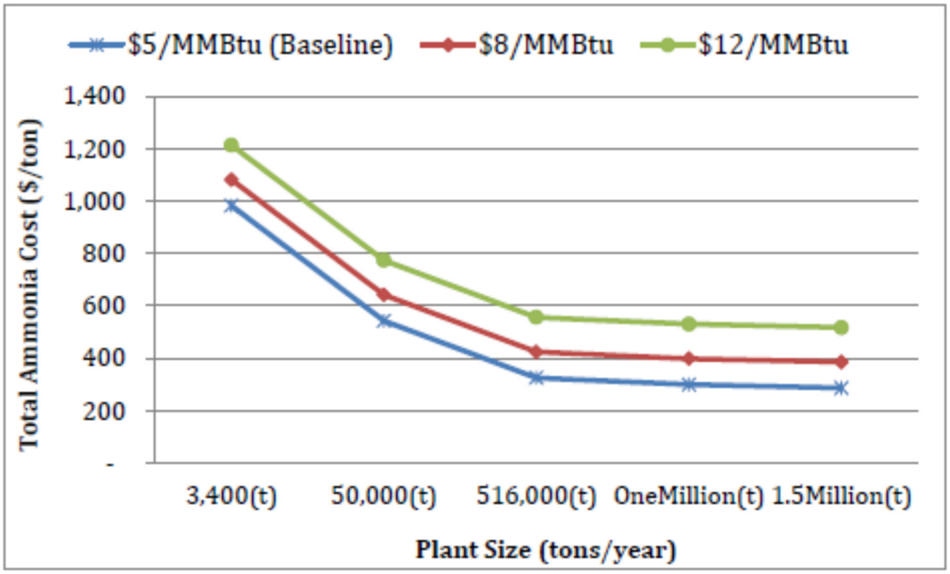


Figure 3.1. Impact of changes in natural-gas prices with change in size of plant on production cost of ammonia (Maung et al., 2012, p. 14).

Price of natural-gas as reported to be trading at Henry-Hub is treated as measure of price of natural-gas. It is treated as discrete in base case with known value from year 2012. The volatility reflected in HH historically required it to be treated as random and stochastic variable to account for probable changes in future based on distribution fit of historical values. Variation in natural-gas prices adds significant risk to investment in construction of new fertilizer plant (Figure 3.2). Cost of natural-gas has substantial impact on production of ammonia (Figure 3.1). With increase in price of natural-gas from $5/MMBtu to $12/MMBtu, the production cost of ammonia increases significantly from $325/ton to $556/ton for a plant with production capacity of 516,000 tons/year. Change in cost of natural-gas prices can translate into critical factors for survival of fertilizer plant during early production phase. Rise in natural-gas cost may prove to be detrimental during initial phases of operation when realization of economies of scale is crucial. Historically, the natural-gas cost has been at a high of $15.1/MMBtu in 2006 and at a low of $2.00/MMBtu in late 2009 and 2010. In addition to this temporal change in natural-gas prices, spatial variation also exists, wherein natural-gas prices are different at different geographical locations, on any given day. This spatial difference on price of natural-gas plays critical role in deciding location of new proposed fertilizer plants. Low natural-gas prices are certainly important for keeping production cost of ammonia low, but it is also important to be located in geographical region where natural-gas prices are at lower than national average. Location of fertilizer plant is fixed, thus it is important to be close to a region where natural-gas prices are cheaper.

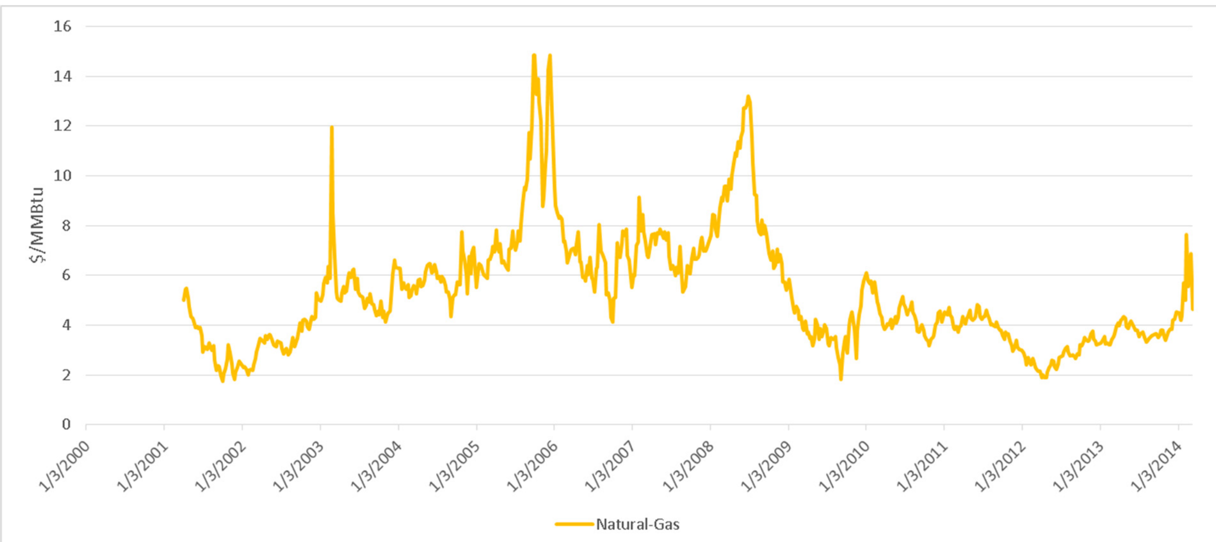


Figure 3.2. Spot-prices for natural-gas as reported from Henry-Hub.

3.1.3. Imports

Nitrogen based fertilizers can be imported from U.S.-Gulf via barge and Canada via rail or truck. Import price at U.S.-Gulf are taken into account and allowed as competing source of supply in order to meet demand at county level in United States. Few geographic locations are chosen as point of start for imports into the model for U.S.-Gulf. For Canadian imports, approximate location of fertilizer plants are treated as point of production, and allowed to enter Untied State at specific port of entries via rail or truck. An upper limit on amount of imports is set based on known quantities of anhydrous ammonia, urea and UAN fertilizers imported in year 2012 to better reflect current structure of supply chain. This limit on imports by type in essence acts as supply constraint for import locations just as fertilizer plant capacities for plants. When stochastic model is applied to account for changes in current structure of supply chain, the constraint on imports is lifted to allow for enough slack in model. Historic variation of imported price for nitrogen-based fertilizer through U.S.-Gulf is shown in Figure 3.3. Recent decline in imported price via U.S.-Gulf coupled with reduced natural-gas prices have led to many firms to announce expansion of existing fertilizer plants or construction of new fertilizer plants. Historic levels of import price for anhydrous ammonia, urea, and UAN peaked in 2008-09. Distribution of import prices for each fertilizer type is taken into account to allow for random correlated draw for prices in year 2018, while also accounting for correlation with Henry-Hub.

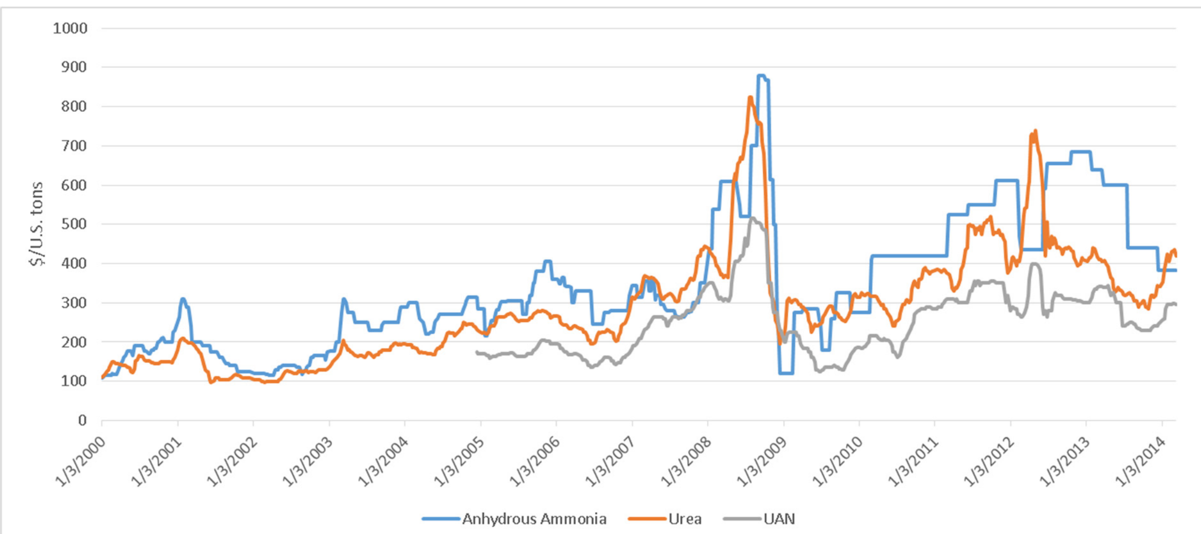


Figure 3.3. Historical change in price for anhydrous ammonia, urea, and UAN for U.S.-Gulf region.

3.1.4. Mode of Transport and Distance of Transportation

Cost of transportation is based on not only on the mode of transport but also on distance between starting point and destination (demand). An important factor is thus the distance between all relevant origins to all counties by alternative modes of transportation. A complete trip for transportation may include for example first half via barge from point of import A to a location B and second half may include transportation from location B to a location at county C. Transportation cost will be different for A to B and B to C, depending on mode and distance. In order to derive distances, rail and road network for U.S and Canada (U.S. Census Bureau Geography and U.S. Department of Commerce 2012; U.S. Department of Transportation n.d.), and waterway network for U.S [3] is used to calculate geographic distances between origin points to destination points as travelled by respective mode of rail or truck within reasonable acceptable limits of errors using geographical information systems (GIS) techniques. This step is critical as in absence of distance between origin and destinations, extensive collection of data from all fertilizer plants to end destination is required in order to know the structure of supply chain.

With knowledge of supply (fertilizer plants and import points) and demand (at crop growing counties) at various geographic locations for nitrogen-based fertilizer for the year 2012, it needs to be allocated among various modes of transportation subject to respective costs per mile and change of modes (where applicable). The transportation network model is utilized and optimized under linear assumption (for base case of year 2012) to derive flows between any pair of origin and destination. Linear assumption here means that the cost of transportation increases linearly with increase in distance between origin and destination. Post optimization, all destination counties need are identified based on fertilizer plant (origin) by which it is supplied. If a set of counties [ϕ^A] are supplied by plant A, then those counties can be assumed as geographic market boundary of plant A, in discrete base case. In case of stochastic optimization, the plant A can supply to set of counties that may be same or different for each optimized iteration, therefore probability of plant A supplying to each county needs to be calculated at the end of repeated optimization during stochastic simulation. Market boundary in the case for plant

A comprises a set [$\phi^{A}{}_{1}$], counties that supplied by plant A in every iteration of optimization and set [$\phi^{A}{}_{2}$], counties that are supplied sometimes by plant A with a certain probability (ratio of number of iteration it is supplied by plant A to total number of iterations of repeated optimization). It may also be interesting to find out overlapping market boundaries for more than one fertilizer plant in a particular region. This will be especially important in determining the market competition between say two plants A and B where overlapping market boundaries are as represented by set of counties set [$\phi^{A}{}_{2}{}^{B}{}_{2}$] = {set [$\phi^{A}{}_{2}$] ∩ set [$\phi^{B}{}_{2}$]}.

3.2. Market Boundaries

Concepts used for market boundary in this are mainly derived from theory put forward for market equilibrium under different market prices and interregional trade under spatial arbitrage (Bressler & King, 1970). For a single market for example market A where a certain price for say corn is available, let's consider producers (corn growers) located at geographical distance, with incremental distance of 100 miles, market price available at market A is \$50, with transportation cost of \$10 per mile, their profit function Π is defined as:

$$\pi = X_{iA}(50 - .10 * Dist_{iA}) \qquad \textit{(Eq. 3.1)}$$

Where:

X_{iA} is quantity shipped from producer located at anywhere on isoquant line i to market A.

$Dist_{iA}$ distance traversed between producer's location and market A.

The resulting profit function can be summarized as in Figure 3.4 where producers that are located closer to the market get higher profit for their produce owing to lesser transportation cost, *ceterus paribus*. It is assumed here that transportation costs are linear. Producers are likely to continue shipping to market A from farther away distances as long as they profit is positive.

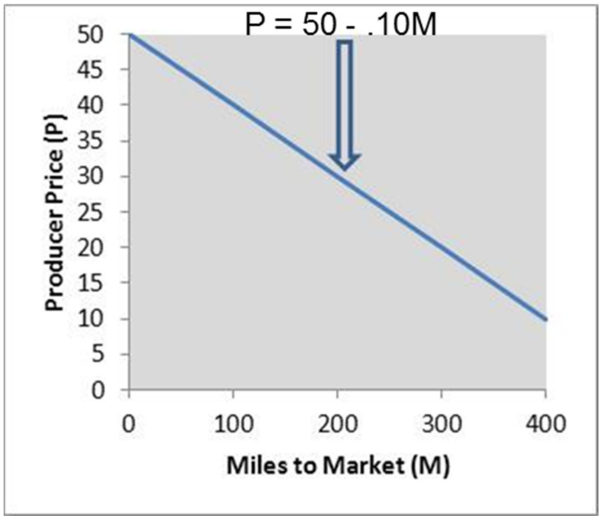


Figure 3.4. Graph of a market area with dispersed production and a central consumption point (transportation costs = .10 per mile).

A hypothetical example of markets A and B where in isoquant lines (represent sellers located at equal distance from market points) show decreasing price a seller would recieve at either of markets with increase in distance (Figure 3.5). In case of choice to a producer between two markets A and B, let's say the isoquant lines represents producers located at same geographical distance from market located at their center, with same, producers located at MB will be get equal profit if market prices offered at market A and market B are $50. At this point producers located anywhere on MB are indifferent to selling their produce at either of the markets and thus can be considered as market boundary under equilibrium at the said market prices. MB represents market boundaries when prices at markets A and B are same and MB' when prices at market A is higher than price at market B. This market boundary changes from MB to MB' if price at market B stays at $50 but price at market A is increased to $60, everything else remaining same. The market area between MB and MB' is said to be the gain for market A.

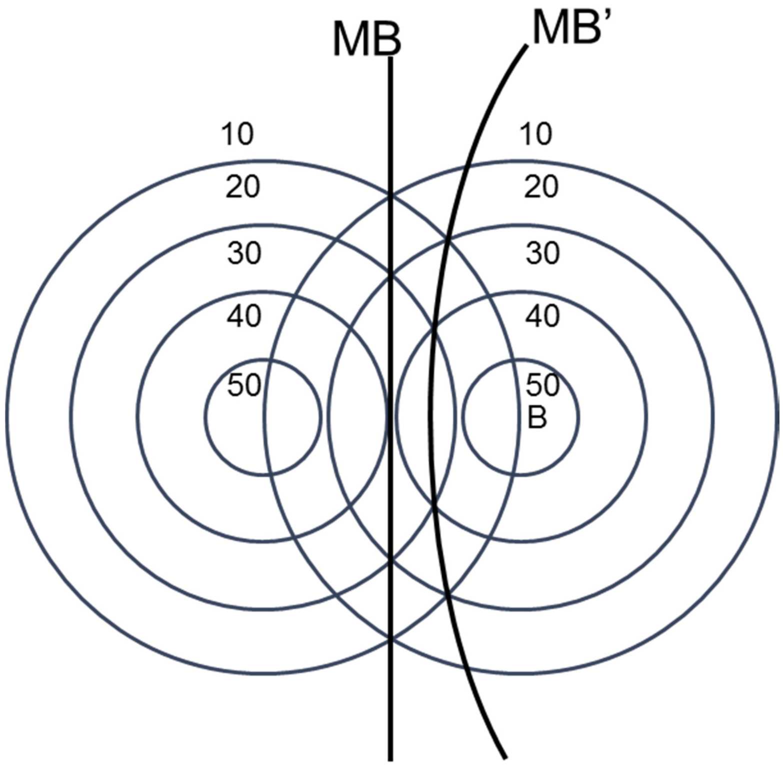


Figure 3.5. A hypothetical example of markets A and B. MB and MB’ represents market boundaries for same and different prices at markets A and B, respectively.

Agricultural prices and commodity markets are random and stochastic in nature due to associated volatility (Ferris, 2005). The basic concept is of arbitrage is that commodity flows from origin to destination till the destination provides the maximum price. In essence the commodity flows to dominant market given the same transportation cost. As the flow of commodity occurs, the prices at destinations changes and the flow of commodity adjust to new prices at the destinations. Commodity flow continues till an equilibrium level of markets is achieved. In case there are two markets that offer a same price, then flow will occur to the destination that has least transportation cost. Therefore, for example shown in Figure 3.5, market boundaries will keep changing over period of time. A new market boundary will exist for every new equilibrium reached for any change in prices at market A or B or both, subject to knowledge of producers. This is a continuous and ongoing process that makes the inherent process of deriving market boundaries only good given parameters at an instant in time. With a change in market price at either of markets, a new equilibrium represented by a new market boundary will be obtained (Figure 3.6). A hypothetical market scenario for two markets A (left vertical axis) and B (right vertical axis) with market price on vertical axis, and geographical distance of supplying locations between them on horizontal axis. The intersection of profit lines for each market represent the locations to the left of market boundary will ship to market A and all producers to the right of intersection will prefer to ship to market B. All the producers on intersection point will be indifferent to shipping to either of the markets A and B. this intersection point will change with any change in market prices or transportation costs.

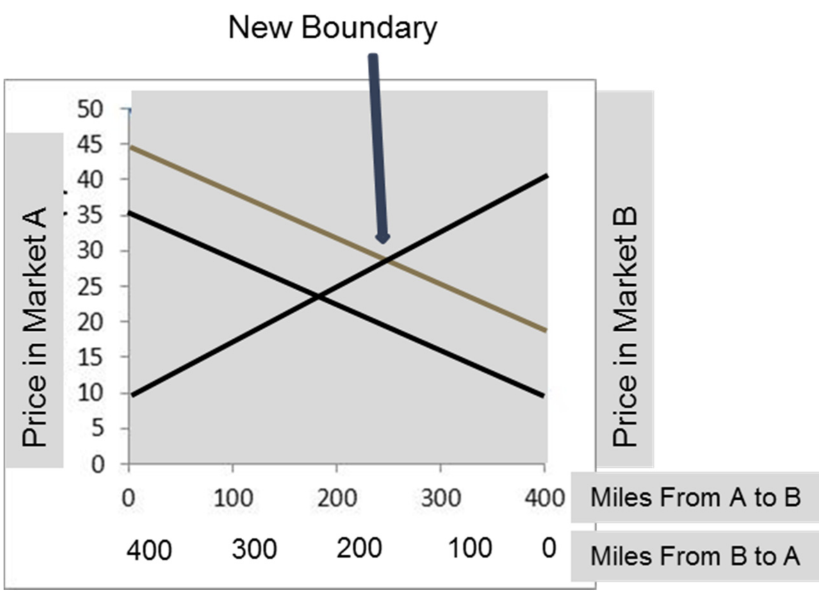


Figure 3.6. A hypothetical market scenario for two markets A and B with market price on vertical axis, and geographical distance of suplying locations between them on horizontal axis.

The relationship between length of haul and cost of transfer services is called a transfer cost function (commonly denoted by T)(Bressler & King, 1970, p. 109). A common example for fixed rate of shipping irrespective of distance is first-class postal mail rates in United States represented by horizontal line (Type A in Figure 3.7). A more conventional zone-rate system, where charges for shipping rates increase in incremental steps, albeit through a series of discontinuous steps, is represented by type B, for example, courier rates for freight. Cost represented by intercept covers terminal and other costs that are independent of distance. Type C represents a straight line relationship with distance to cover transportation costs that are function of distance only, with initial non distance cost (T_c). Commercial transportation rates can be best described as Type D where in the transportation costs increases with distance at decreasing rate. Transfer costs influenced by many factors besides linear distance. Conditions such as terrain, topography are important along with type of carrier and amount of traffic. Technology of transportation, characteristics of products, and regulations governing the shipments add to the transfer costs.

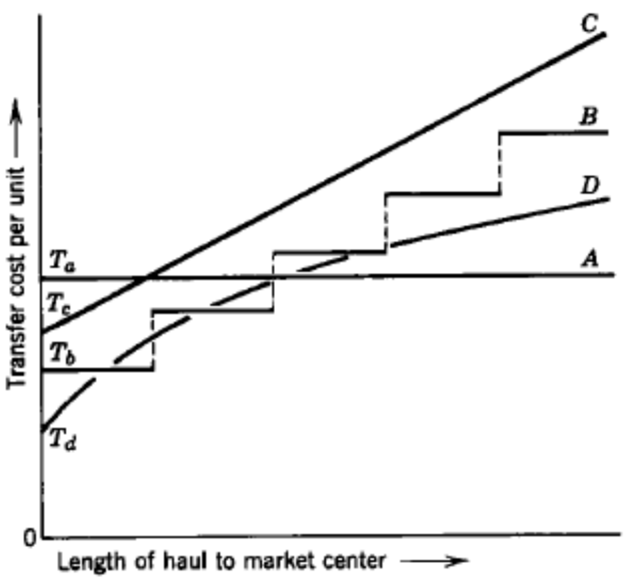


Figure 3.7. Transfer cost functions for commonly observed distance-transfer cost relationships (Bressler & King, 1970, p. 109).

In actual geographic conditions, topography like hills, valleys, mountain ranges, and rivers etc characterized by non-uniform spatial distributions of resources give rise to unique distribution of human populations. Network of transportation routes or network of alternative modes of transportation connects the population centers with some areas better than others in a particular mode of transportation. For example, transportation in hilly terrain is costly than in plains, for same distance, hauled by similar vehicle for same distance. Such distance and cost distortions thus lead to destruction of smoothness and symmetry of locational solutions suggested by theoretical discussions (Bressler & King, 1970), still holding the basic concepts. Under given set of irregular pattern of transportation costs, it is possible to define appropriate transport cost contours for commodities. Population densities and production densities determine aggregate volume of products shipped and availability of back-hauls, thereby influencing the utilization of available capacity within existing transportation network. Consider a plant located in the middle of a large producing territory, representing a small market. To attract larger volumes it will be necessary to offer higher prices for the product be supplied to it by neighboring producing region. So long as the plant is away from other competitor plants other plants, its supply or producing territory will take the form of a circle centered on the plant (Bressler & King, 1970, p. 141). The relationship between total volume collected at plant and collection costs is dependent on particular geographic pattern of production. This geographic pattern of production determines the extent of plant area (market boundary) for any selected volume. In general, the relationship indicates that total collections costs increase with total volume at an increasing rate; the increase in rate of collection costs is more when density considered is lower. In absence of economies of scale in plant operation, then under optimum organization, a plant would be situated at center of every production location. In practical case, the plants are subject to economies of scale, thus larger plants with a volume adjusted to the available capacity operate at lower average costs than smaller plants. Optimum organization involves a balancing of the decreasing average plant cost against increasing collection costs. Minimum combined costs involve lower volumes collected with decrease in density. Decrease in density leads to lower volume collected therefore, accompanied by expansions in the geographic area served by the plant. In such an isolated situation, organization under optimum balancing between average plant cost and collection costs, will lead to an adjustment such that plant is located at center of a circular supply area[6].

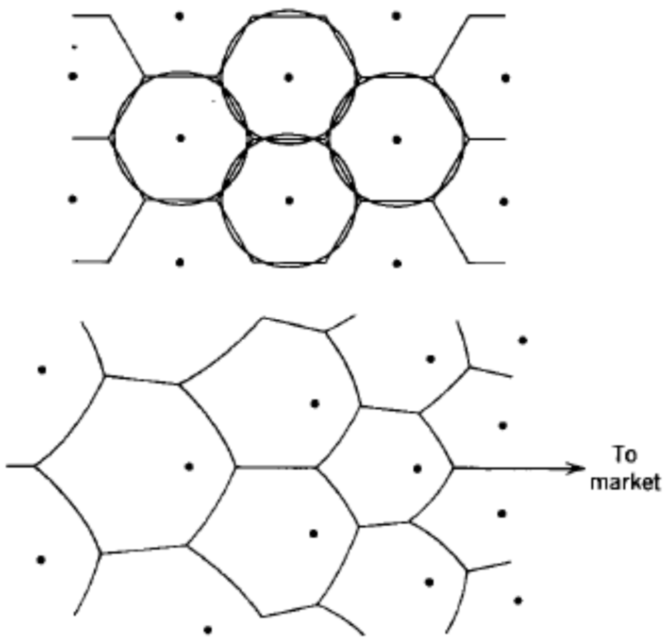


Figure 3.8. Hexagonal market areas in an idealized allocation of market areas among collection plants; a variation of such idealized solution (Bressler & King, 1970, p. 144).

With entry of competing plants to serve an entire producing region, final equilibrium would determine the location size and number of plants as well as allocation of geographical territory among plants; just as in case of competing markets. A system of circular areas cannot fully all of the areas without either overlapping or leaving out some of the area. Overlapping areas would be eliminated by the case of producers towards most favorable market. In practice, however, this is not the case, as same region may be well within market boundary region of more than one market and producers supply to more than one market (stochastic representation of market boundaries present such case in stochastic models of this dissertation). The idealized

[6] An example provided by case study of broilers (Henry, Chappell, & Seagraves, 1960).

solution to plant size and allocation of geographical boundaries appear to involve a regular system of hexagonal market boundaries for plants where in the plants are located at geometric center. Plants located at other than center will have different at-plant prices and thus results in distorted interplant boundaries. This distortion from idealized hexagonal shape is enhanced with variation in production density of regions allocated to markets under equilibrium; alternative modes of transportation and variation in technological efficiency of markets, and different cost of inputs by location and plant size, add to the distortion of market boundaries to an irregular shape.

In this dissertation, market boundaries are derived from the perspective of fertilizer plants (supply points) such that with changes in cost of production (natural-gas price), such that fertilizer plants can supply the counties to meet their respective demand for anhydrous ammonia, urea, and UAN, at lowest cost. In comparison to the example given earlier about collection plant being located in center of a circular supply area, the fertilizer plants are located such that they supply to counties (as demand points) around them at lowest cost while balancing maximum supply at lowest cost of transportation and lowest average plant cost. Initially demand at counties, price of natural-gas (Henry-Hub), and import prices are treated as discrete, but later these are treated as random stochastic distribution to derive dynamic market boundaries (most likely under the any given market condition) for each of fertilizer plant. Lower transportation cost means a fertilizer plant can supply counties that are geographically farther away from it. Lower cost of production either due to lower natural-gas prices or electricity cost or better technology (operational cost) or larger size (better economies of scale) may also mean that one fertilizer plant can compete better than another fertilizer plant in same vicinity of geographical area.

3.3. Transportation Network Model

Graphical or network representation helps in analyzing many important optimization problem. A graph of network is defined by two set of symbols namely nodes and arcs. Nodes are set of points or vertices (set V). An arc consists of an ordered pair of vertices and represents a possible direction of motion that may occur between vertices (a set of A) (Winston, 2003). Also a sequence of arcs such that every arc has exactly one vertex in common with the previous arc is called a chain (Winston, 2003). Lastly a path is a chain in which the terminal node of each arc is identical to the initial node of the next arc (Winston, 2003).

This dissertation utilizes the approach of finding the flows through each arcs in the network that minimizes the total cost of flow for the network while meeting demand at each demand node, subject to the constraints of supplying nodes, demand nodes, arcs, and conservation of flow. These are elaborated in context as related to this dissertation. Constraints of supplying nodes include the maximum amount of production or supply that can be assigned to a supplying node such as import points and fertilizer plants. Such constraints are treated separately for each type of fertilizer. Constraints for demand nodes refer to amount of demand to be met at county nodes (geographic centroid) for each type of fertilizer. Constraints related to an arc is the minimum or maximum amount of flow allowed between a pair of nodes. For example, a maximum number of containers via barge between import points to Minneapolis can be set to a limit for the arc of Import to Minneapolis.

As an example, if a network contains an arc (j,k), then the possible motion for flow of quantity is from node j to node k. Lets say nodes, 1, 2, and 3 represents cities and each arc represents one-way road linking cities. For this network, V={1,2,3} and arc A = {(1,2),(2,3),(2,3),(3,1)}. For the arc (j,k), node j is the initial or origin node, and node k is the terminal or destination node. The arc (j,k) is said to go from node j to node k. thus arc (1,2) has origin node 1, and destination node 2 and it goes from node 1 to node 2. In Figure 3.9 shows that travel is allowed between node 1 to node 2 for arc (1,2) and from node 2 to node 3 as well as from node 3 to node 2 for arc (2,3). In this example, (3,1)-(1,2), (3,2) is a chain but not a path whereas (1,2)-(2,3) is a chain and a path.

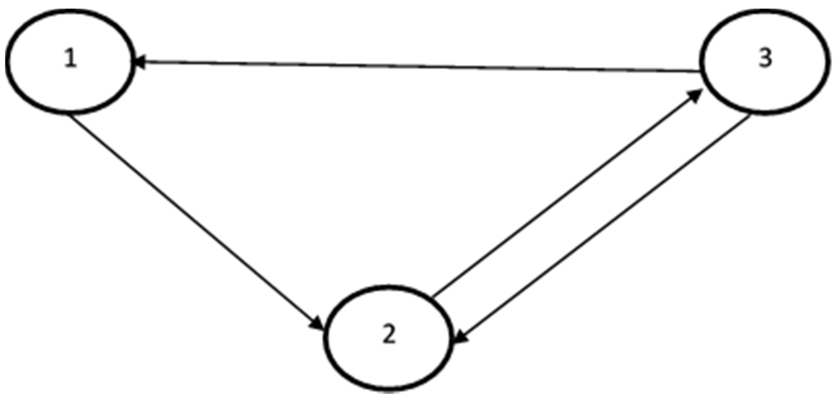


Figure 3.9. A hypothetical network showing flow between nodes and corresponding arcs showing direction of movement allowed.

A general description of transportation problem as relevant to this dissertation, can be specified as follows:

1. A set of m supply points from which fertilizer can be shipped. Supply point i can supply at most s_i units of shipped good (for example, this is the fertilizer plant capacity).
2. A set of n demand points from which fertilizer can be shipped. Demand point j must receive at least d_j units of shipped good (for example, this is the amount of a type of fertilizer a county must receive).
3. Each unit produced at supply point i and shipped to demand point j incurs a variable cost of c_{ij} (for example, tuck cost per mile times the distance between supply point i and demand point j).

4. Let X_{ij} is the number of units shipped from supply point i to demand point j then the general formulation of a transportation problem is

$$\sum_{i=1}^{i=m} \sum_{j=1}^{j=n} C_{ij} X_{ij} \quad \text{(Eq. 3.2)}$$

Subject to

$$\sum_{j=1}^{j=n} X_{ij} \leq S_i \;\; (i=1,2,\ldots,m) \;\; \text{(Supply constraints)} \quad \text{(Eq. 3.3)}$$

$$\sum_{i=1}^{i=m} X_{ij} \geq d_j \;\; (j=1,2,\ldots,n) \;\; \text{(Demand constraints)} \quad \text{(Eq. 3.4)}$$

$$X_{ij} \geq 0 \;\; (i=1,2,\ldots,m;\, j=1,\, 2,\, \ldots n) \quad \text{(Eq. 3.5)}$$

In addition there can be also a transshipment point through which goods can be transhipped on their journey from supply point to a demand point., and it can both receive goods from other points and send goods to other points (Winston, 2003), and has no consumption or production of its own. In this dissertation, an example of the transshipment point considered is St. Louis, MO which can receive shipments from import points via barge, and can send fertilizer to destination points of counties via rail or truck with production or consumption of its own. At such transshipment nodes, additional costs like loading and unloading costs (if applicable) or change costs for changing of mode of transportation related costs are also considered.

4. EMPIRICAL MODEL

4.1. Model Specification

The analytical framework developed in this study is a spatial competitive (network flow) model of the U.S. fertilizer industry. The model is calibrated and used to analyze fertilizer production, imports, and flows (quantity) from origins to destinations. Primary activities include producing fertilizer in existing and proposed plants, importing fertilizer and shipping from origins to demand. Costs are derived for each of these activities. Fertilizer plants are at the actual locations. Imports are through the U.S. Gulf (Louisiana and Texas). Demand is modeled at the county level. And, each activity is modeled for the 3 types of nitrogen fertilizer, anhydrous ammonia, urea and UAN (UAN).

Demand is determined at the county level for each crop and then aggregated by type of fertilizer. The model includes production at 29 existing plants, and 12 proposed plants. Proposed plants include new plants as well expansion in capacity at existing plants. Each plant produces different types of fertilizer and has capacity restrictions for each Imports from Canada are modeled similar to U.S. production. Imports of fertilizer by type at the U.S. Gulf is based on import prices, and shipping costs to the destinations.

The model is calibrated and solved for the base case period which is 2010-2012. Then projections are made for a number of the important exogenous variables to the year 2018. These are used as values in the model to derive the equilibrium for 2018. Comparisons are then made to outputs of interest between the base case and projection period. The variables of particular interest are demand, production of fertilizer by type at each plant, imports and shipments by model from origins to destinations. The model is later extended to account for changes in market boundaries under randomness of variables like demand, cost of production by state (due to price of natural-gas) and more importantly import prices. In order to account for such randomness, model for base case (year 2012, static) is expanded to stochastic linear and stochastic mixed-integer programming for future case in year 2018.

4.1.1. Objective Function

The model specified is based on spatial competition using simple transportation model with supply and demand nodes to account for changes in market boundaries. Market boundaries for a supply node (fertilizer plant) are the all the demand nodes supplied by it. It uses linear programing that is integrated with GIS data structure. Figure 4.5 provides a description of the major features of the model. The mathematical model specification is described below:

$$Min\ Cost = \left[\sum_{r,s,T,M}^{n} X6_{r,s,T,M} * CostCim_{r,T} + \left(\sum_{q,p,T,M}^{n} X5_{q,p,T,M} + \sum_{q,j,T,M}^{n} X1_{q,j,T,M} \right) * CostIm_{T} + \left(\sum_{i,j,T,M}^{n} X4_{i,j,T,M} + \sum_{i,p,T,M}^{n} X7_{i,p,T,M} \right) * CostUS_{i,T} \right] + \left[\sum_{r,s,anhy,M}^{n} X8_{r,s,anhy,M} * \left(CostCanBor_{r,s,anhy,M} \right) + \sum_{s,i,anhy,M}^{n} X9_{s,i,anhy,M} * \left(CostBorUS_{s,i,anhy,M} \right) + \sum_{q,p,anhy,Barge}^{n} X12_{q,p,anhy,Barge} * \left(CostImpTrans_{q,p,anhy,Barge} \right) + \sum_{p,i,anhy,M}^{n} X13_{p,i,anhy,M} * \left(CostTransUS_{p,i,anhy,M} \right) \sum_{q,i,anhy,M}^{n} X11_{q,i,anhy,M} * \left(CostImpUS_{q,i,anhy,M} \right) + \sum_{i,i,anhy,M}^{n} X10_{i,i,anhy,M} * \left(CostUSUS_{i,i,anhy,M} \right) \right] + \left[\sum_{r,s,T,M}^{n} X6_{r,s,T,M} * \left(CostCanBor_{r,s,M,T} \right) + \sum_{s,j,T,M}^{n} X3_{s,j,T,M} * \left(CostBorDmd_{s,j,M,T} \right) + \sum_{q,p,T,Barge}^{n} X5_{q,p,T,Barge} * \left(CostImpTrans_{q,p,T,Barge} \right) + \sum_{p,j,T,M}^{n} X2_{p,j,T,M} * \left(CostTransDmd_{p,j,T,M} \right) + \sum_{q,j,T,M}^{n} X1_{q,j,T,M} * \left(CostImpDmd_{q,j,T,M} \right) +$$

$$\sum_{i,p,T,M}^{n} X7_{i,p,T,M} * \left(CostUSTrans_{i,p,T,M}\right) +$$

$$\sum_{i,j,T,M}^{n} X4_{i,j,T,M} * \left(CostUSDmd_{i,j,T,M}\right)] \quad \textit{(Eq. 4.1)}$$

S.T.

$$\sum_{r,anhy}\left(\sum_{s,M}^{n} X6_{r,s,anhy,M} + \sum_{s,M}^{n} X8_{r,s,anhy,M}\right) \leq CanCap_{r,anhy} \quad \textit{(Eq. 4.2)}$$

$$\sum_{i,anhy}\left(\sum_{j,Barge}^{n} X7_{j,p,anhy,Barge} + \sum_{j,M}^{n} X4_{i,j,anhy,M} + \sum_{i,M}^{n} X10_{i,i,anhy,M}\right) \leq USCap_{i,anhy} \quad \textit{(Eq. 4.3)}$$

$$\sum_{i}\left(\sum_{s,M}^{n} X9_{s,i,anhy,M} + \sum_{q,M}^{n} X11_{q,i,anhy,M} + \sum_{p,M}^{n} X13_{p,i,anhy,M} + \sum_{i,M}^{n} X10_{i,i,anhy,M} \right) = \sum_{i}\left(\sum_{j,M}^{n} X4_{i,j,urea,M} + \sum_{p,M}^{n} X7_{i,p,urea,M}\right) * .58 + \sum_{i}\left(\sum_{j,M}^{n} X4_{i,j,UAN,M} + \sum_{p,M}^{n} X7_{i,p,UAN,M}\right) * .302 \quad \textit{(Eq. 4.4)}$$

$$\sum_{i}\left(\sum_{i,M}^{n} X10_{i,i,anhy,M}\right) = \sum_{i}\left(\sum_{j,M}^{n} X4_{i,j,urea,M} + \sum_{p,M}^{n} X7_{i,p,urea,M}\right) * .58 + \sum_{i}\left(\sum_{j,M}^{n} X4_{i,j,UAN,M} + \sum_{p,M}^{n} X7_{i,p,UAN,M}\right) * .302 \quad \textit{(Eq. 4.5)}$$

$$\sum_{r,urea}^{n} \sum_{s,M}^{n} X6_{r,s,urea,M} \leq CanCap_{r,urea} \quad \textit{(Eq. 4.6)}$$

$$\sum_{r,UAN}^{n} \sum_{s,M}^{n} X6_{r,s,UAN,M} \leq CanCap_{r,UAN} \quad \textit{(Eq. 4.7)}$$

$$\sum_{i,urea}\left(\sum_{j,M}^{n} X4_{i,j,urea,M} + \sum_{p,Barge}^{n} X7_{i,p,urea,Barge}\right) \leq USCap_{i,urea} \quad \textit{(Eq. 4.8)}$$

$$\sum_{i,UAN}\left(\sum_{j,M}^{n} X4_{i,j,UAN,M} + \sum_{p,Barge}^{n} X7_{i,p,UAN,Barge}\right) \leq USCap_{i,UAN} \quad \textit{(Eq. 4.9)}$$

$$\sum_{s,anhy}\left(\sum_{r}^{n} X8_{r,s,anhy,M}\right) = \sum_{s,anhy}\left(\sum_{i}^{n} X9_{s,i,anhy,M}\right) \quad \textit{(Eq. 4.10)}$$

$$\sum_{s,T,M} \sum_{r}^{n} X6_{r,s,T,M} = \sum_{s,T,M} \sum_{j}^{n} X3_{s,j,T,M} \quad \textit{(Eq. 4.11)}$$

$$\sum_{p,anhy}\left(\sum_{q}^{n} X12_{q,p,anhy,Barge}\right) = \sum_{p,anhy}\left(\sum_{i}^{n} X13_{p,i,anhy,M}\right) \quad \textit{(Eq. 4.12)}$$

$$\sum_{p,T}\left(\sum_{q}^{n} X5_{q,p,T,Barge} + \sum_{i}^{n} X7_{i,p,T,Barge}\right) = \sum_{p,T}\left(\sum_{j}^{n} X2_{p,j,T,M}\right) \quad \textit{(Eq. 4.13)}$$

$$\sum_{r,s,anhy,M}^{n} X1_{r,s,anhy,M} + X5_{r,s,anhy,Barge} + X11_{r,s,anhy,M} \leq 4{,}978{,}890 \qquad (Eq.\ 4.14)$$

$$\sum_{r,s,urea,M}^{n} X1_{r,s,urea,M} + X5_{r,s,urea,Barge} \leq 5{,}163{,}843 \qquad (Eq.\ 4.15)$$

$$\sum_{r,s,anhy,M}^{n} X1_{r,s,anhy,M} + X5_{r,s,anhy,Barge} \leq 2{,}626{,}192 \qquad (Eq.\ 4.16)$$

$$\sum_{r,s,anhy,M}^{n} X6_{r,s,anhy,M} + X8_{r,s,anhy,M} \leq 1{,}022{,}944 \qquad (Eq.\ 4.17)$$

$$\sum_{r,s,urea,M}^{n} X6_{r,s,urea,M} \leq 1{,}774{,}719 \qquad (Eq.\ 4.18)$$

$$\sum_{r,s,UAN,M}^{n} X6_{r,s,UAN,M} \leq 619{,}498 \qquad (Eq.\ 4.19)$$

$$\sum_{j,T,M}^{n} X1_{Galveston,j,urea,Rail} \leq 721{,}000 \qquad (Eq.\ 4.20)$$

$$\sum_{p,T,Barge}^{n} X2_{p,MNBarge,T,Barge} \leq 20{,}000 \qquad (Eq.\ 4.21)$$

Where:

T= Type of fertilizer namely: anhydrous ammonia, urea and UAN

M=Mode of transportation, namely: Rail, Truck, Pipe and Barge

i=fertilizer plants located within United States (USPlants)

j= County level demand points

p=Inland Trans-shipment locations (where Barge is incoming mode of flow and rail and truck is outgoing mode of flow).

q=Gulf Import port locations

r=Canadian fertilizer plant locations

s=Canada/USA cross-border points also called as port of entry (POE)

$CostIm_T$=Cost of procuring imports at Gulf port locations by type *T*.

$CostCim_{r,T}$=Cost of procurement at Canadian plant *r* by type *T*.

$CostUS_{i,T}$= Cost of Procurement at USA Plant *i* by type *T*.

CostCanBor= cost of shipping between Canada and border points

CostBorUS=cost of shipping between border points and USPlants.

CostImpTrans=Cost of shipping between import port locations to transshipment points.

CostTransUS=cost of shipping between transshipment points to USPlants

CostImpUS= cost of shipping between import port locations to USPlants.

CostUSUS=cost shipping between USPlants to USPlants.

CostTransDmd=Cost of shipping between transshipment to demand points (counties).

CostImpDmd=cost of shipping between import port locations directly to demand points.

CostUSTrans=Cost of shipping between USPlants (selective) to transshipment points.

CostUSDmd=Cost of shipping between USPlants to demand points.

$USCap_{i,T}$=USA capacity at plant *i* by type *T*.

CanCap= Canada capacity at plant *r* by type *T*.

$Demand_{j,T}$=Demand at county *j* by type *T*.

Objective function's first part of right hand side is for procurement cost, second being shipping cost for anhydrous ammonia as intermediate product referred to as 'Anhy-only' in this dissertation . Last part of shipping cost is for final products to next node or consumption point. Each element is represented within bracket of right hand side of objective function. Procurement cost is the cost of production at the fertilizer plant. The second part of objective function corresponds to production of Anhy-only flow, a prerequisite for producing urea and UAN fertilizer. This is important part of objective function as it allows for consideration of the fact that first anhydrous ammonia has to be produced in order to make urea or UAN at additional cost of conversion. Anhy-only therefore is an intermediate product for production of urea and UAN. The third part of objective function corresponds to anhydrous flow that is shipped out as anhydrous without any conversion and consumed as anhydrous ammonia, referred to as Anhy in this dissertation henceforth.. Anhy-only and Anhy flows are treated as separate flows to keep track of different types of demand per county.

Supply constraints for Anhy-only for Canadian plants is represented by Eq. 4.2, such that sum of anhydrous ammonia produced for Anhy-only (X8) and Anhy (X6) is less than capacity of plant. Supply constraint for Anhy-only for USPlants (Eq. 4.3), such that sum of Anhy-only (X10) and Anhy (X7 and X4) is less than the capacity of each plant. The constraint for conversion of intermediate (Anhy-only) to end product (anhydrous ammonia, urea, UAN) for USPlants is shown in Eq. 4.4. It takes .58 tons of anhydrous to produce 1 ton of urea. It takes .302 tons of anhydrous ammonia to make 1 ton of UAN solution. This also acts as a balance equation. The constraint for balance equation to force internal anhydrous produced at USPlants (X10) to be equal to total urea and UAN shipped out (Eq. 4.5). The supply constraint for Canada plants production for urea (Eq. 4.6), UAN (Eq. 4.7), and U.S. plants production for urea (Eq. 4.8), UAN (Eq. 4.9) limits production at less than or equal to capacity for each plant, type and country.

Equation 4.2 is a balance equation for Canadian shipments for Anhy-only to USPlants, such that what goes in to border points, has to equal what comes out of border points. Border points are therefore treated purely as transshipment points with no production or consumption of their own. It is to be noted that this equation allows the production of anhydrous at Canadian plants to be converted into urea or UAN at fertilizer plants in United States (Eq. 4.10). The flow conservation equation for border points acting as transshipment node such that amount of incoming and outgoing flows at border points for urea and UAN are equal thus acts as balance equation is represented by (Eq. 4.11). Eq. 4.12 is balance equation for inland transshipments points within United States, such that what comes in equals to what comes out of it for Anhy-only. The balance equation for inland transshipments points in United States such that sum of production at USPlants and imports, for anhydrous ammonia, urea, and UAN, is equal to total flow out from transshipments to demand points is represented by (Eq. 4.13). The equation for the flow constraint for total fertilizer that can be consumed (determined by demand), by type, at county level (Eq. 4.14). Imports from U.S. Gulf to inland transshipment points are restricted to maximum of year 2012 by type in equations 4.15-17. Total imports from Canada are restricted to maximum of year 2012 by type in equations 4.18-20. Constraint for rail shipments of urea fertilizer originating out of Galveston, TX for observed value as in December 2013 by Eq. 4.21. To account for seasonality in barge traffic to Minnesota, shipment volume to the transloading point was limited to 20,000 metric tons (Eq. 4.22).

4.2. Data and Derivations

There are a number of critical variables used in the model which are described in this section. These include the demand for fertilizer, import prices and volumes, plant locations and capacities by fertilizer type, and processing costs.

4.2.1. Fertilizer Demand

Demand for fertilizer was constructed at the county level using data on nitrogen use by crop type and acres planted. Acres planted were for barley, canola, corn, cotton, peanuts, rice, sorghum, soybeans, wheat (treated separately for hard red spring, durum and hard red winter) and potatoes for 2010-1012 (USDA-NASS, 2013b). Nitrogen use by crop type was obtained from (USDA-ERS, 2013a) and (USDA-NASS, 2013a) on a state level basis and applied to all counties within the state. Total demand for Nitrogen by type anhydrous ammonia, urea, UAN was obtained by taking county level demands and multiplying these with the proportion of state level demands by type (AAPFCO Publications & Programs, 2013).

Forecasted demand for 2018 was estimated by assuming planted acres by crop within a county increase by the average annual rate of change for planted acres from 2000-2012. These were used to estimate the change in planted acres from 2012 to 2018. Percentages of acres planted to each crop were derived. County map showing total demand for fertilizers is presented in Figure 4.1. County maps for demand by individual type are presented in Figure A.1for Anhy, Figure A.2 for urea and Figure A.3 for UAN. These were then applied to total county acres in 2012 to reflect changes in crop mix rather that planted area expansions.

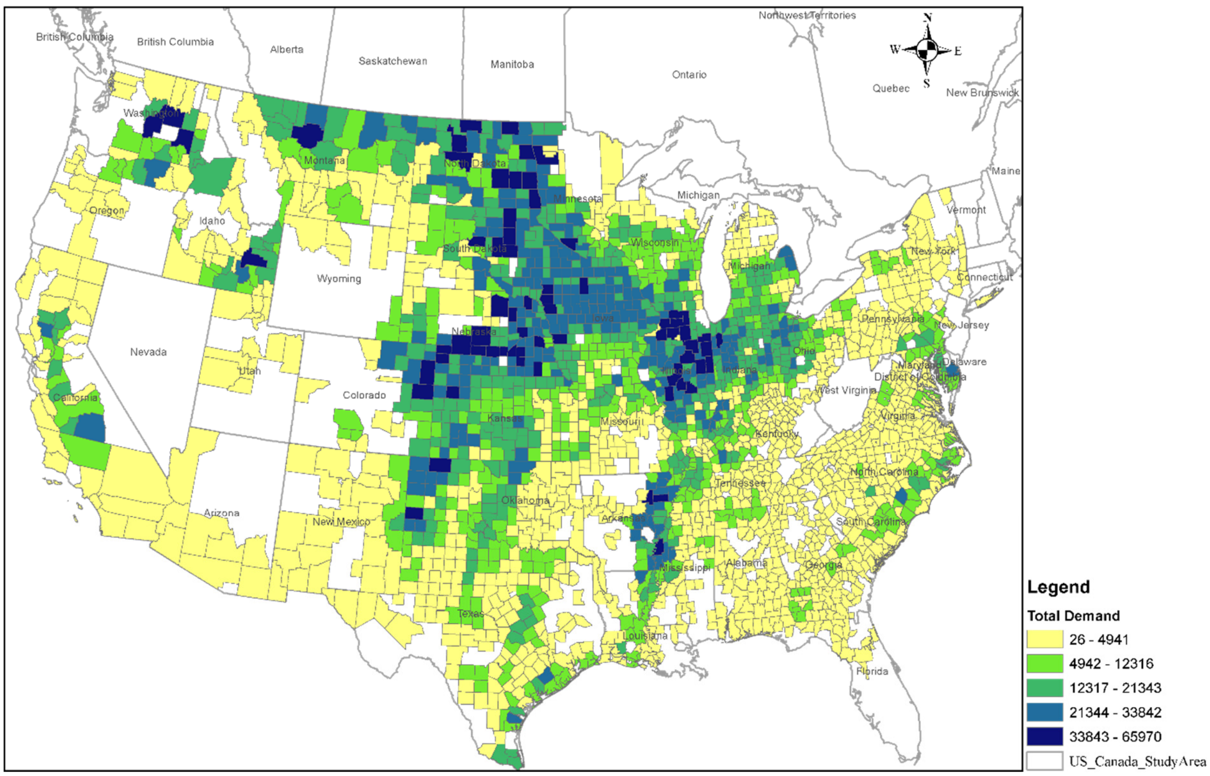


Figure 4.1. Total demand by counties (demand nodes) shown as graduating colors.

The recent expansion of corn and soybean acres in the 2000's were reflected in large increases in total planted acres in selected counties. To reduce this effect, it was assumed total planted acres would be unchanged and acreage would reflect shifts from one to the other based on proposed percentages of each crop, rather than expansions in area planted). The new acres were multiplied by nitrogen use by crop which was also increased to reflect increased use for higher yields to obtain total nitrogen demand by county. These were converted to demand by type, by applying state level proportions for anhydrous ammonia, urea, and UAN to county level nitrogen demand (AAPFCO, 2011).

The results from this procedure indicate the 2018 demand to increase by 4.7% from the 2010-12 base case. This would be comprised partly by the impact of greater yields (2%), and partly due to the shift in the composition of area planted (2.7%). The change in demand by type will vary. These results suggest a 5.6% increase in anhydrous, 5.5% increase in urea and 3.8% increase in UAN. The states with the largest increases are: Anhydrous: IL, IA, MN, ND; urea: AR, MN, ND, SD and UAN: IL, IN., IA, NE, OH. These differences are due to state level preferences of fertilizer by type; and there is there is no evidence of changes in preferred N type in this data.

Imports: Import volumes from Canada to the U.S. were from Statistics Canada, 2013. These were averaged for 2010/11 to 2011/12 and used as constraint for maximum Canadian imports. Imports for U.S. ports were aggregated to U.S.-Gulf and obtained from (USDA-ERS, 2013b). Prices were obtained for these from Bloomberg and Greenmarkets.

4.2.2. Fertilizer Plants Capacities and Costs

Plant capacities were obtained from IFDC, (2013). These list capacity by type (anhydrous ammonia, urea, and UAN) for North America (Table 4.3). Data on new or prospective plants were obtained from IFDC, 2013, Agweek, and from press releases, from Greenmarkets, and other industry sources. All existing and potential expansion or new plants are presented in Figure 4.2for anhydrous, Figure 4.3for urea, and Figure 4.4for UAN.

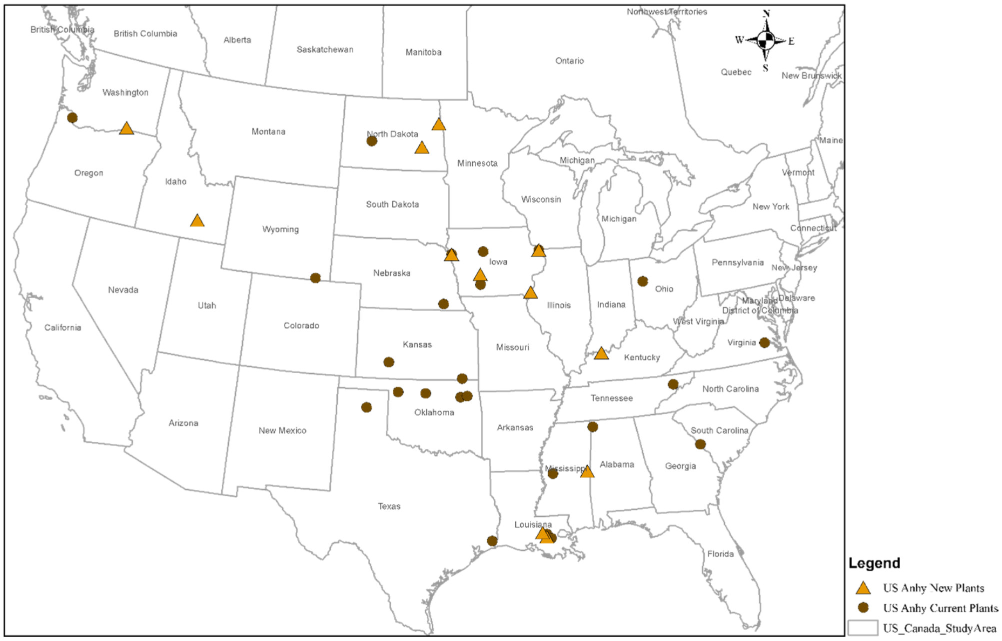


Figure 4.2. Anhydrous fertilizer plants that are treated as current (in year 2012) and expected to be operational in future (in year 2018).

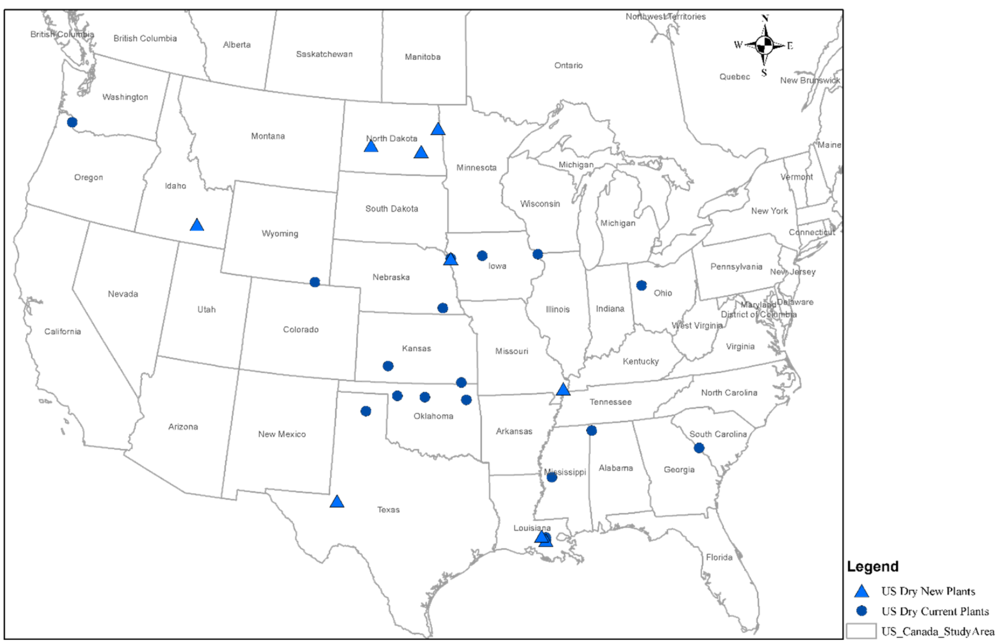


Figure 4.3. Urea fertilizer plants that are treated as current (in year 2012) and expected to be operational in future (in year 2018).

Costs of production by product were assumed related to those estimated by Maung et al,(2012). Specifically, the costs represented in that study which reflect the economies and input requirements for modern state of art plants, were re-engineered to develop costs functions for fertilizer manufacturing. Costs for anhydrous ammonia, urea, and UAN were estimated as a function of costs of Natural-gas, electricity, other costs and total capacity to reflect economies of size.

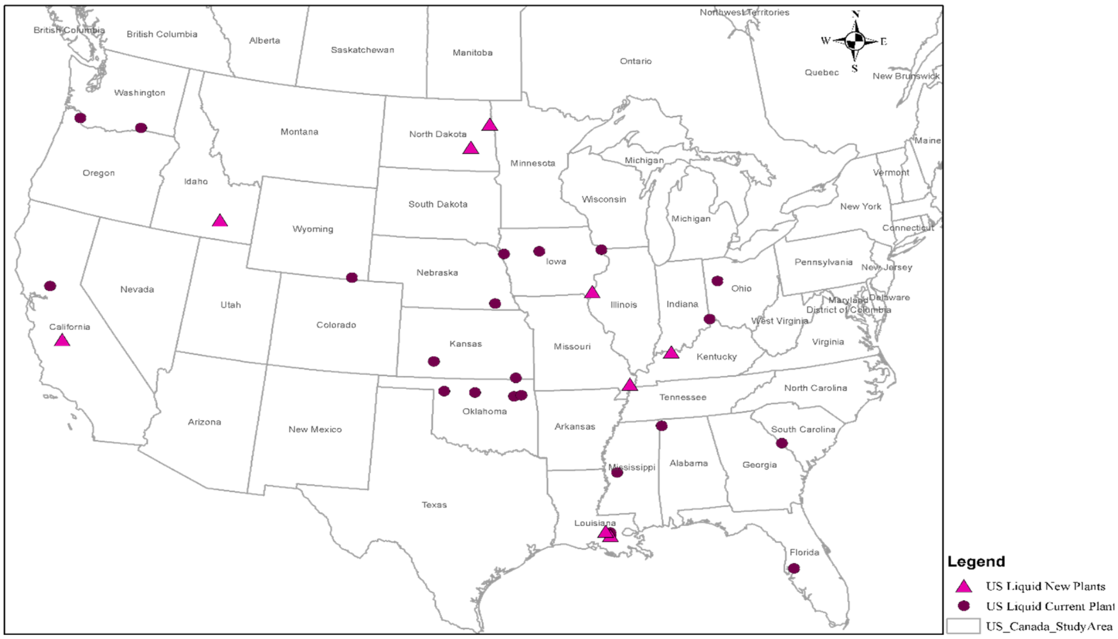


Figure 4.4. UAN fertilizer plants that are treated as current (in year 2012) and expected to be operational in future (in year 2018).

Costs for natural-gas by state were taken from EIA 2013a and were the average of monthly Industrial Prices from Jul 2010 to Feb 2013. The natural-gas spread for each state was estimated as the spread between Industrial Prices and Henry-Hub Futures for the current 2010-2012 case and for the future case. Spatial basis levels were assumed unchanged, while Henry-Hub prices were reflective of current estimates for 2018 Henry-Hub (HH) prices. Electricity costs were also obtained by state from EIA, 2013b and reflect average cents/kw hour from for 2010-2012.

Costs for anhydrous ammonia were assumed to be a function of cost of natural-gas, electricity, O&M, Capital Costs following Maung et al. 2012, where:

$$\text{NGas Cost}_i = 33\ \text{MMBtu/ton} * (\text{NG Spread}_i + HH) * \text{Capacity}_i \qquad \text{(Eq. 4.22)}$$

$$\text{Elect Cost}_i = (1919 - 119.16 * \text{Ln}(\text{Capacity}_i) * \text{Capacity}_i * \text{Elec Price}_i / 100 \qquad \text{(Eq. 4.23)}$$

$$O\&M\ \text{Cost}_i = (40.023 - .000007 * \text{Capacity}_i) * \text{Capacity}_i \qquad \text{(Eq. 4.24)}$$

$$\text{Capital Cost}_i = (121053 * \text{Capacity}_i^{.6505}) / \sum_{n=1}^{N} 1/(1+i)^n \qquad \text{(Eq. 4.25)}$$

$$\text{Anhydrous Cost}_i = \text{NGas Cost}_i + \text{Elect Cost}_i + \text{O\&M Cost}_i + \text{Capital Cost}_i \qquad \text{(Eq. 4.26)}$$

Costs for urea were derived from Anhydrous Cost where:

$$\text{Urea Cost}_i = (\text{Anhydrous Cost}_i * .58) + (\text{NG Spread}_i + HH) * 5.166667 + 22 \qquad \text{(Eq. 4.27)}$$

Costs for UAN were estimated as a function of urea costs where:

$$\text{UAN Cost}_i = (-1242.3 + 257.15 * \ln(\text{Urea Cost}_i)) \qquad \text{(Eq. 4.28)}$$

In total, the processing costs included operating, capital, natural-gas and electricity. The base case used these input values by state for the period 2010-12 and the projected period used EIA estimates for the period 2018 by state based on HH and the state level differential relative to the projected HH value. These costs were then included as inputs into a re-engineered analytical model (i.e. from above) and ultimately used to derive cost for each individual plants. These are shown Figure 2. Important are the obvious economies of size, and the variability across products. The variability across plants is largely due to natural-gas and electricity prices, location, and size.

Shipping Costs: Shipping costs were derived and/or estimated from each origin to the county destination for each of rail and truck and combinations of shipments with barge. Costs were estimated by type (Anhydrous, urea, and UAN).

Rail costs were derived and estimated on a mileage based relationships from current mileage based tariffs for rail (BNSF, 2013c, 2013a, 2013b). These were reviewed by industry participants to identify some shipments which deviated substantially from rates depicted in these functions. In these cases, the rates suggested by industry were used.

Truck rates were collected from 3 major firms. These were based on mileage and truck capacity. These were derived for each and the average across the three firm's quotes were used. Barge rates were used for northbound shipments by barge and the data was from River Transport News for Inland Water Industry(River Transport News, 2013).

4.3. Solution Strategy

The methodology for spatial competition model is based on transportation problem which is then used in linear and mixed-integer form to address various scenarios in model. The transportation problem is solved for minimum cost to derive flows between nodes while allocating supply among demand nodes. Demand for each type is set to be met at demand nodes at cheapest cost from any of supply nodes. In order to achieve this, a unique combination of statistical package for optimization and data visualization in geographic information systems (GIS) is used.

As inputs, capacities of fertilizer plants are brought in as tabular data for set of U.S. (set i) and Canada (set r) plants. Cost of production at each of the elements in is indexed in by sets.

Another set for mode is created that stores cost of transportation per mile per ton of product by mode. A separate set each for U.S.-Canada border points (set s), transshipment points in United States(set p), and import port locations (set q) is created (Table 4.1). Another set is created for county points that stores demand (set j) at county level (by type of product Anhy, urea and UAN is also specified) (Table 4.2). Lastly, in order to get cost of shipping between all elements of origin sets to all elements of destination sets, origin-destination (OD) matrixes were obtained using GIS and imported into optimization model. In absence of this approach, getting shipping costs between any pair of nodes would not have been feasible and thus is a major advantage of approach used in this dissertation.

Table 4.1. Origin nodes and transshipment points that are treated as various sets in model.

Canada Plants	ID set (i)
Medicine Hat, AB	612
Redwater, AB	617
Belle Plaine, SK	644
Canada-U.S. Border Points	ID set (s)
POE:Kingsgate	9163
POE:Coutts	9303
POE:Portal	9384
Northgate	3800141
Emerson	8800451
Imports:U.S. Gulf	ID set (q)
New Orleans, LA	2200374
Galveston, TX	4800608
Inland Trans-shipment Points	ID set (p)
Minneapolis, MN	2700093
St Louis, MO	2900310
Catoosa, OK	4000131

Table 4.2. A sample format of demand nodes (all counties with positive demand) for anhydrous ammonia, urea and UAN (AC, DC and LC refer to demand in year 2012 for anhydrous ammonia, urea and UAN respectively).

ID set (j)	AC	DC	LC
38051	4249.296	7736.651	1175.727
38053	733.4	1335.294	202.9226
38055	12905.66	23497.2	3570.833
38057	1707.015	3107.945	472.3096
38059	8439.5	15365.71	2335.104
38061	4470.321	8139.069	1236.882
38063	2071.043	3770.728	573.0317

In order to address large number of ODs, this dissertation follows a naming convention for OD matrix as Origin-to-Destination-mode (without spaces) to account for number characters that can be used to name an element of set. Origins from Canada are named as 'Can' and United States as 'U.S.'. In order to keep model consistent for ODs, road network was supplied to create ODs for pipe as mode transport as data for pipe was not obtained. This is structure OD for pipe is similar to others except the distance values are ignored in optimization model subjective values between selective pairs of origin destination are used. Following set of plant to plant movements were accounted in OD matrixes:

1. Border To Demand Rail
2. Border To Demand Road
3. Can To Border Rail
4. Can To Border Road
5. Imports To Demand Rail
6. Imports To Demand Road
7. Imports To Inland Barge
8. Inland To Demand Rail
9. Inland To Demand Road

10. U.S. To Demand Rail

11. U.S. To Demand Road

12. U.S. To Inland Barge

Following set of plant to demand movements were accounted in OD matrixes:

1. Border To U.S. Rail
2. Border To U.S. Road
3. Can To Border Rail
4. Can To Border Road
5. Imports To Inland Barge
6. Imports To U.S. Pipe
7. Imports To U.S. Rail
8. Imports To U.S. Road
9. Inland To U.S. Rail
10. Inland To U.S. Road
11. U.S. To Inland Barge
12. U.S. To U.S. Pipe
13. U.S. To U.S. Rail
14. U.S. To U.S. Road

Origins and destinations points in model are treated as nodes. These include demand and supply points along with transshipment points. County centroid are treated as demand nodes such their demand by for anhydrous ammonia, urea and UAN has to be met. This demand is to be met by either of the modes. A sample data for few counties is shown in Table 4.2. As seen from Figure 4.1 that shown most of demand is concentrated in Midwest and upper Midwest region.

Centroid of each county is treated as demand node. Demand by type (anhydrous ammonia, urea and UAN) are shown in Figure A.1, Figure A.2, and Figure A.3

U.S. and Canada fertilizer plants, for anhydrous (Figure 4.2), urea (Figure 4.3) and UAN (Figure 4.4) are treated as origin nodes. The capacities of origin nodes of U.S. and Canada plants by their identification number is shown in Table 4.3 and description of each fertilizer plant by identification number is provided in Table A.1. Import points from U.S. Gulf .are also treated as origin nodes Figure 4.6 whereas border points between U.S. and Canada are treated as transshipment points. At the border points the mode stays constant for incoming and outgoing shipments. Three inland transshipment points are also used where the incoming mode is barge, but changes to either truck or rail for outgoing shipments Table 4.1.

Flows between nodes are allowed by mode of rail, truck, barge and pipe for each type (of . anhydrous ammonia, urea and UAN).Normal flow of shipment is allowed between nodes for anhydrous ammonia, urea and UAN, and anhydrous only flow, the shipment of anhydrous that is allowed to be shipped only for conversion purposes in model A plant needs to produce or get anhydrous in order to make urea or UAN.

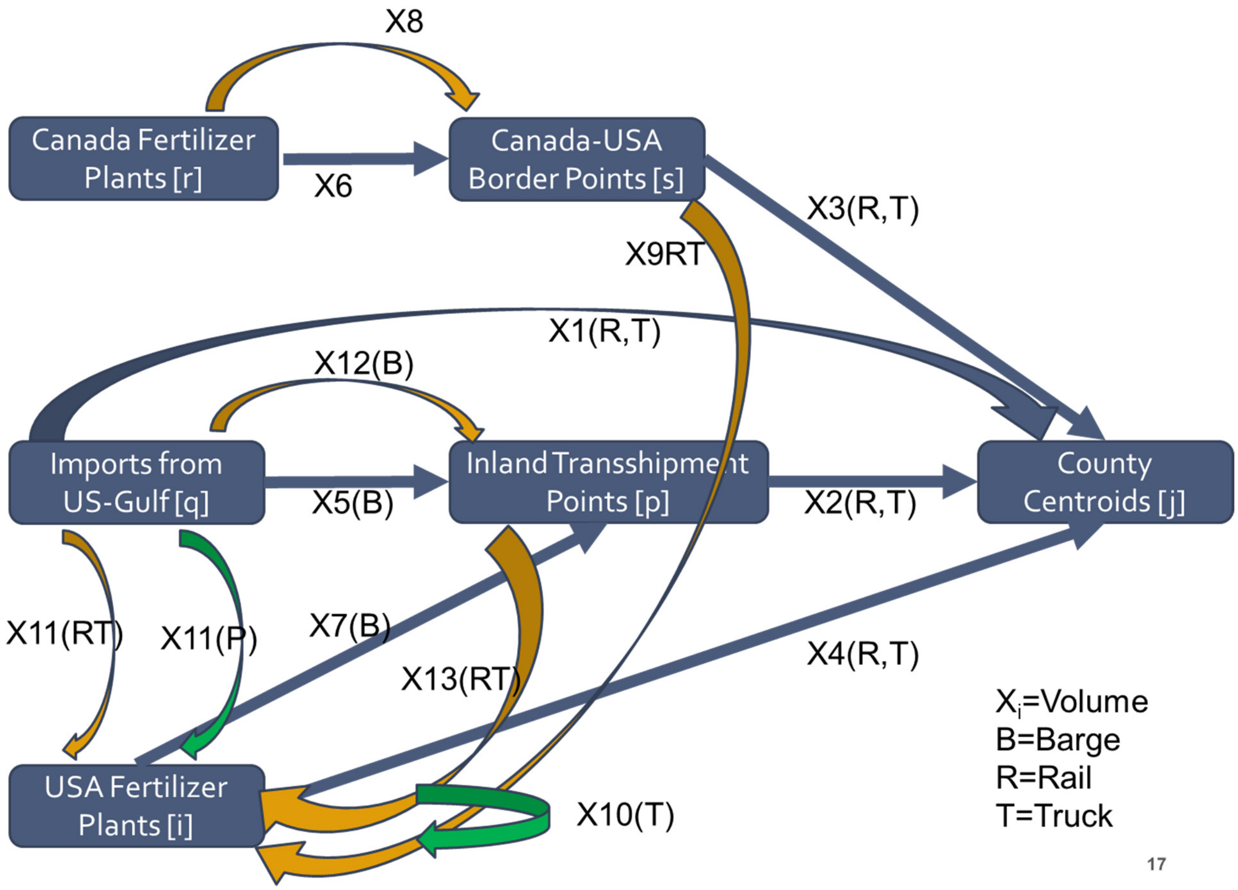


Figure 4.5. Full model showing nodes, flows between nodes, and type of modes allowed between nodes, and name of flows representing quantity of fertilizer shipped. (R=Rail, T=Truck, B=Barge, P=Pipe, blue solid arrows represent normal shipments of anhydrous ammonia, urea and UAN, brown colored arrows represent anhydrous only shipments for conversion into urea or UAN at destination).

Table 4.3. Fertilizer plant capacities for U.S and Canada fertilizer plants. (CpCurA, CpCurD, CpCurL are plant capacities in base case for year 2012.(values in 1000 U.S. short tons). CpFutA, CpFutD, CpFut are plant capacities for future case in year 2018.

Zipcode	CpCurA	CpFutA	CpCurD	CpFutD	CpCurL	CpFutL
23860	620	620	0	0	0	0
30901	867	867	623	623	640	640
33619	0	0	0	0	110	110
35616	167	167	240	240	289	289
37809	68	68	0	0	0	0
39194	560	560	20	20	160	160
39358	0	22	0	0	0	0
45052	0	0	0	0	205	205
45804	674	674	458	458	250	250
47635	0	823	0	0	0	1020
50164	0	55	0	0	0	0
50501	386	386	190	190	540	540
50801	35	35	0	0	0	0
51054	380	1229	50	1398	800	800
52658	0	661	0	0	0	1462
58203	0	2200	0	800	0	500
58481	0	210	0	790	0	238
58523	391	391	0	385	0	0
61025	306	372	163	163	390	390
63869	0	0	0	750	0	500
67337	384	384	275	275	1050	1050
67801	309	309	90	90	255	255
68310	292	292	70	70	200	200
70346	2985	4259	1680	2366	2415	4183
70734	500	500	446	446	1133	1133
70765	0	1274	0	686	0	1768
70792	565	565	0	0	0	0
73701	1100	1100	555	555	90	90
73801	480	480	25	25	800	800
74019	1121	1121	0	0	1965	1965
74362	255	255	153	153	416	416
77627	275	275	0	0	0	0
79007	540	540	109	109	0	0
79776	0	0	0	700	0	0
82001	196	196	105	105	210	210
83211	0	182	0	655	0	528
93627	0	0	0	0	0	230
95691	0	0	0	0	225	225
97051	111	111	125	125	62	62
99337	0	218	0	0	475	475
99611	0	1416	0	1201	0	0
612	1250	1250	1250	1250	1250	1250
617	720	720	720	720	720	720
644	719	719	719	719	719	719

Post optimization, the results obtained are named as mode-origin-destination where in a column is manually created to store values for mode of transportation and flow (normal and anhydrous only). In case of base case following set of resulting ODs are obtained:

1. Railcanplantsborder
2. Truckcanplantsborder
3. Railborderdemandpt
4. Truckborderdemandpt
5. Railimportsdemandpt
6. Truckimportsdemandpt
7. Bargeimportsinland
8. Railinlanddemandpt
9. Truckinlanddemandpt
10. Bargeinlandinland
11. Railusplantsdemandpt
12. Truckusplantsdemandpt
13. Railcanplantsborderanhy
14. Truckcanplantsborderanhy
15. Railborderusplantsanhy
16. Truckborderusplantsanhy
17. Railusplantsusplantsanhy
18. Truckusplantsusplantsanhy
19. Pipeusplantsusplantsanhy
20. Railimportsusplantsanhy

21. Truckimportsusplantsanhy

22. Pipeimportsusplantsanhy

23. Bargeimportsinlandanhy

24. Railinlandusplantsanhy

25. Truckinlandusplantsanhy

26. Supusadmddual (dual of supply constraint for Anhy)

27. Supusddmddual (dual of supply constraint for urea)

28. Supusldmddual (dual of supply constraint for UAN)

29. Modelcost (model cost by iteration))

30. (dual of supply constraint for anhydrous)

In the stochastic simulated cases of repeated optimization a set of such output of ODs is obtained while each being indexed with simulation number. Owing to limitation of hardware resources, values are read once and optimization model is solved for 150 iterations. This was an optimum trade off point for this model when compared to either (1) reading all the inputs and solve the optimization model for each iteration to create a set of output ODs which would have required increased post processing of results or (2) reading the input once and solve all simulations together, the hurdle in which was that system runs out of memory at 165th or 167th iteration depending upon combination of random input variables.

After optimization, the results obtained are processed for further insights. All these steps start from output ODs obtained from optimization using either linear or mixed-integer. First 25 output ODs from optimization step are appended and joined back in GIS to visualize results. The results of this step is a graphic picture of lines representing a flow between a pair of origin and destination wherein the color of lines represent different modes of transportation and relative thickness represents volume of flow. This has tremendous value in terms of verification and calibration of model rather than looking at 2.7+ million rows of data all together as an output from optimization model. In case of simulation, mean volumes are calculated for same pair of origins and destinations by pair of origin- destination, by mode, by flow (normal and Anhy-only). Secondly, dual values are calculated in case of simulation in linear programming by constraints for anhydrous ammonia, urea, and UAN, the result of which is shadow price by USPlants. In case of simulation, mean shadow prices are calculated as a final result which are presented in both tabular and graphical form. Third step is to calculate market boundary using output ODs from optimization results. In order to calculate market boundary for each plant, data is processed such that mean flow, from a plant to all the counties that it supplies to, is calculated across all simulations.

The end result of processing results obtained as output from optimization is set of counties that are supplied by a fertilizer plant with corresponding mean flow and probability. The resulting table can be joined in GIS with shapefile (a file format that shows polygons corresponding for each county) for counties in United States, to obtain counties that are part of market boundary for an individual plant (end shapefile shows the counties that are supplied by fertilizer plant and not the rest of counties). The process can be repeated for all the fertilizer plants of interest and importance in terms of spatial competition. Considering the volume of data and number of fertilizer plants, this approach of bringing the tabular results into GIS clearly indicates as to where a fertilizer plant is likely to ship and with what probability. The change in market boundary also indicates the effect of competitor fertilizer plant. Lastly, the output ODs are also summarized by origin nodes to arrive at mean so as to be able to fit them onto a distribution. Fitting the mean outputs by origin node by type (but not by Type) provides us the distribution and thereby gives us a better picture of model under random variables considered. Cumulative probabilities are derived from the end result of this step that further provides insights about the riskiness of new plants.

4.4. Model and Assumptions

A detailed spatial equilibrium model was developed and solved using optimization techniques and extracting results in GIS. The model included the most important spatially dependent supply chain costs. These include processing costs for each individual fertilizer plant; shipping costs of products by rail, truck and/or barge/truck or barge rail combinations. Imports were modeled endogenously for Canadian produced products, and for import products through the U.S. Gulf.

4.4.1. Base Case Current

The base case included a number of assumptions. The base case was specified to be reflective of the market conditions in the period 2010-2012. Value used for U.S.-Gulf imports are based off of world market price data (extracted from Bloomberg) and were the average over this period. The results were reviewed with industry representatives, and a number of assumptions or restrictions were imposed to calibrate the model to reflect market flows and operations in recent years. Nitrogen based fertilizer plants of United States and Canada are allowed to work at current known production capacities for anhydrous ammonia, urea and UAN. Demand at county level is total demand per county for all the crops grown by type: anhydrous ammonia, urea and UAN for year 2012. Imports from U.S.-Gulf are limited at observed imports for year 2012, by type. Imports of fertilizer across U.S.-Canada border is also limited to no more than that observed in year 2012.

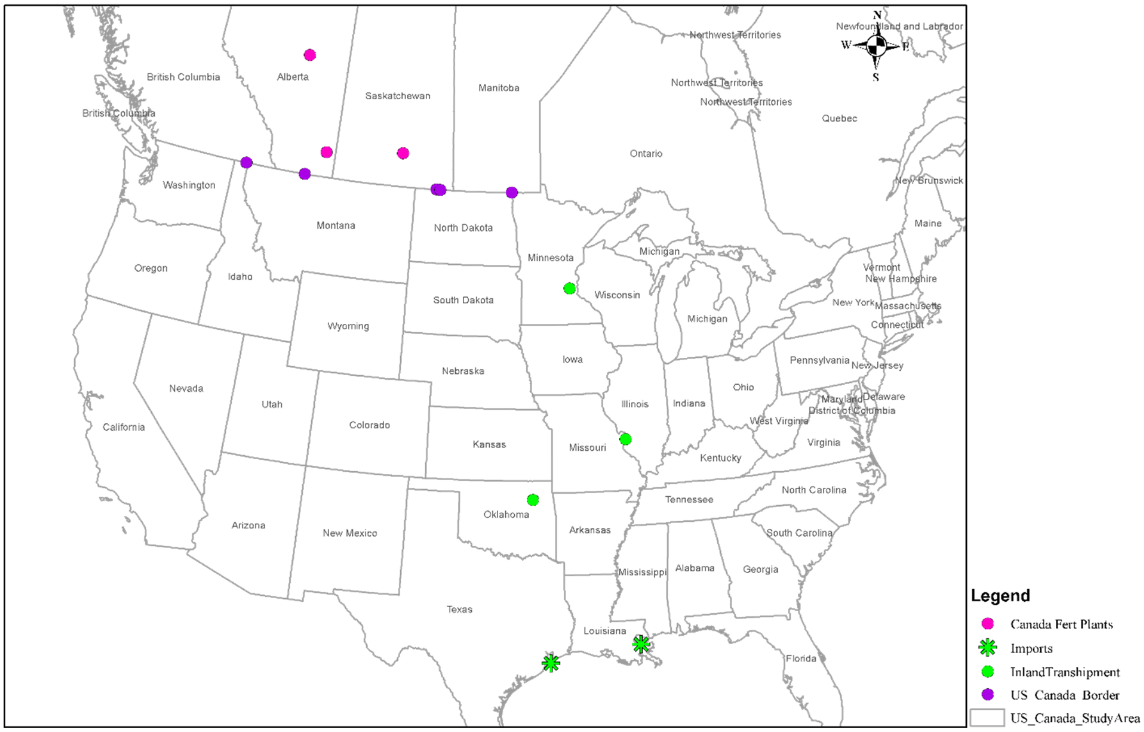


Figure 4.6. Location of Canadian nitrogen fertilizer plants, import nodes, U.S-Canada border nodes,and inland (U.S.A) transhipment nodes.

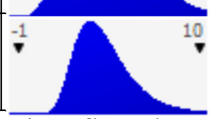
Cost of production (as a function of Henry-hub, electricity cost by state, and size of plant) is treated at discrete and known for each plant for production by type. Cost of transportation is applied from origin to transshipment (if applicable) and to demand is applied by mode (rail, truck, and barge) and by type (anhydrous ammonia, urea, and UAN).

There were 29 U.S. plants operating and three Canadian plants. Anhydrous imports from U.S. Gulf were restricted to be less than 4,978,890, those of urea were less than 5,163,843 and UAN less than 2,626,192 tons. Imports from Canada were limited to 1,022,944, 1,774,719 and 619,498 tons for anhydrous ammonia, urea and UAN respectively. Also, output from Texas plant by rail was limited to be less than 721,000 tons. In order to account seasonal nature of Barge service from Minneapolis, a limit of 20,000 tons was applied as per the input from industry experts in order to better reflect the current scenario in model.

4.4.2. Stochastic Linear Future Case 2018

Nitrogen based fertilizer plants of United States and Canada are allowed to work at current known production capacities for anhydrous ammonia, urea and UAN. In addition all the newly announced plants are allowed to operate in model. Demand at county level is total demand per county for all the crops grown by type: anhydrous ammonia, urea and UAN for year 2012 multiplied by growth factor by type. Demand is treated as random at this stage where in the distribution of demand is based on historical demand by type for each county from 2000–2012 Table 4.4. Processing costs were determined for each individual plant and were adjusted to reflect the 2018 EIA projections for Henry-Hub natural-gas values. These were then adjusted for each individual state using current state level differentials from EIA relative to Henry-Hub.

Table 4.4. Distribution for variables treated as random for future cases (linear and mixed-integer).

Name	Graph	Function/ Distribution	Parameter 1*	Parameter 2*	Parameter 3
Demand / Anhydrous		Triangular	94.6	100.0667	105.6
Demand / Urea		Triangular	94.5	100	105.5
Demand / UAN		Triangular	96.2	100	103.8
Import Anhydrous		Normal-Corrmat	478.39	155.48	
Imported Urea		Invgauss-Corrmat	250.48 (398.14)	927.22 (130.19)	Shift=147.66
Imported UAN		Weibull-Corrmat	2.3348 (281.2)	209.97 (84.64)	Shift=95.149
Henry-Hub		Lognorm-Corrmat	4.29	1.61	

*Value in parenthesis reflect the mean of parameter1 and standard deviation for parameter 2 for shifted distributions.

There are 12 new plants in addition to those in base case that are either expansion to existing or a separate new plants. In case of expansion, the capacity by type is used in to model. All new plants were allowed to operate. Review of historical data and relationships indicate these values are near the bottom range of values, though there is a high degree of volatility.

Imports from U.S.-Gulf are limited at observed imports for year 2012, by type. Import costs at U.S.-Gulf are treated as random, and the distribution for random costs by type is based on fit of historical observed import costs from year 2000 -2012. Imports of fertilizer across U.S.-Canada border is also limited to no more than that observed in year 2012Table 4.4. Derived cost of production (as a function of Henry-Hub which is treated as random, electricity cost by state, and size of plant) is treated as random and known for each plant for production by type. Cost of transportation is applied from origin to transshipment (if applicable) and to demand is applied by mode (rail, truck, and barge) and by type (anhydrous ammonia, urea, and UAN). Henry-hub is treated as random based on fit of distribution of historical values from 2008-2012. Fit for HH for last four years is used to generate random numbers, in order to better reflect the recent changes affecting the industry of nitrogen-based fertilizer industry and major factor behind the expansion of existing fertilizer plants or announcement for new plants. HH data from 2000-2012 is used to derive correlation between HH, import costs and demand. Simple linear Spearman correlation (Table 4.5) between demand by type, import costs at U.S.-Gulf by type, and Henry-hub was used to generate random variables and then solve spatial equilibrium model while minimizing cost. Solutions are categorized by type, mode ad simulation number. A total of 1000 simulation were conducted to accommodate variability of random variable and combination thereof.

Table 4.5. Spearman correlations between import prices by type and Henry-Hub.

	Imported Anhydrous Ammonia	Imported Urea	Imported UAN	Henry-Hub
Imported A. Ammonia	1.000			
Imported Urea	0.667	1.000		
Imported UAN	0.741	0.880	1.000	
Henry-Hub	-0.097	-0.024	0.142	1.000

4.4.3. Stochastic Mixed-Integer Future Case 2018

Nitrogen based fertilizer plants of United States and Canada are allowed to work at current known production capacities for anhydrous ammonia, urea and UAN. In addition, the newly announced plants are allowed to operate in model as binary variable, and if they operate, they operate at least 70 percent of production capacity. Demand at county level is total demand per county for all the crops grown by type: anhydrous ammonia, urea and UAN for year 2012 multiplied by growth factor by type Table 4.4. Demand is treated as random at this stage where in the distribution of demand is based on historical demand by type for each county from 2000 – 2012. Imports from U.S.-Gulf are limited at observed imports for year 2012, by type. Import costs at U.S.-Gulf are treated as random, and the distribution for random costs by type is based on fit of historical observed import costs from year 2000 -2012Table 4.4. Imports of fertilizer across U.S.-Canada border is also limited to no more than that observed in year 2012. . Derived cost of production (as a function of Henry-Hub which is treated as random, electricity cost by state, and size of plant) is treated as random and known for each plant for production by type. Cost of transportation is applied from origin to transshipment (if applicable) and to demand is applied by mode (rail, truck, and barge) and by type (anhydrous ammonia, urea, and UAN). Henry-hub is treated as random based on fit of distribution of historical values from 2008-2012. Fit for HH for last four years is used to generate random numbers, in order to better reflect the recent changes affecting the industry of nitrogen-based fertilizer industry and major factor behind the expansion of existing fertilizer plants or announcement for new plants. HH data from 2000-2012 is used to derive correlation between HH, import costs and demand. Simple linear Spearman correlation (Table 4.5) between demand by type, import costs at U.S.-Gulf by type, and Henry-hub was used to generate random variables and then solve spatial equilibrium model while minimizing cost. Solutions are categorized by type, mode ad simulation number. A total of 1000 simulation were conducted to accommodate variability of random variable and combination thereof.

A binary variable to control the operating for few of the new plants is used. If the binary variable allows these plants, then the plant is allowed to work at least 70 percent of its capacity. This done in order to account for initial break even cost of plants to realize economies of scale.these plants are Spiritwood (j=58481), GradForks (j=58203), Russian (j=70765), Beulah (j=58523), Ector (j=79776), PortNeal (j=51054), and Weaver (j=52658).

$$\sum_{i \in FutSel_{Anhy}, Anhy} \left(\sum_{p,Barge}^{n} X7_{i,p,Anhy,Barge} + \sum_{j,M}^{n} X4_{i,j,Anhy,M} + \sum_{i,M}^{n} X10_{i,i,Anhy,M} \right) \leq USCap_{i,Anhy} * Bin_{i,Anhy} \qquad \textit{(Eq. 4.29)}$$

Where $FutSel_{Anhy}$={58481, 58203, 70765, 52658} for Spiritwood-ND, Grand Forks-ND, Iberville-LA, and Weaver-IA respectively.

$$\sum_{i \in FutSel_{urea}, urea} \left(\sum_{p,Barge}^{n} X7_{i,p,urea,Barge} + \sum_{j,M}^{n} X4_{i,j,urea,M} \right) \leq USCap_{i,urea} * Bin_{i,urea} \qquad \textit{(Eq. 4.30)}$$

Where $FutSel_{urea}$={58481, 58203, 70765,58523,79776,51054} for Spiritwood-ND, Grand Forks-ND, Iberville-LA, Beulah-ND, Ector-TX, and Port Neal-IA respectively.

$$\sum_{i\in FutSel_{UAN},UAN} \left(\sum_{p,Barge}^{n} X7_{i,p,UAN,Barge} + \sum_{j,M}^{n} X4_{i,j,UAN,M}\right)$$

$$\leq USCap_{i,UAN} * Bin_{i,UAN} \qquad \textit{(Eq. 4.31)}$$

Where $FutSel_{UAN}$={58481, 58203, 70765, 52658} for Spiritwood-ND, Grand Forks-ND, Iberville-LA, and Weaver-IA respectively.

$$\sum_{i\in FutSel_{Anhy},Anhy} \left(\sum_{p,Barge}^{n} X7_{i,p,Anhy,Barge} + \sum_{j,M}^{n} X4_{i,j,Anhy,M}\right.$$

$$\left. + \sum_{i,M}^{n} X10_{i,i,Anhy,M}\right) \geq USCap_{i,Anhy} * Bin_{i,Anhy} * .7 \qquad \textit{(Eq. 4.32)}$$

$$\sum_{i\in FutSel_{urea},urea} \left(\sum_{p,Barge}^{n} X7_{i,p,urea,Barge} + \sum_{j,M}^{n} X4_{i,j,urea,M}\right)$$

$$\geq USCap_{i,urea} * Bin_{i,urea} * .7 \qquad \textit{(Eq. 4.33)}$$

$$\sum_{i\in FutSel_{UAN},UAN} \left(\sum_{p,Barge}^{n} X7_{i,p,UAN,Barge} + \sum_{j,M}^{n} X4_{i,j,UAN,M}\right)$$

$$\geq USCap_{i,UAN} * Bin_{i,UAN} * .7 \qquad \textit{(Eq. 4.34)}$$

4.4.4. Sensitivity 1 for Stochastic Linear Future Case 2018

Compared to Future Case 2018 Linear 4.4.2, distribution for demand was allowed to go up to 110 percent of that in base case. After a subjective thought, distribution for import prices was shifted to the right and upward using triangular distribution as shown in Table 4.6. Henry-Hub that reflects the price of natural-gas, is allowed to slightly higher mean of 4.717 but the variability was kept same.

Table 4.6. Distribution for variables treated as random for sensitivities for future cases (linear and mixed-integer).

Name	Function/ Distribution	Parameter 1*	Parameter 2*	Parameter 3
Demand / Anhydrous	Triangular	94.6	100	110
Demand / urea	Triangular	94.5	100	110
Demand / UAN	Triangular	96.2	100	110
Import Anhydrous	Normal-Corrmat	239	200	140.5
Imported urea	Invgauss-Corrmat	478	400	281
Imported UAN	Weibull-Corrmat	1015.75	850	597.125
Henry-Hub	Lognorm-Corrmat	4.717	1.61	

4.4.5. Sensitivity 2 for Stochastic Mixed-Integer Future Case 2018

Compared to Future Case 2018 Mixed 4.4.3, distribution for demand was allowed to go up to 110 percent of that in base case. After a subjective thought, distribution for import prices was shifted to the right and upward using triangular distribution as shown in Table 4.6. Henry-Hub that reflects the price of natural-gas, is allowed to slightly higher mean of 4.717 but the variability was kept same. The lower limit for plant if it is to work was kept same at 70 percent all other random variables were kept same.

5. RESULTS

5.1. Overview

In order to analyze spatial competition among nitrogen-based fertilizer plants in United States and their respective market boundaries, a stochastic spatial optimization model was applied. This dissertation also derived structure of supply chain for nitrogen-based fertilizer in United States as a base case for year 2012. The base case is treated as discrete static model wherein the values of all input parameters are known. Later on, stochastic parameters including demand at county level, price of natural-gas (based on volatility in Henry-Hub) and price of imported fertilizer for all three type of fertilizer, are allowed to vary as per historical distribution. All of the fertilizer plants (existing and planned) are allowed to operate in the model as expected in year 2018. This scenario is referred to as Stochastic Linear Future Case. In order to consider the most likely scenario where in not all the fertilizer plants will be operational, selective fertilizer plants were subjected to binary decision variable. This binary variables subjects the newly built plant to either operate in the model or not, and if it does operate then it has to operate in excess of 70 percent of its capacity. This scenario is referred to as Stochastic Mixed-Integer Future Case. A sensitivity for each of the stochastic scenarios for linear and mixed-integer is conducted to allow for slight variations in demand (higher), Henry-Hub (higher with same variation) and import price fertilizer were also analyzed.

Results are categorized in each section for Base Current, Stochastic Linear Future case, and Stochastic Mixed-Integer Future Case. Thereafter sensitivities for Stochastic Linear Future Case and Stochastic Mixed-Integer Future Case are presented. Each section of the results comprises of following general elements: origination-destination flows depicting shipments of overall structure of supply chain, shadow prices (if applicable), market boundaries showing the counties that are served by fertilizer plants, cumulative distribution functions (if applicable) by the fertilizer plant showing distribution of fertilizer production, utilization rates, and lastly, the distribution fit of output parameters.

To maintain continuity to the reader, some of the important graphs are presented here in text for illustration, and the rest are presented in appendixes. Appendix A: Model Inputs provides most of tables and figures as related to inputs that are used in the model. Base Case has results and graphs for Base Case Current for year 2012. Stochastic Linear Future Case 2018 has results for stochastic linear future case for year 2018, Stochastic Mixed-Integer Future Case 2018 has results for stochastic mixed-integer future case for year 2018, Stochastic Linear Future Case 2018 Sensitivity has results for sensitivity of future linear case for year 2018, and Stochastic Mixed-Integer Future Case 2018 Sensitivity has results for sensitivity of future mixed-integer case for year 2018. All the results are categorized by into respective scenarios as mentioned. Lastly, all the cumulative distribution functions across scenarios are presented in Summary Results Across Scenarios.

Cumulative distribution functions for fertilizer plants were also derived across scenarios and are presented to give a better picture to reader, that highlight the differences (plant production and risk) across scenarios. These are different cumulative distribution function derived earlier by plant for all fertilizer types.

5.2. Base Case Current

Results from optimization model were plotted in GIS to show the overall structure of supply chain for anhydrous Figure 5.1, urea Figure B., and UAN Figure B.2.Each line represents a flow between a pair of origin and destinations where in different color represents different mode of transport and relative thickness represents volume of flow between the pair. This methodology of plotting helps in deciding the supply chain structure for anhydrous ammonia, urea and UAN and has tremendous advantage than looking at a large tabular. Some of highlights from Figure 5.1 is that Rail dominates as mode of transport, which is expected. Moreover, majority of anhydrous imports from U.S.-Gulf are via Barge to transshipment points, especially St. Louis, MO and then Rail thereafter. Rail is primarily the mode from Canadian anhydrous imports. Truck constitutes a small portion mainly for short distances. This is consistent with current knowledge of the industry from experts.

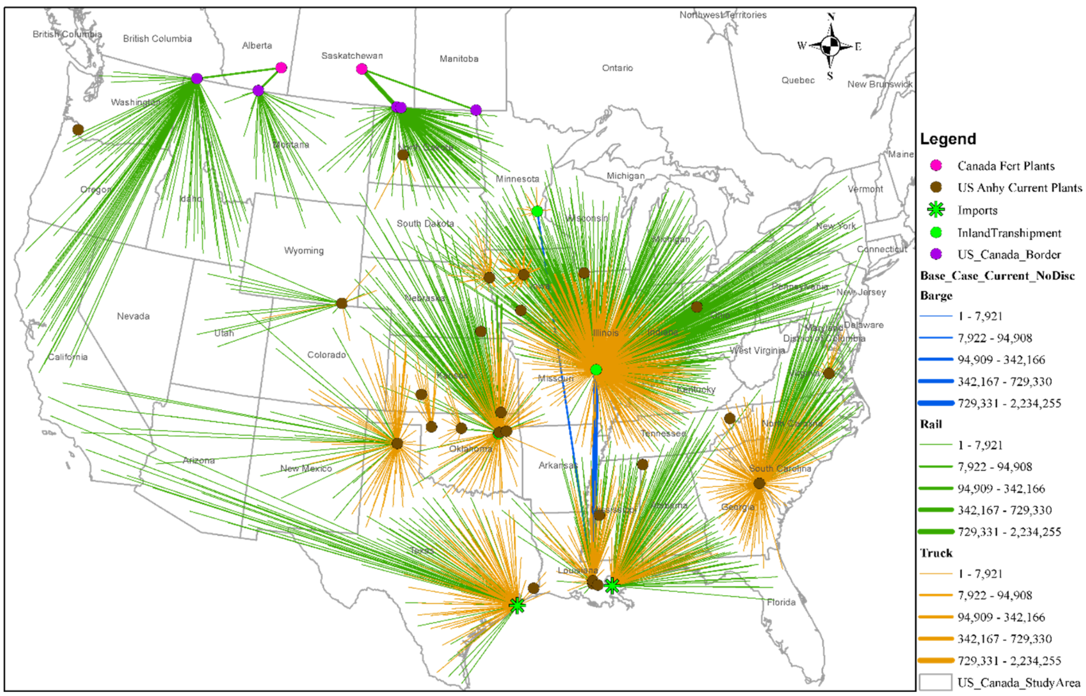


Figure 5.1. Structure of supply chain for anhydrous ammonia for base case by mode (Rail=Green, Truck=Orange, Barge=Blue).

In base case that reflects current scenario of fertilizer industry, only few of the plants are at capacity. This may vary depending upon how far away the assumptions of model are from reality. This model was calibrated repeatedly to reflect current scenario with input from industry experts and literature. Shadow prices were extracted post optimization. It may be noted that based on shadow prices, although most valuable place to expand is for plants in Sacremento, CA (j=95691) and Kennewick, WA (j=99337), however, with subjective knowledge we know that it is less likely to happen so in California as land cost etc may be prohibitive.

Table 5.1. Shadow prices for existing plants running at capacity for base case and corresponding flow quantities. (Dual_A, Dual_B, Dual_L are dual values for anhydrous ammonia, urea and UAN, respectively.

USplants	Dual_A	Dual_D	Dual_L
23860	0	-8	-80
30901	0	0	-54
35616	0	0	0
45804	0	0	-13
50501	-18	0	-25
51054	-31	0	-30
58523	0	0	-116
61025	0	0	-3
67801	0	0	-4
68310	0	0	-9
70346	-72	0	-72
70734	-2	0	-26
73701	0	0	-4
73801	0	0	-9
74019	-5	0	-1
79007	0	0	-49
82001	0	0	-29
95691	-296	0	0
97051	0	0	-15
99337	-225	0	0

Shadow prices for other plants in base case are presented in Table 5.1. Figure 5.2, Figure B.3, and Figure B.4. present the value of shadow prices in spatial perspective to give reader a better idea regions that are more valuable than others in terms of competition. Louisiana seems to be most important in terms of allowing for expansion or opening up of new plant. Another plant in western Iowa is more valuable than in central Iowa. These plants in Iowa gain even more significance in stochastic scenarios when opening of new fertilizer plants in Midwest regions subjects them to competition (e.g Grand Forks, ND).

Figure 5.2. Shadow prices for anhydrous ammonia in base case.

Market boundaries were also derived for each plant. This step is done post optimization in order to find out all the counties and the total volume for each of these counties from a fertilizer plant. These are then joined to counties to get a market boundary for a plant. This step was repeated for each plant. Market boundary for selective plants is presented here for demonstration purpose in dissertation. The market boundary is presented for plants j=50501, j=51054Figure 5.3 (both current plants). Later another plant planned for opening new is also used for comparison. The plants in Wever, IA and Port Neal, IA have large market boundaries while supplying more to counties closer to them (darker color in map) and lesser to counties farther away. Each of these plants have clearly defined market boundaries (shown in different color).

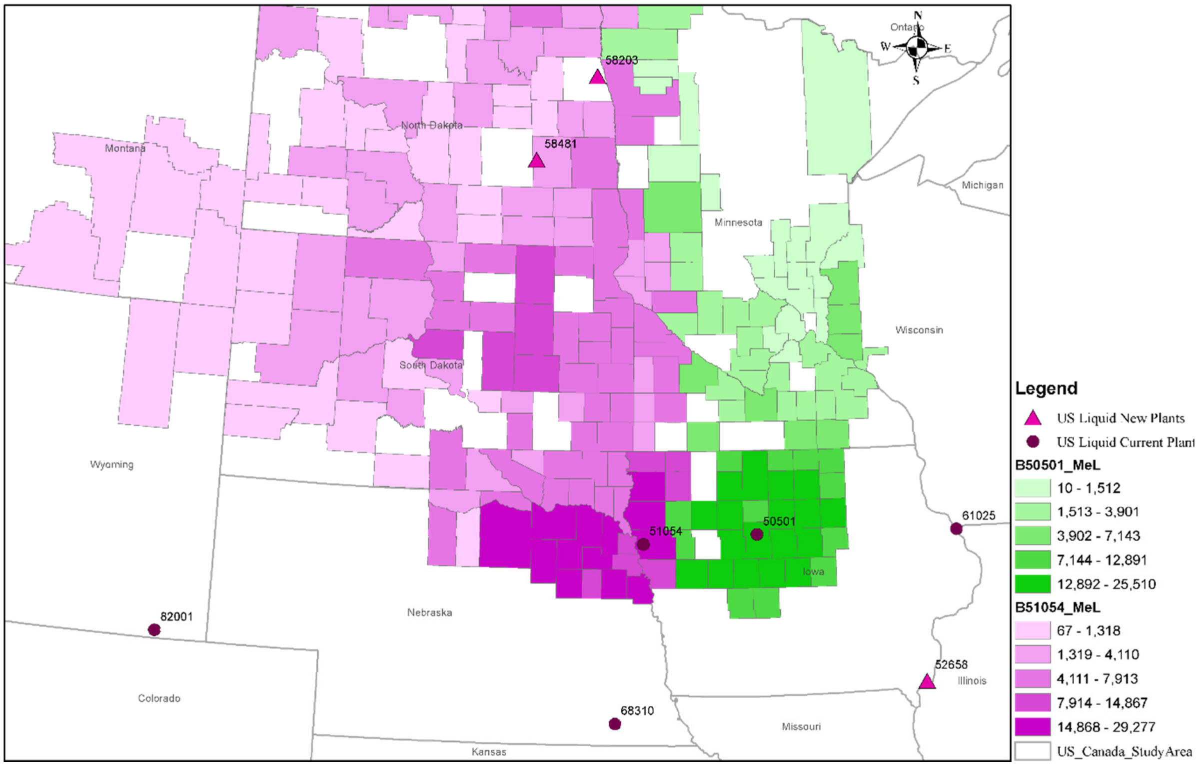


Figure 5.3. Market boundaries for plant i= 50501, i= 51054 for UAN.

As it can be seen in market boundaries for anhydrous ammonia in Figure B.5 that plant 51054 ships most of its product to the counties east of it and plant 50501 to north east of it. This is important from competition perspective. Counties that are being shipped lesser quantities and farther away are most likely to be taken away when there is increased competition from nearby plant. Market boundaries for UAN as shown in Figure B.6 are much widespread. Again most of quantities are shipped to nearby place, the geographic area to which the two plant together serve is huge due to absence of any other plant that produces UAN.

Table 5.2. Utilization rate of fertilizer plants shown in actual tons (U.S. tons) and percentage for base case by type of fertilizer (anhydrous ammonia, urea and UAN).

ID Set(i)	City, state of fertilizer plant	Anhy	urea	UAN	Anhy (%)	urea (%)	UAN (%)
23860	Hopewell VA	876			0%		
30901	Augusta GA	11,736		640,000	1%	0%	100%
33619	Tampa FL						
35616	Cherokee AL			257,557	0%	0%	89%
37809	Mosheim TN						
39194	Yazoo City MS						
39358	Kemper County MS						
45052	North Bend OH						
45804	Lima OH			250,000	0%	0%	100%
47635	Rockport IN						
50164	Menlo IA						
50501	Fort Dodge IA	222,920		540,000	58%	0%	100%
50801	Creston IA						
51054	Port Neal IA	138,400		800,000	36%	0%	100%
52658	Wever IA						
58203	Grand Forks ND						
58481	Jamestown ND						
58523	Beulah ND	8,846			2%		
61025	East Dubuque IL			390,000	0%	0%	100%
63869	New Madrid MO						
67337	Coffeyville KS						
67801	Dodge City KS			255,000	0%	0%	100%
68310	Beatrice NE	5,444		200,000	2%	0%	100%
70346	Donaldsonville LA	2,255,67		2,415,00	76%	0%	100%
70734	Geismar LA	157,834		1,133,00	32%	0%	100%
70765	Iberville LA						
70792	Faustina LA						
73701	Enid OK	30,664		90,000	3%	0%	100%
73801	Woodward OK	52,077		800,000	11%	0%	100%
74019	Verdigris OK	527,570		1,965,00	47%		100%
74362	Pryor OK						
77627	Beaumont TX						
79007	Borger TX	174,616	1,65		32%	2%	
79776	Penwell TX						
82001	Cheyenne WY	10,454	49	210,000	5%	0%	100%
83211	American Falls ID						
93627	Helm CA						
95691	W. Sacremento CA						
97051	St. Helens OR			62,000	0%	0%	100%

Plant utilization is an important indicator that summarizes the overall optimization process. In simplest terms, utilization rate tells us how much of capacity of fertilizer plant is utilized annually (Table 5.2). In practice this may happen in few months of the year or spread throughout the year.

It is worth noting that after meeting all the demand at county level for each type of Anhy, urea and UAN, there is still a surplus capacity of 7,827,893 tons for anhydrous ammonia, 4,927,293 tons for urea and 31,443 tons for UAN. These values are significant. This tells us that import prices are very competitive and takes big share in meeting the demand. There is significant amount of surplus capacity that exists within domestic production of nitrogen-based fertilizer plants. (ignoring conversion its 12,786,629). Other related graphs and figures for Base Case Current are presented in Base Case.

5.3. Stochastic Linear Future Case 2018

Instead of single set of optimized results for base case results, this scenario was simulated with 1000 iterations. Structure of supply chain looks very different from base and accounts for variation and randomness of variables like demand, cost of production (Henry-Hub), and import prices. And since all the fertilizer plants, current and new, were allowed to operate with no restriction on utilization of plant capacity, this scenario is most informative as to what is likely to be the structure of supply chain in year 2018. This scenario allows for all existing and all planned potential fertilizer plants to operate. Mean flows for anhydrous Figure 5.4, urea Figure C.2, and UAN Figure C.3, present the extent to which fertilizer plants can serve demand. Figure shows the potential of supply chains under given assumptions for stochastic future linear case in year 2018 where in all new plants are allowed to operate under random stochastic variables (explained earlier in 4.4.2). Each line represents a mean flow that occurred during one or more iterations out

1000 for which the optimization results were collected. It is to be noted that Midwest is dominated by imports from Canada by rail and shipments from transshipment points at Minneapolis, St Louis, MO and Catoosa, OK. When compared with anhydrous flows in base case, there are numerous flows from St. Louis, MO, Catoosa, OK and imports from Canada and U.S.-Gulf.

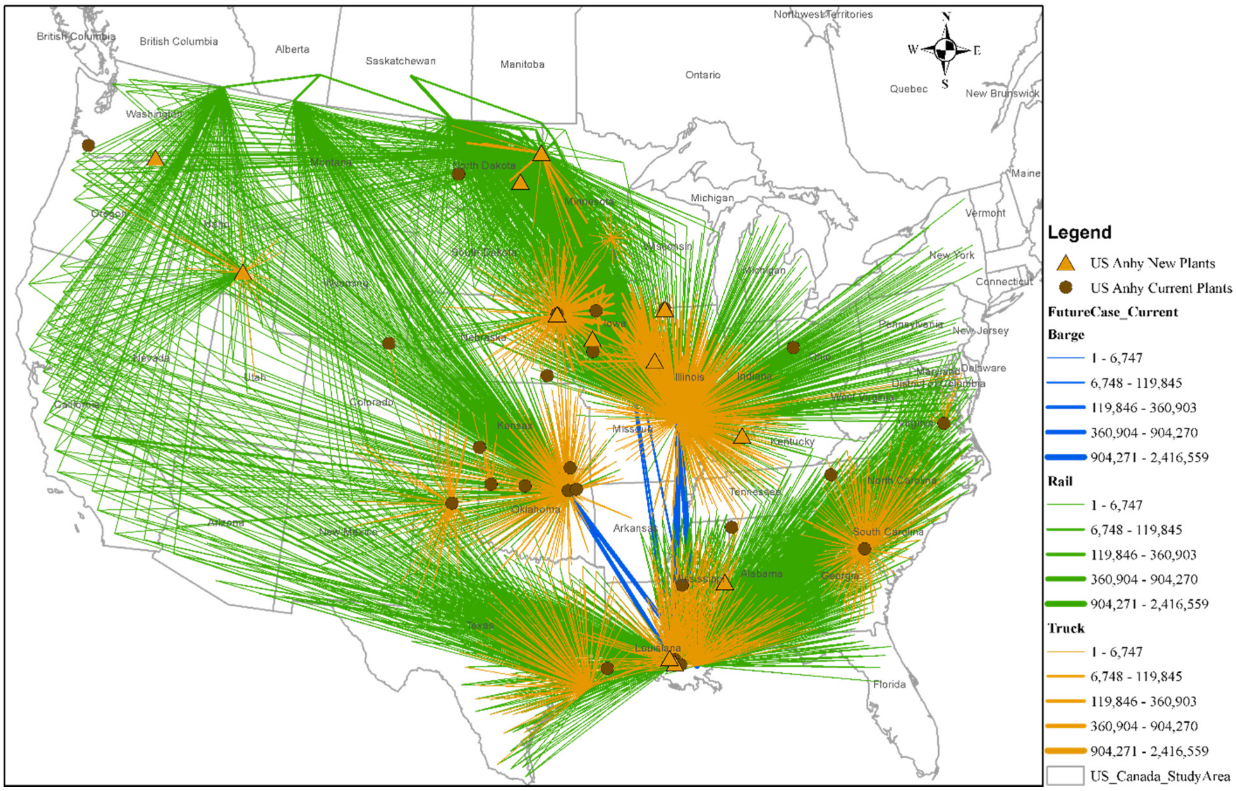


Figure 5.4. Structure of supply chain for anhydrous ammonia for future case linear by mode (Rail=Green, Truck=Orange, Barge=Blue).

Shadow prices for each optimization were captured and mean was calculated for plants running at capacity. Since base case represents only the current scenario, shadow prices from base case represent only one time recommendation.

Table 5.3. Shadow Prices for plants running at capacity for Future case linear and corresponding flow quantities. (Dual_A, Dual_B, Dual_L are dual values for anhydrous ammonia, urea and UAN).

USplants	Dual_A	Dual_D	Dual_L
23860	0	-10	-71
30901	0	0	-41
35616	0	0	0
39194	0	0	0
45804	0	0	-4
47635	0	0	0
50501	0	0	-10
51054	-29	0	-48
52658	0	-12	-4
58203	0	-19	0
58481	-18	0	-44
58523	0	0	-68
61025	0	0	0
67337	0	0	0
67801	0	0	-5
68310	0	0	-10
70346	-39	-6	-8
70734	-1	0	-3
70765	-16	-6	-7
70792	0	0	0
73701	0	0	-2
73801	0	0	-8
74019	0	-7	0
77627	0	0	0
79007	0	-3	-47
79776	-47	0	-142
82001	0	0	0
83211	-5	0	0
93627	-231	0	0
95691	-208	0	0
97051	0	0	-6
99337	0	0	0

Shadow prices of future case linear (Table 5.3) represent the average shadow prices over the full distribution of random variables and thus are much more representative of most valuable plant. Plant 51054 producing anhydrous is 2.5 times more valuable than plant 58203 in Grand

Forks producing urea. Figure C.4, Figure C.5, and Figure C.6 show the average shadow prices for anhydrous ammonia, urea and UAN in spatial format. It can be seen clearly as to where most valuable location for opening up of new plant is for Anhy, urea or UAN (lower the value, the more will be reduction of overall model cost; in other words, the negative value represents reduction in total model cost if one more ton of fertilizer is produced at the plant for example, Port Neal, IA (i=51054)). Similarly, it is to be noticed some of the other plants that had higher shadow price in base case have slightly less value in future case linear (for example plants in California).

Market boundaries present interesting case where new plants directly overtake the market of existing/current plants. Market boundaries for future case linear are calculated in two formats; one by mean quantity shipped for 1000 iterations, and secondly by probability where a plant is likely to ship out of 1000 iterations of simulations. For example, the market boundary of the planned new for anhydrous plant in Grand Forks (j=58203), chips away the market boundary of plants 50501 and 51054 as visible from Figure C.7, Figure C.8, and Figure C.9. These figures show most plausible market boundaries for each of the plants mentioned. The new plant in Grand Forks is 80 percent or more likely to ship towards great lakes region and forces the plant 51054 to ship 80 percent of the time to immediate vicinity of its location. Also, for the same plants, and for the market boundaries derived, Figure C.16, Figure C.17, and Figure C.18 represent mean quantity of fertilizer shipped by plant 50501, 51054 and 58203 respectively. Nonetheless, the plant in Grand Forks covers wide area in Midwest which was earlier supplied by plants in Iowa and imports from Canada.

Market a boundary by mean probability is where fertilizer plants are most likely to ship (Figure 5.5, Figure 5.6, and Figure C.13) are shown for plants 50501, 51054 and 58203 for urea were derived. Darker areas in figures represent the counties where a fertilizer plant is most likely to ship most of the time in year 2018. Similarly, market boundaries by mean quantity shipped (Figure C.19, Figure C.20, and Figure C.21) are also derived wherein darker areas shows the counties where more quantity of fertilizer is shipped from a fertilizer plant on an average. Market boundaries with average mean quantity define the counties where a fertilizer plant is most likely to ship in year 2018. Market boundaries for probability for UAN (Figure C.13, Figure C.14, Figure C.15) and mean quantity (Figure C.22, Figure C.23, Figure C.24) are also derived. The advantage of market boundaries over tabular data is clear indication of where the competition will most intense among fertilizer plants.

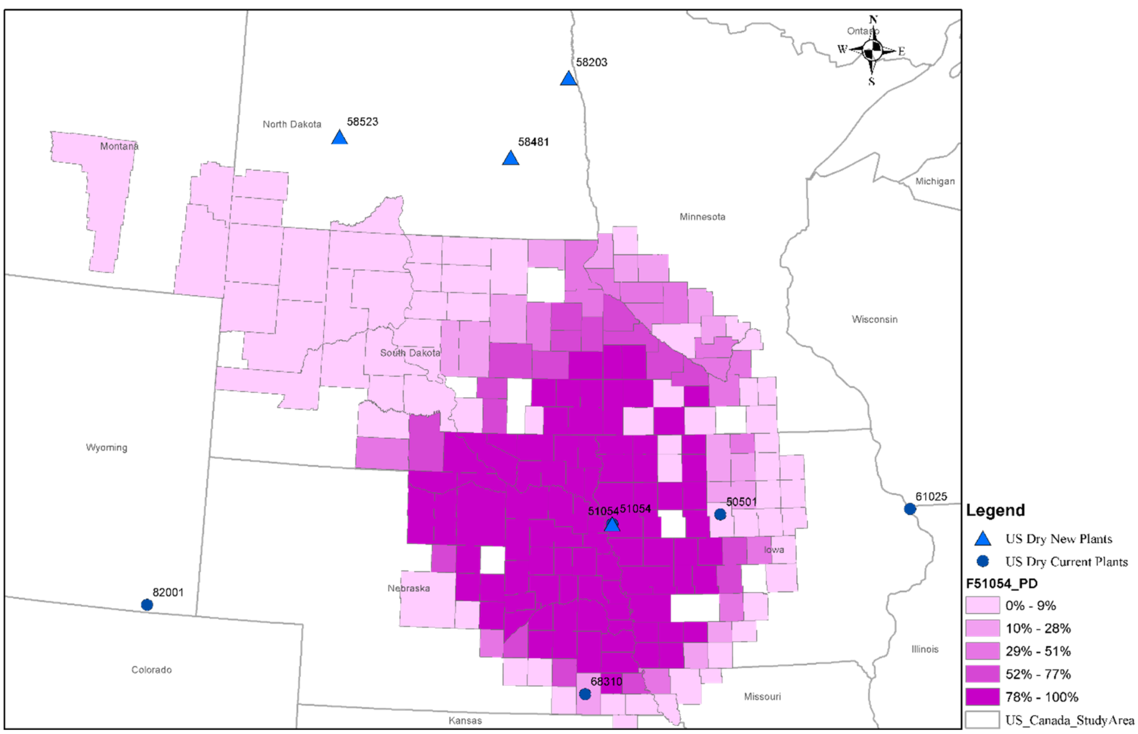


Figure 5.5. Market boundaries for plant i=51054 for urea (probability of shipping for 1000 iterations) in stochastic linear future case 2018.

Utilization rates in stochastic future linear case 2018 represent the average utilization rate of a fertilizer plant for final products shipped over 1000 iterations (Table 5.4). For plants like Woodward, OK (i=73801), average amount of production for anhydrous ammonia shipped, urea shipped and UAN shipped is 17,113 tons, 13,223 tons and 799,036 tons respectively, which is significantly lower than production in base case for anhydrous shipped but higher for urea shipped (base case Table 5.2, 52,077 tons for anhydrous shipped, null for urea, and 800,000 tons for UAN). It is to be noted that intermediate anhydrous ammonia is used to make urea and UAN and is separate from anhydrous ammonia shipped out. Therefore it is more economical for fertilizer plant to ship out urea after conversion at the cost of shipping out anhydrous only. It is to be noted that UAN production stays almost at capacity.

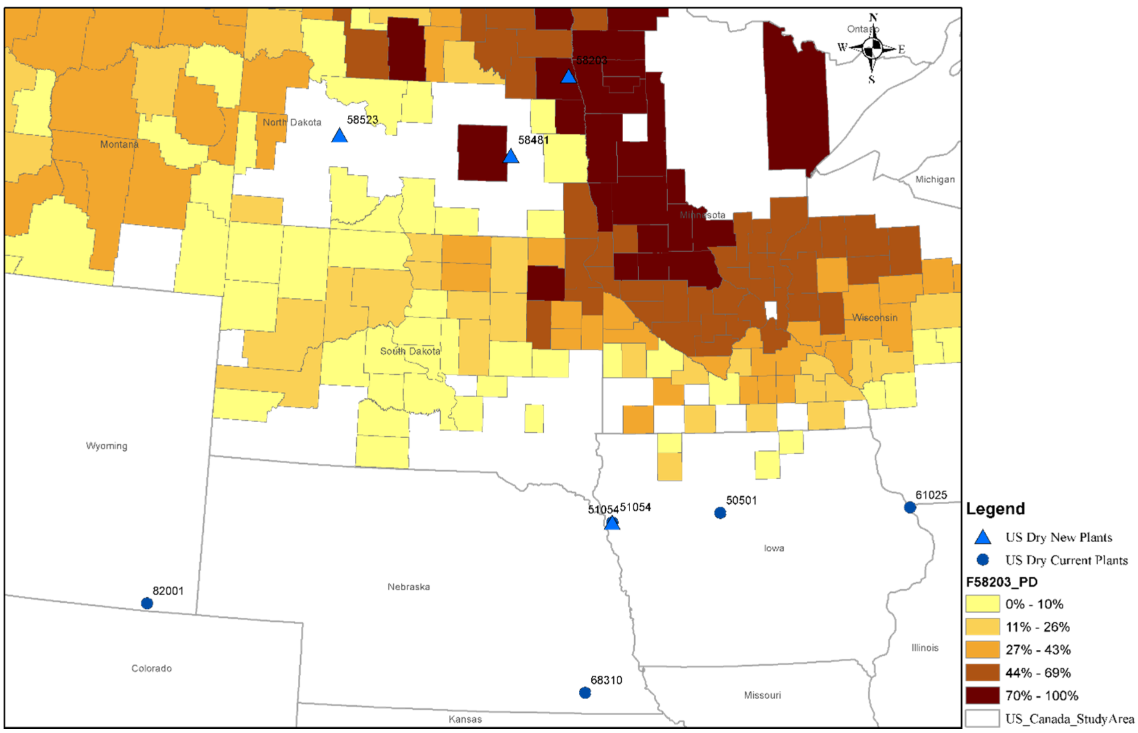


Figure 5.6. Market boundaries for plant i=58203 for urea (probability of shipping for 1000 iterations) in stochastic linear future case 2018.

It is worth noting that after meeting all the demand at county level for each type of anhydrous ammonia, urea and UAN, there is still a surplus capacity of 16,083,235 tons for anhydrous, 5,229,933 tons for urea and 6,022,423 tons for UAN. These values are significant. This tells us that import prices are very competitive and takes big share in meeting the demand. There is significant amount of surplus capacity that exists within domestic production of nitrogen-based fertilizer plants. (ignoring conversion its 27,335,592). Distribution fit for production of output from all existing and planned potential future fertilizer plants is presented in are in Table 5.5. these distributions represent the most likely case for fertilizer production at respective plant in year 2018, if all plants are allowed to operate. This is significant from the fact many of the plants have very low utilization rates. Such plants with low utilization of their production capacity are either manufacturing for products other than nitrogen-based fertilizer (like industrial use) or they are just not going to be viable in future when new plants open up and start operating.

Table 5.4. Utilization rate of fertilizer plants shown in actual tons (U.S. tons) and percentage for stochastic linear future case 2018 by type of fertilizer (anhydrous ammonia, urea and UAN).

ID	City, state of fertilizer	Anhy	urea	UAN	Anhy	urea	UAN(
23860	Hopewell VA	820			0%		
30901	Augusta GA	7,971	19,635	640,000	1%	3%	100%
33619	Tampa FL						
35616	Cherokee AL			240,858	0%	0%	83%
37809	Mosheim TN						
39194	Yazoo City MS			142,729	0%	0%	89%
39358	Kemper County MS						
45052	North Bend OH						
45804	Lima OH			234,325	0%	0%	94%
47635	Rockport IN			396,837	0%		39%
50164	Menlo IA						
50501	Fort Dodge IA	75,630	37,870	540,000	20%	20%	100%
50801	Creston IA						
51054	Port Neal IA	548,775	731,108	800,000	45%	52%	100%
52658	Wever IA	225,195		1,070,1	34%		73%
58203	Grand Forks ND	624,779	790,312	340,881	28%	99%	68%
58481	Jamestown ND		201,480	238,000	0%	26%	100%
58523	Beulah ND		179,874		0%	47%	
61025	East Dubuque IL			237,799	0%	0%	61%
63869	New Madrid MO						
67337	Coffeyville KS		16,690	144,852	0%	6%	14%
67801	Dodge City KS			239,746	0%	0%	94%
68310	Beatrice NE		8	199,962	0%	0%	100%
70346	Donaldsonville LA	2,025,7	2,253,6	2,800,8	48%	95%	67%
70734	Geismar LA		202,054	806,994	0%	45%	71%
70765	Iberville LA	333,491	678,776	1,690,6	26%	99%	96%
70792	Faustina LA						
73701	Enid OK	2,913	57,752	85,078	0%	10%	95%
73801	Woodward OK	17,113	13,223	799,036	4%	53%	100%
74019	Verdigris OK	71,937		810,468	6%		41%
74362	Pryor OK						
77627	Beaumont TX						
79007	Borger TX	81,713	103,015		15%	95%	
79776	Penwell TX						
82001	Cheyenne WY	2,018	2,483	150,185	1%	2%	72%
83211	American Falls ID	24,641	56,096	232,447	14%	9%	44%
93627	Helm CA						
95691	W. Sacremento CA						
97051	St. Helens OR			57,682	0%	0%	93%
99337	Kennewick WA			86,002	0%		18%

Table 5.5. Distributions fit and parameters for output at nodes after 1000 iterations for stochastic linear future case 2018.

	Total Anhydrous	Intermediate Anhy	urea Produced	UAN Produced
23860	Uniform(0,931.76)	Uniform(0,931.76)	N/A	N/A
30901	Weibull(52.615,214936)	Uniform(0,10973)	Uniform(0,38533)	Gamma(62233010.4,0.010284)
35616	InvGauss(72738,9664460)	N/A	N/A	InvGauss(240857,32001523)
39194	Expon(474.15)	N/A	N/A	Expon(1570.0)
45804	Uniform(0,75575)	N/A	N/A	Uniform(0,250250)
47635	Expon(33197)	N/A	N/A	Expon(109923)
50501	BetaGeneral(7.0653,4.9423,0,4434	Uniform(0,164375)	Expon(37869)	InvGauss(540000,4.86000e+022)
51054	Gamma(99.738,12176)	Uniform(0,725708)	Uniform(0,1399399)	Gamma(3.75300e+012,2.13163e-
52658	Uniform(0,661661)	Uniform(0,430338)	N/A	Uniform(0,1463463)
58203	Triang(0,1437258,1513543)	Uniform(0,942158)	Uniform(0,800800)	LogLogistic(0,332172,8.8860)
58481	Triang(0,210000,210000)	N/A	Uniform(0,238383)	Gamma(62233147.9,0.0038243)
58523	Expon(66143)	N/A	Expon(114039)	N/A
61025	Pearson5(74.016,5242126)	N/A	N/A	Pearson5(74.016,17358033)
67337	Expon(12661)	N/A	Expon(3955.5)	Expon(34329)
67801	Uniform(0,77087)	N/A	N/A	Uniform(0,255255)
68310	Gamma(22582.1,2.6744)	N/A	Expon(7.6456)	Gamma(24021.4,8.3243)
70346	Weibull(39.537,4253979)	Uniform(0,2910384)	Uniform(0,2368368)	Uniform(0,4187187)
70734	Uniform(0,500500)	N/A	Expon(118403)	Uniform(0,1134134)
70765	Weibull(12.121,1265278)	Uniform(0,876849)	Uniform(0,686686)	Triang(0,1762854,1807152)
73701	Weibull(4.4128,67948)	Uniform(0,7173.0)	Triang(0,0,138831)	Weibull(13.761,88815)
73801	BetaGeneral(18.507,2.0186,0,2952	Uniform(0,38623)	Uniform(0,25025)	Gamma(1484.9,538.11)
74019	Expon(297969)	Expon(67333)	N/A	Uniform(0,1966966)
79007	Uniform(0,196155)	Uniform(0,132872)	Uniform(0,109109)	N/A
82001	Pearson5(61.931,2972993)	Uniform(0,3058.2)	Uniform(0,4473.1)	Pearson5(47.099,6919115)
83211	Triang(0,182000,182000)	Uniform(0,59629)	Triang(0,0,182823)	Pearson5(30.963,6964904)
97051	Weibull(12.047,18358)	N/A	N/A	Weibull(12.047,60791)
99337	Uniform(0,42471)	N/A	N/A	Uniform(0,140633)

5.4. Stochastic Mixed-Integer Future Case 2018

In previous case of stochastic linear, any fertilizer plant was allowed to enter into market even if they operate only at small percentage of their production capacity. This is unlikely to happen because the newer plants will need to operate at higher capacities to realize economies of scale. Thus a mixed-integer approach was used. Selective plants were subjected tobinary decision variable such that they do not enter the market or if they do get built they operate at in excess of 70 percent of their total production capacity. Structure of supply chain representing origins and destinations are presented for anhydrous (Figure D.), urea (Figure D.2), and UAN (Figure D.3).

Market boundaries of this case present interesting case where in market boundaries of new plants directly overtake the market of existing/current plants. Market boundaries for stochastic mixed-integer future case 2018 are calculated and presented in two formats; one by mean quantity shipped for 1000 iterations, and secondly by probability where a plant is likely to ship out of 1000 iterations of simulations. For example, for anhydrous, the market boundary of planned plant in Grand Forks (j=58203), chips away the market boundary of plants 50501 and 51054 as visible from Figure 5.7, Figure 5.8, and Figure D.4. These figures show most plausible market boundaries for each of the plants mentioned. The new plant in Grand Forks is 80 percent or more likely to ship towards not only the great lakes region but most of Minnesota, North Dakota, and South Dakota, thereby forcing the plant 51054 to ship 80 percent of the times in immediate vicinity of its location.

Table 5.6. Utilization rate of fertilizer plants shown in percentage for stochastic mixed-integer future case 2018 by type of fertilizer (anhydrous ammonia, urea and UAN).

ID Set(i)	City, state of fertilizer plant	Anhy	urea	UAN	Anhy (%)	urea (%)	UAN(%)
23860	Hopewell VA	785			0%		
30901	Augusta GA	7,059	18,455	640,000	1%	3%	100%
33619	Tampa FL						
35616	Cherokee AL			239,733	0%	0%	83%
37809	Mosheim TN						
39194	Yazoo City MS			142,729	0%	0%	89%
39358	Kemper County						
45052	North Bend OH						
45804	Lima OH			224,933	0%	0%	90%
47635	Rockport IN			392,087	0%		38%
50164	Menlo IA						
50501	Fort Dodge IA	71,339	27,226	537,643	18%	14%	100%
50801	Creston IA						
51054	Port Neal IA	381,171	1,026,292	800,000	31%	73%	100%
52658	Wever IA	191,235		1,184,350	29%		81%
58203	Grand Forks ND	956,565	800,000	395,480	43%	100%	79%
58481	Jamestown ND	75,124	0	238,000	36%	0%	100%
58523	Beulah ND	5	314,387		0%	82%	
61025	East Dubuque IL			230,841	0%	0%	59%
63869	New Madrid MO						
67337	Coffeyville KS		19,403	146,438	0%	7%	14%
67801	Dodge City KS			237,544	0%	0%	93%
68310	Beatrice NE		29	199,803	0%	0%	100%
70346	Donaldsonville	2,049,186	2,197,451	2,828,489	48%	93%	68%
70734	Geismar LA		193,183	783,843	0%	43%	69%
70765	Iberville LA	305,187	685,433	1,715,071	24%	100%	97%
70792	Faustina LA						
73701	Enid OK	2,005	52,691	79,768	0%	9%	89%
73801	Woodward OK	13,803	11,945	796,249	3%	48%	100%
74019	Verdigris OK	59,691		788,209	5%		40%
74362	Pryor OK						
77627	Beaumont TX						
79007	Borger TX	72,644	97,988		13%	90%	
79776	Penwell TX						
82001	Cheyenne WY	1,851	2,574	140,558	1%	2%	67%
83211	American Falls	23,376	60,590	230,688	13%	9%	44%
95691	W. Sacremento						
97051	St. Helens OR			53,246	0%	0%	86%
99337	Kennewick WA			85,174	0%		18%

Table 5.7. Distributions fit and parameters for output at nodes (fertilizer plants) after 1000 iterations for stochastic mixed-integer future case 2018.

	Total Anhydrous	Intermediate Anhy	urea Produced	UAN Produced
23860	Uniform(0,931.76)	Uniform(0,931.76)	N/A	N/A
30901	Weibull(39.698,213872)	Uniform(0,10906)	Triang(0,0,44843)	Gamma(62233010.4,0.010284)
35616	Pearson5(101.43,7270009)	N/A	N/A	Pearson5(101.43,24072880)
39194	Expon(474.15)	N/A	N/A	Expon(1570.0)
45804	Uniform(0,75575)	N/A	N/A	Uniform(0,250250)
47635	Expon(30313)	N/A	N/A	Expon(100374)
50501	InvGauss(249498,3424293)	Triang(0,0,220036)	Expon(27226)	Gamma(1031.4,521.30)
51054	Gamma(123.30,9878.6)	Uniform(0,447724)	Uniform(0,1399399)	InvGauss(800000,1.03994e+023)
52658	Uniform(0,661661)	Uniform(0,352285)	N/A	Uniform(0,1463463)
58203	Uniform(0,1541541)	Uniform(0,971272)	Uniform(0,800800)	Uniform(0,500500)
58481	Uniform(0,147147)	Uniform(0,75199)	Expon(0.00026465)	Uniform(0,238238)
58523	Expon(80608)	Expon(2.0045)	Expon(138644)	N/A
61025	LogLogistic(0,66462,12.615)	N/A	N/A	LogLogistic(0,220073,12.615)
67337	Expon(13037)	N/A	Expon(4559.8)	Expon(34412)
67801	Uniform(0,77087)	N/A	N/A	Uniform(0,255255)
68310	Gamma(4018.5,15.020)	N/A	Expon(28.736)	Gamma(4211.4,47.443)
70346	Weibull(38.873,4253870)	Uniform(0,2889609)	Uniform(0,2368368)	Uniform(0,4187187)
70734	Uniform(0,500500)	N/A	Expon(114364)	Uniform(0,1134134)
70765	Uniform(0,1275275)	Expon(302440)	Uniform(0,686686)	Uniform(0,1769769)
73701	Weibull(3.0693,63293)	Expon(2004.6)	Triang(0,0,153244)	Triang(0,90000,90000)
73801	BetaGeneral(13.616,1.8138,0,2949	Expon(13802)	Uniform(0,25025)	Gamma(87.189,9132.5)
74019	Expon(269876)	Expon(51931)	N/A	Expon(685742)
79007	Uniform(0,196155)	Uniform(0,132872)	Uniform(0,109109)	N/A
82001	LogLogistic(0,44158,15.839)	Uniform(0,3026.5)	Uniform(0,4473.1)	LogLogistic(0,134313,16.476)
83211	Triang(0,182000,182000)	Uniform(0,56622)	Triang(0,0,220109)	Pearson5(27.463,6105692)
97051	Triang(0,18724,18724)	N/A	N/A	Triang(0,62000,62000)
99337	Uniform(0,42471)	N/A	N/A	Uniform(0,140633)

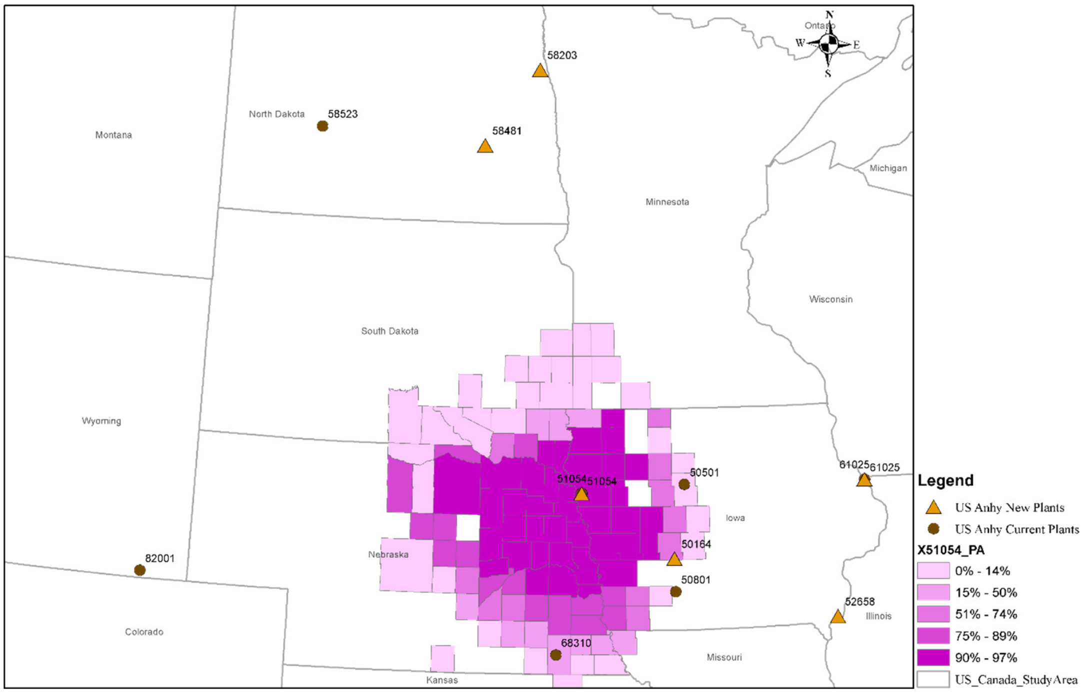


Figure 5.7. Market boundaries for plant i=51054 for anhydrous ammonia (probability of shipping for 1000 iterations) in future case mixed.

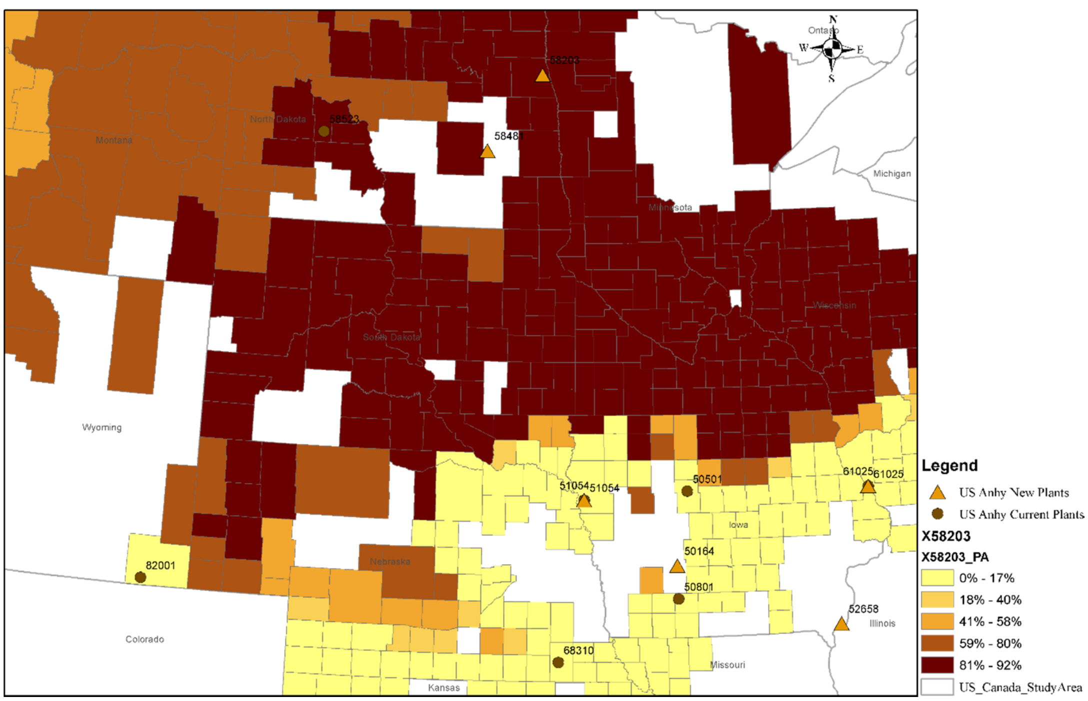


Figure 5.8. Market boundaries for plant i=58203 for anhydrous ammonia (probability of shipping for 1000 iterations) in future case mixed.

The market boundary of the Grand Forks plant has increased with higher probability to a larger region. This gains significance for the fact, that in stochastic mixed-integer case, the Grand Forks plant is working at 70 percent of its capacity and is detrimental to the existence of other existing plants. The market boundaries of plants in Beulah, Jamestown, and northern Iowa is obliterated when the Grand forks plants operates at 70 percent of its capacity in geographic region where it ships with 80 percent of the probability. Also, for the same plants, and for the market boundaries derived, Figure C.16, Figure C.17, and Figure C.18 represent mean quantity of fertilizer shipped by plant 50501, 51054 and 58203 respectively. Nonetheless, the plant in Grand Forks covers wide area in Midwest which was earlier supplied by plants in Iowa and imports from Canada in base case.

In addition to market boundaries analysis for market competition was done for future case mixed in order to clearly get a picture of regions where the competition would be most intense and ruinous. This area comprises of the counties that are common to the market boundaries of more than one plant. In case of anhydrous, regional competition will become increasingly intense with opening up of new plant for example in Grand Forks (58203). Market boundaries for same set of plants: Port Neal, IA(existing plant), Wever, IA (existing plant) and Grand Forks, ND(planned plant) 50501, 51054 and 58203 market boundaries for anhydrous (Figure D.4, Figure D.5, Figure D.6) urea (Figure D.7, Figure D.8, Figure D.9) and UAN (Figure D.10, Figure D.11, Figure D.12) are presented. However in order to highlight the competition in counties where the competition would be most intense, spatial selection (same geographical regions overlaid on top of each other for comparison) in GIS was done to arrive at the common counties that are part of market boundaries where each of the three plants are most likely to ship (Figure 5.9) .

The market boundary (a set of counties) for Port Neal, IA (i=51054) is when put on top of the market boundary of Grand Forks, ND (i=58203), a clear demarcation in form of market boundaries on grand forks is obtained in form of over lapping market boundaries. This is can be called as overlapping market boundaries. It is to be noted that all the area shown in Figure 5.9 is within the market boundary of the new plant in Grand Forks (Figure 5.8 for comparison). Figure 5.9 shows market boundary of the dark colored area shows higher competition between plant 58203 with the rest of the two (51054=pink, 50501=green). Darker areas represent higher probability for a county to be shipped by Grand Forks, ND in future year 2018, whereas pink color represents the market area of Port Neal, IA and Green represents the market boundary of Wever , IA (i=50501) (Figure 5.9). Most intense competition is in close periphery of Port Neal and Weaver plants. In other words, effect of opening of new plants is felt close to existing plants, in this case.

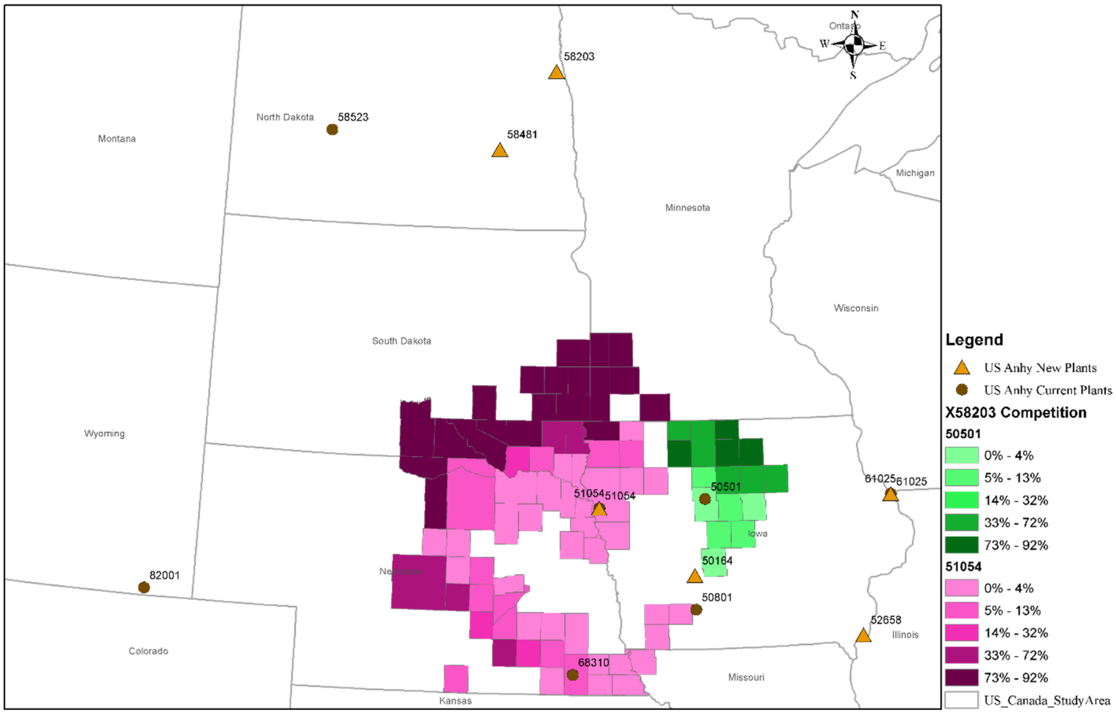


Figure 5.9. Counties for plant 58203 anhydrous ammonia production that are also served by plants 50501 and 51054. Darker region represents higher likelihood of being served. (51054=pink, 50501=green).

The new plant in Grand Forks is not struggling in its close vicinity, instead giving out tough competition to existing plants, far from its location. In fact, market boundary of Grand Forks is so wide to the west, it is covers most of south Dakota, south west Minnesota, north belt of North Dakota and eastern Montana, which were earlier supplied by imports from Canada by Rail and plant in Beulah, ND . It is to be noted, the probability that Grand Forks supplies to counties in Montana is far less than the probability of it supplying to counties in much of eastern North Dakota, South Dakota and Minnesota (Figure C.9). The counties that Grand Forks supplies most of volume on an average is in North Dakota are those in close vicinity of Beulah, ND (i=58523) and Jamestown, ND (i=58481).

Utilization rates in stochastic future linear case 2018 represent the average utilization rate of a fertilizer plant for final products shipped out over 1000 iterations (Table 5.6). For plants like Enid, OK (i=73701), average amount of production for UAN shipped is 90,000 tons, at full capacity, (base case Table 5.2, 30,664 tons of anhydrous, zero for urea, and 90,000 tons for UAN). It is to be noted that intermediate anhydrous ammonia is used to make urea and UAN and is separate from anhydrous ammonia shipped out. Therefore it is more economical for fertilizer plant to ship out UAN after conversion at the cost of shipping out anhydrous only. It is to be noted that UAN production stays at capacity.

It is worth noting that after meeting all the demand at county level for each type of Anhy, urea and UAN, there is still a surplus capacity of 15,914,975 tons for Anhy, 5,066,352 tons for urea and 5,897,123 tons for UAN. These values are significant. This tells us that import prices are very competitive and takes big share in meeting the demand. There is significant amount of surplus capacity that exists within domestic production of nitrogen-based fertilizer plants. (ignoring conversion its 26,878,451). Distribution fit for production or flows coming out are presented in are in Table 5.7

5.5. Sensitivity 1 for Stochastic Linear Future Case 2018

In the case of stochastic linear sensitivity for future case for year 2018, the distributions for stochastic random variables were slightly higher but conservative. The demand was allowed to vary up to 110 percent of the demand in year 2018. Henry-Hub and import prices were also adjusted to allow for most conservative estimate of distribution. All the plants, both existing and future planned are allowed to operate without any restriction on utilization of production capacity. As a major result in this case, it is more economical to devote all of anhydrous produced to be shipped out as UAN after conversion and UAN shipments via truck dominate the in structure of supply chain (Figure 5.1). Imports tend to be cheaper for anhydrous and urea fertilizer as such.

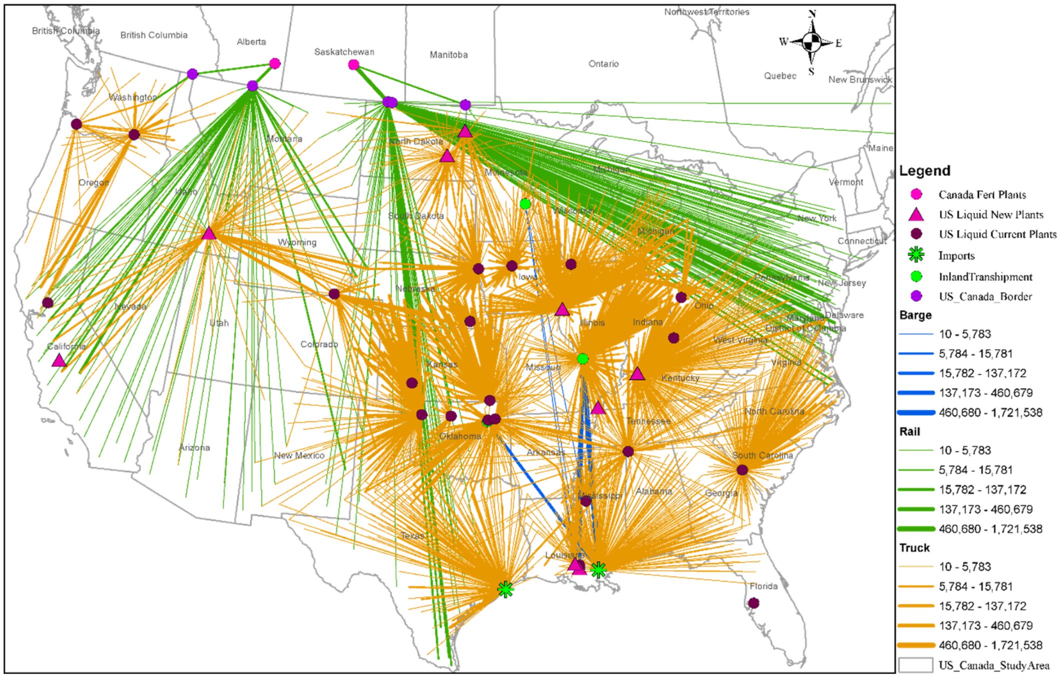


Figure 5.10. Structure of supply chain for UAN for future case linear sensitivity by mode (Rail=Green, Truck=Orange, Barge=Blue).

Table 5.8. Utilization rate of fertilizer plants shown in percentage for stochastic linear future case 2018 sensitivity by type of fertilizer (anhydrous ammonia, urea and UAN).

ID	City, state of fertilizer	Anh	ure	UAN	Anhy	urea	UAN(%
23860	Hopewell VA						
30901	Augusta GA			640,000	0%	0%	100%
33619	Tampa FL						
35616	Cherokee AL			282,071	0%	0%	98%
37809	Mosheim TN						
39194	Yazoo City MS			160,000	0%	0%	100%
39358	Kemper County MS						
45052	North Bend OH						
45804	Lima OH			250,000	0%	0%	100%
47635	Rockport IN			1,020,00	0%		100%
50164	Menlo IA						
50501	Fort Dodge IA			540,000	0%	0%	100%
50801	Creston IA						
51054	Port Neal IA			800,000	0%	0%	100%
52658	Wever IA			1,462,00	0%		100%
58203	Grand Forks ND			106,082	0%	0%	21%
58481	Jamestown ND			238,000	0%	0%	100%
58523	Beulah ND						
61025	East Dubuque IL			390,000	0%	0%	100%
63869	New Madrid MO						
67337	Coffeyville KS			907,926	0%	0%	86%
67801	Dodge City KS			255,000	0%	0%	100%
68310	Beatrice NE			200,000	0%	0%	100%
70346	Donaldsonville LA			798	0%	0%	0%
70734	Geismar LA			15,394	0%	0%	1%
70765	Iberville LA			73,730	0%	0%	4%
70792	Faustina LA						
73701	Enid OK			90,000	0%	0%	100%
73801	Woodward OK			800,000	0%	0%	100%
74019	Verdigris OK			108,125	0%		6%
74362	Pryor OK			65,473	0%	0%	16%
77627	Beaumont TX						
79007	Borger TX						
79776	Penwell TX						
82001	Cheyenne WY			210,000	0%	0%	100%
83211	American Falls ID			179,130	0%	0%	34%
93627	Helm CA						
95691	W. Sacremento CA						
97051	St. Helens OR			62,000	0%	0%	100%
99337	Kennewick WA			188,503	0%		40%

Table 5.9. Distributions fit and parameters for output at nodes (fertilizer plants) after 1000 iterations for stochastic linear future case 2018 sensitivity.

	Total Anhydrous	Intermediate Anhy	urea Produced	UAN Produced
23860	-	-	-	-
30901	Gamma(62232886.4,0.0031058)	N/A	N/A	Gamma(62233010.4,0.010284)
35616	Weibull(42.060,86653)	N/A	N/A	Weibull(42.060,286933)
39194	Gamma(62233202.8,0.00077643)	N/A	N/A	Gamma(62233175.4,0.0025710)
45804	InvGauss(75500,2.10982e+021)	N/A	N/A	Gamma(3.65552e+012,6.83897e-
47635	Gamma(1.81597e+012,1.69629e-	N/A	N/A	Gamma(1.67545e+012,6.08793e-
50501	InvGauss(163080,1.36602e+022)	N/A	N/A	InvGauss(540000,1.36217e+023)
51054	InvGauss(241600,7.48561e+021)	N/A	N/A	Gamma(3.75300e+012,2.13163e-
52658	Gamma(62233457.4,0.0070946)	N/A	N/A	Gamma(62233587.9,0.023492)
58203	Pearson5(40.569,1266281)	N/A	N/A	Pearson5(40.569,4192983)
58481	InvGauss(71876,2.53976e+021)	N/A	N/A	Gamma(62233147.9,0.0038243)
58523	-	-	-	-
61025	Gamma(4.46786e+012,2.63616e-	N/A	N/A	Gamma(3.65552e+012,1.06688e-
67337	Weibull(8.1857,291944)	N/A	N/A	Weibull(8.1857,966703)
67801	Gamma(3.70362e+012,2.07932e-	N/A	N/A	Gamma(2.40577e+012,1.05995e-
68310	InvGauss(60400,1.73696e+021)	N/A	N/A	Gamma(1.73750e+012,1.15108e-
70346	Expon(51.836)	N/A	N/A	Expon(171.64)
70734	Expon(88.332)	N/A	N/A	Expon(292.49)
70765	Expon(8127.3)	N/A	N/A	Expon(26911)
73701	Gamma(4.77076e+012,5.69720e-	N/A	N/A	Gamma(2.60625e+012,3.45324e-
73801	InvGauss(241600,7.30469e+021)	N/A	N/A	Gamma(3.75300e+012,2.13163e-
74019	Triang(0,0,96055)	N/A	N/A	Triang(0,0,318064)
79007	-	-	-	-
82001	InvGauss(63420,2.63958e+021)	N/A	N/A	InvGauss(210000,6.04463e+023)
83211	Pearson5(31.000,1620675)	N/A	N/A	Pearson5(31.000,5366476)
97051	InvGauss(18724,4.52442e+020)	N/A	N/A	Gamma(62233106.5,0.00099625)
99337	Gamma(512.32,111.12)	N/A	N/A	Gamma(512.32,367.94)

The structure of supply chain looks very different for UAN in sensitivity for stochastic future linear case compared to UAN flows in base case (Figure B.2) and stochastic future linear case (Figure C.3). Most of the UAN is produced domestically from fertilizer plants, and shipped out via trucks over shorter distances. There are negligible shipments from USPlants via barge to transshipment points. There are significant shipments for UAN from Canada. St. Louis, MO is the only significant transshipment point.

Utilization rates in sensitivity for stochastic future linear case 2018 represent the average utilization rate of a fertilizer plant for final products shipped out over 1000 iterations (Table 5.8). For plants like Enid, OK (i=73701), average amount of production for UAN shipped is 90,000 tons, which is significantly lower than production in base case for (base case Table 5.2, 800,000 tons for UAN). It is to be noted that intermediate anhydrous ammonia is used to make urea and UAN and is separate from anhydrous ammonia shipped out. Therefore it is more economical for fertilizer plant to ship out UAN after conversion at the cost of shipping out anhydrous only.

It is worth noting that after meeting all the demand at county level for each type of Anhy, urea and UAN, there is still a surplus capacity of 18,830,000 tons for Anhy, 10,233,000 tons for urea and 10,379,766 tons for UAN. These values are significant. This tells us that import prices are very competitive and takes big share in meeting the demand. There is significant amount of surplus capacity that exists within domestic production of nitrogen-based fertilizer plants. (ignoring conversion its 39,442,766). Distribution fit for production or flows coming out are presented in are in Table 5.9

5.6. Sensitivity 2 for Stochastic Mixed-Integer Future Case 2018

In the case of stochastic mixed-integer sensitivity for future case for year 2018, the distributions for stochastic random variables were slightly higher but conservative. The demand was allowed to vary up to 110 percent of the demand in year 2018. Henry-Hub and import prices were also adjusted to allow for most conservative estimate of distribution. All the plants, both existing and future planned are not allowed to operate. Instead selective fertilizer plants are subjected to a binary decision variable for either entering the market by operating or not. If the fertilizer plants does enter the market then it operates in excess of 70 percent of its production capacity. In this case of stochastic mixed-integer sensitivity for future case for year 2018, it is more economical to devote all of anhydrous produced to be shipped out as UAN after conversion. Imports tend to be cheaper for anhydrous and urea fertilizer as such (Figure F.Figure F.2). Compared to sensitivity for stochastic future linear, the stochastic future mized integer case has higher density of truck flows from domestic fertilizer plants (Figure 5.11).

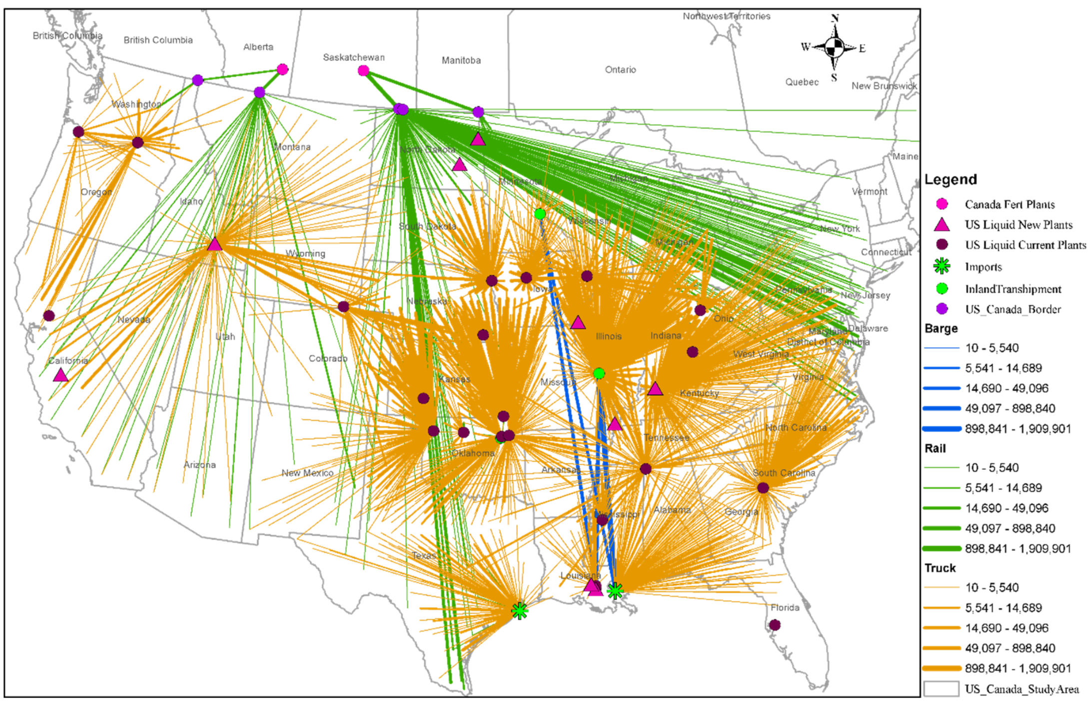


Figure 5.11. Structure of supply chain for anhydrous ammonia for future case mixed-integer sensitivity by mode (Rail=Green, Truck=Orange, Barge=Blue).

It is worth noting that after meeting all the demand at county level for each type of Anhy, urea and UAN, there is still a surplus capacity of 14,485,000 tons for Anhy, 7,957,000 tons for urea and 6,474,422 tons for UAN. These values are significant. This tells us that import prices are very competitive and takes big share in meeting the demand. There is significant amount of surplus capacity that exists within domestic production of nitrogen-based fertilizer plants. (ignoring conversion its 28,916,422).

Utilization rates in sensitivity for stochastic future linear case 2018 represent the average utilization rate of a fertilizer plant for final products shipped out over 1000 iterations (Table 5.10). For plants like Enid, OK (i=73701), average amount of production for UAN shipped is 90,000 tons, which is significantly lower than production in base case for (base case Table 5.2, 800,000 tons for UAN). It is to be noted that intermediate anhydrous ammonia is used to make urea and UAN and is separate from anhydrous ammonia shipped out. Therefore it is more economical for fertilizer plant to ship out UAN after conversion at the cost of shipping out anhydrous only. Distribution fit for production or flows coming out are presented in are in Table 5.11

Table 5.10. Utilization rate of fertilizer plants shown in percentage for stochastic mixed-integer future case 2018 sensitivity by type of fertilizer (anhydrous ammonia, urea and UAN).

ID Set(i)	City, state of fertilizer plant	Anhy	urea	UAN	Anhy (%)	urea (%)	UAN(%)
23860	Hopewell VA						
30901	Augusta GA			640,000	0%	0%	100%
33619	Tampa FL						
35616	Cherokee AL			289,000	0%	0%	100%
37809	Mosheim TN						
39194	Yazoo City MS			160,000	0%	0%	100%
39358	Kemper County MS						
45052	North Bend OH						
45804	Lima OH			250,000	0%	0%	100%
47635	Rockport IN			1,020,00	0%		100%
50164	Menlo IA						
50501	Fort Dodge IA			540,000	0%	0%	100%
50801	Creston IA						
51054	Port Neal IA			800,000	0%	0%	100%
52658	Wever IA						
58203	Grand Forks ND						
58481	Jamestown ND						
58523	Beulah ND						
61025	East Dubuque IL			390,000	0%	0%	100%
63869	New Madrid MO						
67337	Coffeyville KS			1,050,00	0%	0%	100%
67801	Dodge City KS			255,000	0%	0%	100%
68310	Beatrice NE			200,000	0%	0%	100%
70346	Donaldsonville LA			184,771	0%	0%	4%
70734	Geismar LA			948,067	0%	0%	84%
70765	Iberville LA						
70792	Faustina LA						
73701	Enid OK			90,000	0%	0%	100%
73801	Woodward OK			800,000	0%	0%	100%
74019	Verdigris OK			289,617	0%		15%
74362	Pryor OK			302,525	0%	0%	73%
77627	Beaumont TX						
79007	Borger TX						
79776	Penwell TX						
82001	Cheyenne WY			210,000	0%	0%	100%
83211	American Falls ID			307,450	0%	0%	58%
95691	W. Sacremento CA						
97051	St. Helens OR			62,000	0%	0%	100%
99337	Kennewick WA			193,149	0%		41%

Table 5.11. Distributions fit and parameters for output at nodes (fertilizer plants) after 1000 iterations for stochastic mixed-integer future case 2018 sensitivity.

s	Total Anhydrous	Intermediate Anhy	urea Produced	UAN Produced
23860	Uniform(0,931.76)	Uniform(0,931.76)	N/A	N/A
30901	Weibull(39.698,213872)	Uniform(0,10906)	Triang(0,0,44843)	Gamma(62233010.4,0.010284)
35616	Pearson5(101.43,7270009)	N/A	N/A	Pearson5(101.43,24072880)
39194	Expon(474.15)	N/A	N/A	Expon(1570.0)
45804	Uniform(0,75575)	N/A	N/A	Uniform(0,250250)
47635	Expon(30313)	N/A	N/A	Expon(100374)
50501	InvGauss(249498,3424293)	Triang(0,0,220036)	Expon(27226)	Gamma(1031.4,521.30)
51054	Gamma(123.30,9878.6)	Uniform(0,447724)	Uniform(0,1399399)	InvGauss(800000,1.03994e+023)
52658	Uniform(0,661661)	Uniform(0,352285)	N/A	Uniform(0,1463463)
58203	Uniform(0,1541541)	Uniform(0,971272)	Uniform(0,800800)	Uniform(0,500500)
58481	Uniform(0,147147)	Uniform(0,75199)	Expon(0.00026465)	Uniform(0,238238)
58523	Expon(80608)	Expon(2.0045)	Expon(138644)	N/A
61025	LogLogistic(0,66462,12.615)	N/A	N/A	LogLogistic(0,220073,12.615)
67337	Expon(13037)	N/A	Expon(4559.8)	Expon(34412)
67801	Uniform(0,77087)	N/A	N/A	Uniform(0,255255)
68310	Gamma(4018.5,15.020)	N/A	Expon(28.736)	Gamma(4211.4,47.443)
70346	Weibull(38.873,4253870)	Uniform(0,2889609)	Uniform(0,2368368)	Uniform(0,4187187)
70734	Uniform(0,500500)	N/A	Expon(114364)	Uniform(0,1134134)
70765	Uniform(0,1275275)	Expon(302440)	Uniform(0,686686)	Uniform(0,1769769)
73701	Weibull(3.0693,63293)	Expon(2004.6)	Triang(0,0,153244)	Triang(0,90000,90000)
73801	BetaGeneral(13.616,1.8138,0,2949	Expon(13802)	Uniform(0,25025)	Gamma(87.189,9132.5)
74019	Expon(269876)	Expon(51931)	N/A	Expon(685742)
79007	Uniform(0,196155)	Uniform(0,132872)	Uniform(0,109109)	N/A
82001	LogLogistic(0,44158,15.839)	Uniform(0,3026.5)	Uniform(0,4473.1)	LogLogistic(0,134313,16.476)
83211	Triang(0,182000,182000)	Uniform(0,56622)	Triang(0,0,220109)	Pearson5(27.463,6105692)
97051	Triang(0,18724,18724)	N/A	N/A	Triang(0,62000,62000)
99337	Uniform(0,42471)	N/A	N/A	Uniform(0,140633)

5.7. Distribution of Stochastic Output Values

Looking at the results for each of the four scenarios other base case, it is clear that there is enough surplus capacity, and that import prices and price of natural-gas have tremendous influence as to which fertilizer plants will utilized to meet the demand. Some fertilizer are currently existing, will face stiff competition when another fertilizer plants opens up in its vicinity. For example, with opening up of fertilizer plant in grand forks (j=58203), it takes major part of market boundary of plants in Iowa (j=50501, 51054) for urea as shown earlier stochastic linear future case and base Figure 5.9. That being said, not all fertilizer plants are going to be viable, some of them not being utilized at all. Not just because they are not part of solution during optimization does not necessarily guarantee that they are not viable, but under free market condition and without any special advantage compared to other firms in market, it is difficult to say that such fertilizer plants will be able to face stiff competition. Cumulative distribution functions graphs provides one more way of looking at how risky a plant can/will be. For example, in case of future case 2018 linear, plant 50501(Figure 5.12) has less variability for producing urea compared to plant 51054 (Figure 5.13). Therefore, there is more uncertainty over utilization of fertilizer plant 51054. On the other hand, for anhydrous, plant in Port Neal, IA is at its capacity while plant Fort Dodge has variability of 180 to 400 thousand tons.

On the other hand, for new plant in Grand Forks (j=58203), there is always a production of urea from the plant. There is very slight chance that plant in grand forks will be at capacity for urea. There is more variability for producing anhydrous, less for UAN, and almost none for urea as shown in Figure 5.14. for anhydrous, the new plant in Grand Forks, ND is interesting for the fact that there is 20 percent chance that the production will be less 1000 thousand tons. Notice the stagnation in the curve for anhydrous ammonia for plant 5203 between 650 to 1000 thousand tons of production.

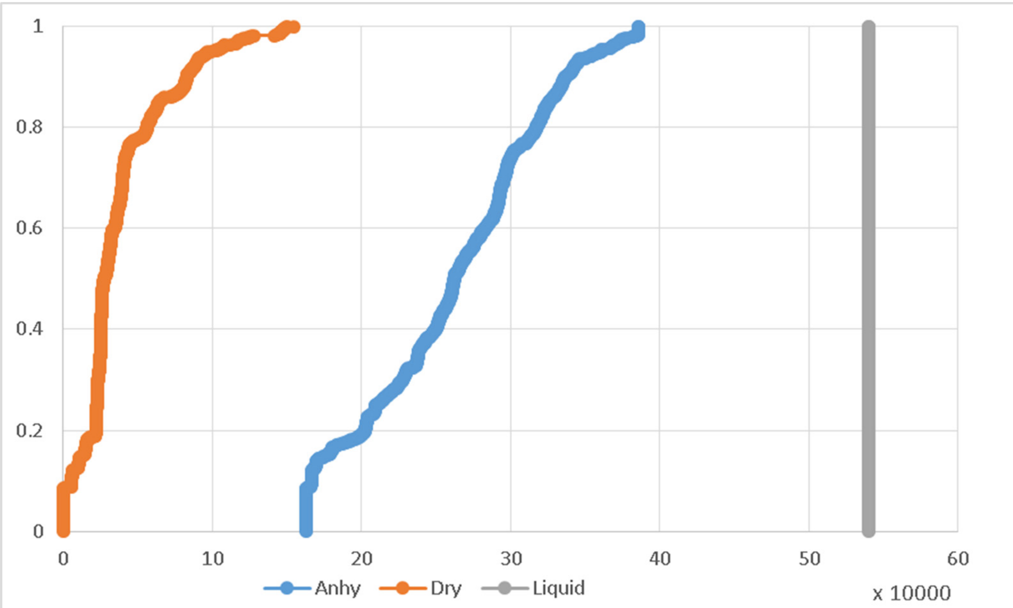


Figure 5.12. Cumulative probability for 50501 (Fort Dodge, IA) stochastic linear future case 2018.

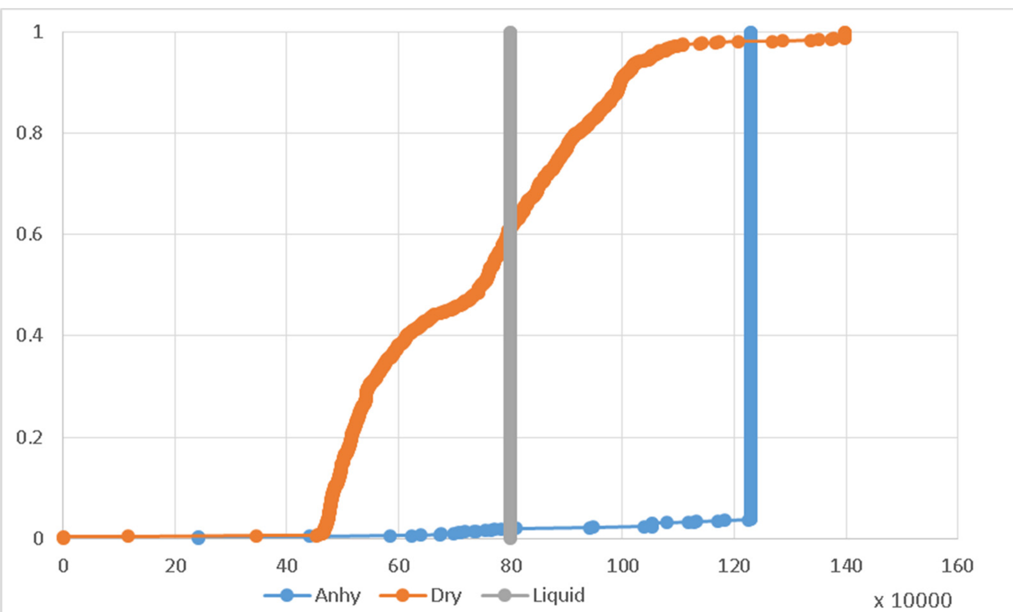


Figure 5.13. Cumulative probability for 51054 (Port Neal, IA) stochastic linear future case 2018.

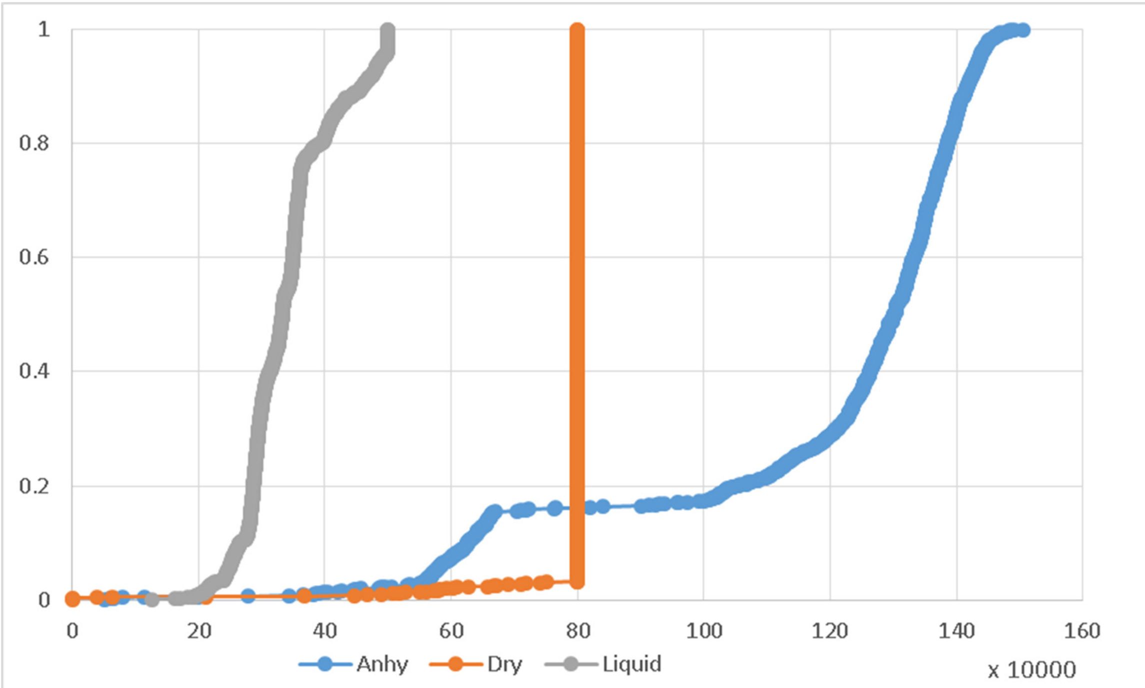


Figure 5.14. Cumulative probability for 58203 (Grand Forks, ND) stochastic linear future case 2018.

More such cumulative distribution function (CDFs) graphs are presented for each node in appendixes. The CDFs in combination with distribution fit presented in appendixes corresponding to respective scenarios. In addition, Table 5.7, Table 5.9, and Table 5.11 provide complete information about parameters and their distribution type for production distribution for any node that a reader may be interested. Such information is as unique as doing a feasibility studies on regional basis while taking care of fertilizer market at national level.

The combined approach of linear and mixed-integer optimization provides greater insights at individual fertilizer plant level, yet provides overall structure of supply chain for verification, visualization, calibration purpose using GIS techniques. Using simple GIS techniques it is also possible to summarize the end results from post optimization analysis to find out places/counties where a fertilizer plant if likely to ship most of the time, the probable market boundary, and also the counties where most of the volume from the plant is shipped.

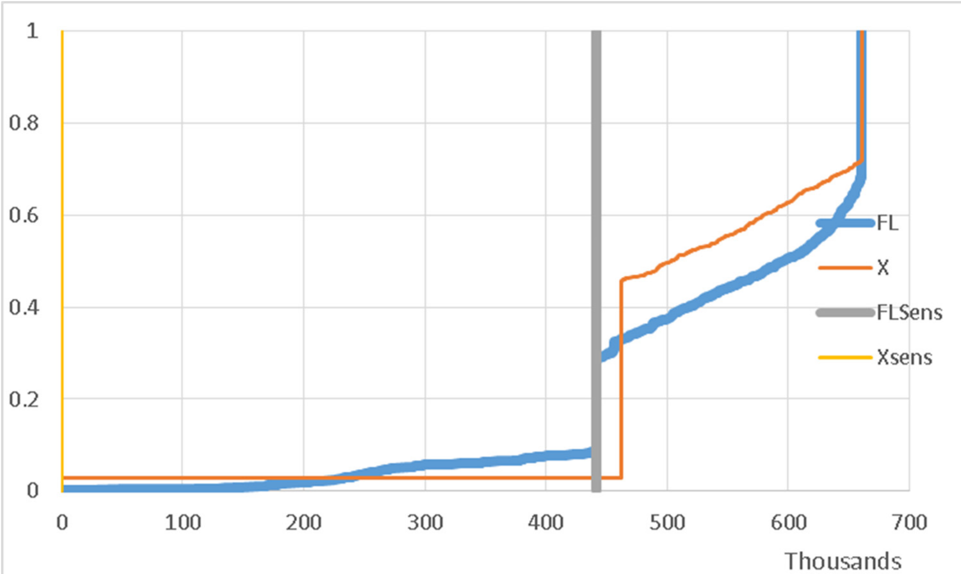


Figure 5.15. Cumulative probability of anhydrous ammonia production for 52658 (Wever, IA) across scenarios of stochastic future linear (FL), future mixed-integer (X), future linear sensitivity (FLSens) and future mixed-integer sensitivity (Xsens).

5.8. Comparison Across Scenarios

Looking at across scenarios for a fertilizer plant in the stochastic linear future case for year 2018, plant in Wever, IA (i= 52658) produces anhydrous ammonia between 441,000 tons and 661,000 tons with cumulative probability of 28 to 68 percent (Figure 5.15). There is 8 to 28 cumulative probability that it will produce 441, 000 tons, thus 20 percent chance that it will produce 441,000 tons. There is 1 in 1000 chance that in stochastic linear case, the plant does not produce anything. For stochastic mixed-integer future case for year 2018, there is a cumulative probability of 3 to 46 percent, 43 percent chance that it will produce 462, 000 tons. It is to be noted that in stochastic mixed-integer, there exists a minimum production limit at 70 percent of plant capacity. There is variability between cumulative probability of 46 to 72 percent for producing anywhere between 462,000 tons to 661,000 tons. There is 75 percent or more chance that the plant in Wever, IA will produce at its capacity in both stochastic linear and stochastic mixed-integer case for future year 2018. In contrast, in sensitivity of both stochastic linear and stochastic mixed-integer they are univariate (single value) at 420,000 tons (approx.) and 0 (zero), respectively. In other words, for stochastic mixed-integer sensitivity, the plant is not competitive, whereas in sensitivity of linear future, it always produces 441,000 tons. This is because in linear sensitivity, producing 441,000 tons is utilizing 66.7 percent of plant capacity, which does not meet the minimum criteria for new plant operation (minimum 70 percent) in sensitivity for stochastic mixed-integer.

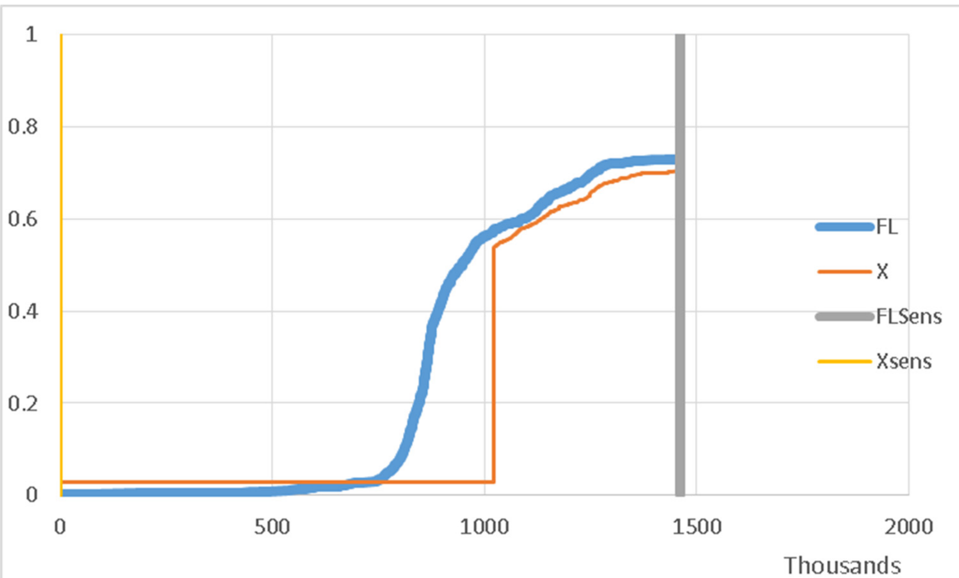


Figure 5.16. Cumulative probability of UAN production for 52658 (Wever, IA) across scenarios of stochastic future linear (FL), future mixed-integer (X), future linear sensitivity (FLSens) and future mixed-integer sensitivity (Xsens).

For production of UAN at Wever, IA, there is less than 1 in 1000 chance that it will not produce in stochastic linear future case. It is likely to produce 740,200 tons steadily increasing to 2.9 percent to 1,032,000 tons at 58 percent cumulative probability respectively. In contrast, production is at 1,023,400 tons during cumulative probability of 2.9 up until 53.9 percent. Production is at capacity of 1,462,000 tons at cumulative probability of 73 percent or more in stochastic future linear, at 70 percent in stochastic mixed-integer case, and all the time in stochastic future linear case. There is no production at Wever, IA for UAN in case of sensitivity for stochastic future linear case.

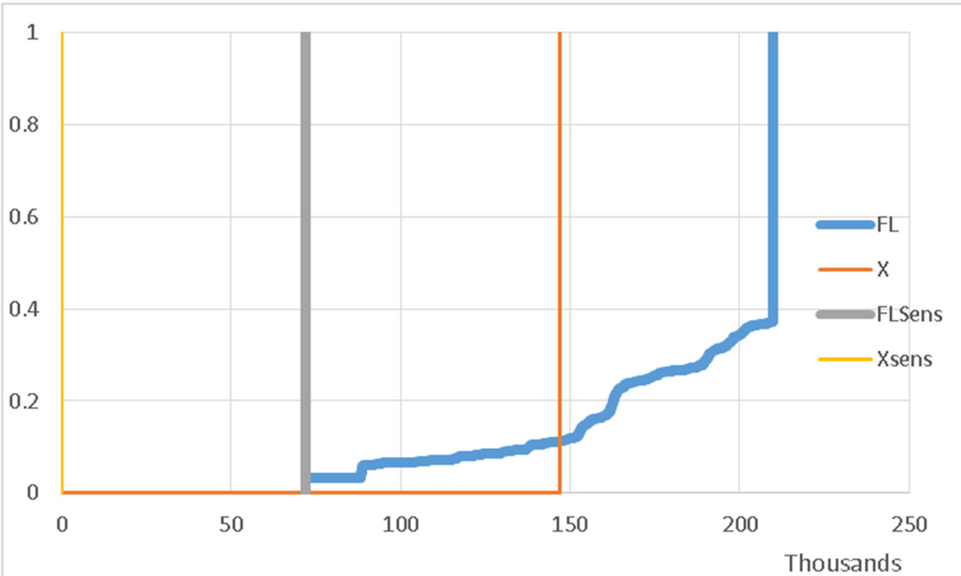


Figure 5.17. Cumulative probability of anhydrous ammonia production for 58481 (Jamestown, ND) across scenarios of stochastic future linear (FL), future mixed-integer (X), future linear sensitivity (FLSens) and future mixed-integer sensitivity (Xsens).

Looking at similar cumulative probabilities for anhydrous production for new plant in Jamestown, ND (i=58481), the minimum production is at 71,876 tons increasing to capacity of 210,000 tons with a large portion of the distribution at capacity (37 to 100 percent cumulative probability) in stochastic linear future case (Figure 5.17). When looked at in stochastic mixed-integer future case, as well as both the sensitivities of future linear and future mixed-integer, the production is at 147,000 tons, 71,876 tons and zero respectively.

More cumulative distribution functions graphs summarized across scenarios are presented in “Summary Results Across Scenarios”

6. SUMMARY

Shale oil development has led to reduced prices of natural-gas. The input cost for producing nitrogen-based fertilizers comprises more than 50 percent of natural-gas. Reduced prices for natural-gas have led to numerous announcements for expanding existing fertilizer plants, or construction of new plants, not all of which are likely to be built. This dissertation considered 13 new fertilizer plants. As many as 25 new plants have been reported for planned expansion or construction by some reports. If some of these 13 plants reach the operation stage, it would lead to increased surplus of domestic level supply. International prices for imported fertilizer (mainly anhydrous ammonia and urea) remain competitive and are another source of uncertainty when determining the viability of operating the existing fertilizer plants and the newly announced fertilizer plants.

Demand is expected to grow, but the cropping pattern, and the usage of nitrogen-based fertilizers are unknown; as a result, there is a source of risk on the demand side. It is difficult and challenging to predict the future scenario for the nitrogen-based fertilizer industry in North America. It was important to analyze the current structure of the supply chain for anhydrous ammonia, urea, and UAN solutions in the United States and Canada in order to ascertain the impact of new fertilizer plants under the stochastic nature of demand, the price for natural-gas, and the price of imported fertilizers. A spatial stochastic competition model was designed to analyze the impacts of random variables and the most likely scenario for 2018, when newly announced plants are expected to start operation. This chapter provides a summary of problems addressed in the dissertation, a short summary of the work done to address to those problems, major results, the dissertation’s contribution to the literature, implications and future work.

6.1. Problem Summary

The fertilizer industry is a high fixed-cost and low marginal-cost industry which has not seen the entry of new firms in the last two decades. With the natural-gas prices at historic lows, there is an increasing incentive for new firms to enter and as well as for current fertilizer plants to increase their capacity. Competing factors that affect increased fertilizer production within the United States are import prices for anhydrous ammonia from the U.S.-Gulf and Canada, transportation costs for different types of fertilizer by various modes (rail, truck, and barge), consumption patterns and total end demand.

Key issues causing competition changes in the fertilizer industry are reduced natural-gas prices in the United States, uncertainty in demand, and prices for imported fertilizer at the U.S.-Gulf. A competitive price for anhydrous ammonia from the U.S.-Gulf and Canada translates to increased competition for domestic production. The uncertainty associated with import prices in the near or long term makes the investment to expand current fertilizer plants and to construct new plants very risky; the large investment required to build a fertilizer plants adds to the challenge. The risk is exacerbated by the planned increase in capacity Urea capacity for East Asia and Africa, especially China which plans to add 25 of the 60 plants worldwide. Many fertilizer firms have announced plans to expand or build new plants in the United States, but plant's viability is subject to future market conditions, including the import price of anhydrous ammonia. If the import price of anhydrous ammonia is economical, it can be consumed as is at demand points (crop-growing counties) or can be readily converted at a relatively low price, adversely affecting new plants. It is expected that new fertilizer plants will need to work at a higher utilization rate for the first few years in order to achieve economies of scale.

Cheaper import prices during or after the initial post-completion period may be detrimental for an investment involving hundreds of millions of dollars, despite the fact that the fertilizer industry already has surplus capacity, thus creating an intense, ruinous pricing war among fertilizer plants (both existing and new) at the regional level. Competition for the survival of fertilizer plants to break even would be the toughest choice. Price competition to supply various demand points may be close to the plant's location or far away from it. The quantity of fertilizer supplied to the locations where this price war is fought, in conjunction with price competitiveness of supplying fertilizer plant, will be major deciding factor in the geographical area where the competition is most fierce. Quantity wise, fewer counties with a high consumption of fertilizer may be the same as many counties with less consumption, supplied by a single fertilizer plant. Traditionally, when the price war among competitors is analyzed, the geographical region of competition is generally ignored. This problem has been specifically addressed in this dissertation by looking at the market boundaries that are defined by the geographical location of fertilizer plants as supply points and the counties as demand points. The location of fertilizer plants plays an important role in their ability to serve demand points that are farther away even, if for smaller quantities. Opening up of new plants may cause a significant loss of geographical market to an existing plants, thereby eroding latter's captive market. In contrast, a new plant may not have enough counties to supply due market domination by existing plants, thereby jeopardizing the very existence and economic viability of the plant itself. A cheaper import price for anhydrous ammonia along the U.S.-Canada border has a significant impact on border-states, including South Dakota and Illinois.

Natural-gas prices are another source of uncertainty which is currently low, but is subject to future market forces. Natural-gas prices, along with electricity rates, vary by state. Together, natural-gas and electricity comprise more than 55 percent of the input cost for fertilizer manufacturing.

Transportation modes are primarily decided by the lowest cost although, sometimes, shipment method is highly dependent on material. For example, anhydrous ammonia needs to be transported with pressurized equipment, whereas urea can be transported in bulk without any need for specialized equipment. Such equipment-dependent transportation only delays the switch between transportation modes. Bulk transportation is primarily handled by railroads and barges (where applicable). Trucks are typically used for transportation over shorter distances (200 to 350 miles. Pipelines are a mode of transportation for which trans-loading points (points where anhydrous ammonia is put into the pipeline or taken out to be shipped via other transportation modes) act as switching point for transportation mode. For security reasons, these data no longer exists in public domain. Variation in the cost of transportation have the capability to change not only the structure of supply chain for fertilizer industry, but also the ability of an individual fertilizer plants to meet demand changes by fertilizer type. Again, fertilizer plant’s location plays an important role in being able to adapt to change for demand type and to choose between transportation modes. The most significant effect of change in the transportation cost is between barge and railroad as transportation mode is for anhydrous ammonia imported from U.S.-Gulf and then transported further inland.

Last, the current demand by fertilizer type consumed at the county level is not known with certainty for the long term (i.e. 5 years and beyond). It is expected that newer crop varieties will be fertilizer intensive, thus a higher demand is expected. A different crop in the same geographical region causes a change in both the quantity and type of fertilizer demanded in the county. Therefore, crop composition by county causes a change for each type of fertilizer. With better crop varieties that are stress tolerant to water and temperature, more geographical area may be planted by such varieties in areas where climatic conditions had been prohibitive in the past. There is an opportunity to export with an increase in the domestic surplus capacity. More demand growth from agriculture could match some of the increased surplus but is unlikely in the short term. Demand in East Asia and Latin America is expected to grow at the highest rate. The type of fertilizer needed at a farm is a function of the crop and soil mix as well as the farmer's preference; all these factors have the potential to change the fertilizer's supply chain.

The purpose of this dissertation was to analyze spatial competition among nitrogen-based fertilizer plants in the United States along with their respective market boundaries. This study also aimed to derive the structure of the supply chain for nitrogen-based fertilizer in the United States while addressing the uncertainty of random variables by designing a stochastic spatial optimization model to account for risk with random variables.

In order to address the problems described previously, a comprehensive model was used to account for the geographical location of the supply and demand nodes. Transportation cost was assigned for the quantity flowing between the supply and demand nodes based on the actual geographical distance traveled by rail, road and barge. Various cost functions were applied to account for the price of natural-gas (varies by state) and the cost of transportation to produce fertilizer. Demand at the county level was met in model by fertilizer type (anhydrous ammonia, urea, and UAN), and quantity flows were represented graphically to map the structure of fertilizer plant's supply chain and market boundaries. Selective market boundaries are presented in this dissertation with a complete selection of production summaries by plant in the form of a cumulative distribution function and production distribution by plant. Stochastic optimization was used to account for uncertainty with the import price, demand, and price of natural-gas. The distribution of parameters treated as random was used to conduct stochastic optimization to capture the probability distribution for production at individual fertilizer plants. Complete stochastic output parameters, distribution fit, and probability distribution for anhydrous ammonia, urea, and UAN were reported for all fertilizer plants that are likely to operate in 2018.

6.2. Model Specification

A static, linear, spatial-competition model was optimized to represent the current structure of the nitrogen-based fertilizer industry in North America. Geographic locations for fertilizer plants, county-level demand points, and distances among them using various transportation modes were used to construct the comprehensive spatial model.

The current structure of the supply chain (for 2012) was modeled by transportation mode for each type of fertilizer, anhydrous ammonia, urea and UAN. The model was then calibrated to account for conversion from anhydrous ammonia to either urea or UAN, an important flexibility in the model that was recommended by industry experts. Quantity flows for each pair of origin-destination were plotted in GIS to represent overall structure of nitrogen-based fertilizer's supply chain, which is helpful in presenting and calibrating the base-case scenario as a summary of analysis (bird's eye view) instead of tabular data with thousands of rows for quantity flows between origins and destinations that are part of optimized solution.

In order to account for future uncertainties associated,(a) import price at the U.S.-Gulf by type of fertilizer, (b)price of natural-gas as reflected by Henry-Hub (an index for the price of natural-gas in the trading market), and (c)demand at the county level by the type of fertilizer consumed were treated as random. The distributions of random variables were derived based on the historic volatility for Henry-Hub prices and import prices. The demand distribution was subjectively decided on a conservative basis. In the absence of known, future market conditions, these distributions were used as inputs in all spatial stochastic models and respective sensitivities. Outputs from the stochastic optimization were captured to analyze which fertilizer plants will operate in 2018, as well as derive shipment distributions for fertilizer plants, shadow prices, market boundaries (with the mean probability of shipping to counties and the mean quantities shipped to each county), and utilization rates for production capacity at each fertilizer plant.

A second stochastic, linear, spatial-competition model for 2018 was created to allow all current and new plants to operate, as needed, to meet demand at the county level. Many fertilizer plants were found to operate at low levels and, many times, only for one or two fertilizer types. Such low utilization rates for a plant may translate to operating at low capacity during longer time periods or at high capacity for a shorter part of the year.

A third spatial, stochastic, mixed-integer optimization was used to account for a few of the new plants under the binary condition of either operating (viable in the future) or not (not viable in the future). If the new fertilizer plants operate in model, then they have to operate at a minimum of 70 percent of the plant capacity. The distribution of inputs treated as random was the same as within stochastic, linear optimization.

Sensitivities for stochastic linear and stochastic mixed-integer optimization were also analyzed. A conservative change in the distribution of parameters being treated as random was allowed. The distributions for random parameters were allowed to shift for slightly higher demand, more upside variability in import prices, and higher Henry-Hub (but with the same variability). The structure of the supply chain for each fertilizer type was derived for all scenarios: base case (year 2012), stochastic linear future case for 2018, stochastic mixed-integer future case for 2018, sensitivity for stochastic linear future case for 2018, and sensitivity stochastic mixed-integer future case for 2018.

Market boundaries and the change in market boundaries were derived for selective fertilizer plants across all scenarios. Instead of mapping market boundaries for each iteration of stochastic optimization scenarios, a single market boundary depicting each (a) mean probability and (b) mean quantity shipped was derived. The market boundary illustrating probability shows the counties that are most likely to be supplied by a fertilizer plant. Market boundaries showing the mean quantity represent the average quantity supplied to a county by the fertilizer plant. Both market boundaries are important because they differentiate counties that are shipped small quantities by a fertilizer, on average, but most of the time (captive market), from those counties that are shipped high quantities, on average, but only few times and are more likely to switch to the market boundary of another fertilizer plant (risky and competitive markets); traditional methodologies do not consider such geographical change in market boundaries on probability basis. Market boundaries for selective fertilizer plants are presented in this dissertation along with the special case of overlapping market boundaries. Overlapping market boundaries show where (counties) the most intense ruinous pricing war is likely to be fought. In some cases, the most intense pricing war is likely to happen close to an existing plant when a new plant, even more than 300 miles away, opens. (A complete list of counties supplied by all fertilizer plants can be requested from the author upon request.)

The fertilizer plant's utilization rates during each stochastic optimization scenario, including sensitivities, were derived and presented. Production per plant for anhydrous ammonia, urea and UAN during the stochastic optimization was fitted, and the distribution parameters were reported (for assessment of different region of interest for reader).Production summaries for each fertilizer as a cumulative distribution function depicting the riskiness and how fertilizer plants fair under market uncertainties were derived and reported for each scenario for all fertilizer plants.

Finally, the cumulative distribution function, summarizing production at an individual plant across all scenarios, was derived and reported. These graphs provide a comparison of production at a fertilizer plant under different scenarios. Selective cumulative distribution function graphs were described as an example in Chapter 5 and should serve as a template for describing the graphs presented in the respective appendix for each scenario.

6.3. Major Results

Outputs from stochastic optimization were captured to further analyze the results and to gain more insight about the spatial-competition model at the regional level as well as complete details of operation at all nodes on supply and demand side. The base-case static scenario for 2012 was used as calibration, and stochastic models were built upon by modification of the base case by accounting random parameters for demand, natural-gas price, and the import price of fertilizer. The end model can be best described, in the most general terms, as a multi-commodity, multi-modal network distribution model, repeatedly optimized as a spatial stochastic model, that also allows conversion from anhydrous ammonia to either urea or UAN solution under supply and demand constraints. Some of the analyzed and presented results in this dissertation include shipment distributions for each fertilizer plant, shadow prices, market boundaries (with the mean probability of shipping to counties and the mean quantities shipped to each county), and utilization rates of production capacity at each fertilizer plant. Some major results are presented in following subsections.

6.3.1. Major Results from the Linear Base Case for 2010-2012

Market boundaries change significantly for fertilizer with varying random variables, such as import price, natural-gas price, and demand. The location of a fertilizer plant and its size play an important role for the viability of new fertilizer plants and their market boundaries at the regional level, providing great insights about where the competition is intense.

6.3.2. Results from Stochastic Models

Not all fertilizer plants that have been announced will reach the operating stage. Some existing fertilizer plants will dominate even after the entry of new competitors. A few plants in Louisiana and North Dakota have higher probability of successfully entering the market. These new plants will have a significant impact on the market boundaries of existing fertilizer plants. Market boundaries for these new plants are vast and come at the cost of market boundaries for existing plants and imports from Canada. Most plants will operate at a lower utilization rate, because there is already a sufficient surplus capacity in the industry, and opening new fertilizer plants will further the surplus capacity. New fertilizer plants will only gain a market due to lower input costs such as a lower natural-gas price, and larger plant sizes (economies of scale). Competition between fertilizer plants varies regionally. Not all fertilizer plants are able to compete equally. For example, new plant in Grand Forks, ND supplies anhydrous fertilizer to the some of the counties with 80 percent probability, geographically next to location of another existing fertilizer plant for anhydrous ammonia in Wever, IA. Such a spatial (geographical) component is not considered with traditional market competition analysis.

6.3.3. Impacts of Random Variables

Import prices for fertilizer were competitive and will likely stay competitive for anhydrous ammonia and urea. Domestic plants tend to produce anhydrous to be converted into

UAN as the final product in stochastic, spatial simulations, suggesting that anhydrous ammonia and urea remain cheaper to import.

6.3.4. Results from Sensitivities

It remains to be seen if future market conditions would allow for the export of fertilizer from the United States. Under the market conditions analyzed with stochastic optimization models in dissertation, imports stay competitive, and only a few newly announced fertilizer plants reach operational stage. Anhydrous ammonia and urea remain competitive imports because they are concentrated forms of nitrogen-based fertilizer. UAN producing domestic fertilizer plants are expected to work at higher utilization rates. The feasibility of newly announced plants is still subject to natural-gas prices staying low during the plant's construction phase (short term) and long after to sustain the advantage of the reduced production cost. Technological advantages and logistical efficiencies would be the primary deciding factors for plants operating in the same state.

6.4. Implications

Some major implications for the private sector are the dilemma to invest in expanding current plants or opening new plants as well as changes in the structure of the supply chain that may warrant different resource allocation to provide services associated with the nitrogen-based fertilizer industry. The first and foremost question facing private industry is whether to invest given recent changes in the price of natural-gas. If decide to invest is made, what is the probability that that fertilizer plant would still be viable by the time the plant reaches the operational stage after construction? What is the market size or market boundary that the new expansion or new fertilizer plant will be able to serve? Who would the competitors be? Where that competition would be spatially located? Because these questions become important when coupled with the uncertainties associated with natural-gas prices, demand, and import prices, this dissertation provides a comprehensive solution to help industry analysts make their best judgment based on the conservative model's assumptions. The resulting implication for industry is to decide on some factors, such as the best location to enter the market and whether to pre-empt the entry of other market firms by making an announcement about the construction of a particular size and location for a plant.

In the current state of the supply chain for fertilizer based on 2010-2012, Sacramento, CA (i=95691), for anhydrous ammonia, and Beulah, ND (i=58523) for the UAN solution, are best suited for expansion when looking at network cost and shadow price. Some newly announced plants best suited for 2018, in case all plants reach operation phase, are Fresno, CA (i=93627) for anhydrous ammonia, Grand Forks, ND (i=58203) for urea, and Ector, TX (i=79776) for UAN. It must be noted that the high shadow prices account higher land prices. For example, even though Fresno, CA, is best suited, other exogenous variables, such as land cost, may still make it a prohibitory candidate for expansion or a new plant. In the stochastic, mixed-integer future case, wherein the plants are subject to a decision variable with the minimum utilization rate of 70 percent, Grand Forks, ND, operates at 956,565 tons; 800,000 tons; and 395,480 tons for anhydrous ammonia, urea, and UAN solution, respectively.

Market boundaries are random due to a multitude of random variables, hence there is intense competition among fertilizer plants that is caused by the new entrant. An overlapping market boundary, in combination with market boundaries for probability, provides the counties where a fertilizer plant is most likely to ship. Moreover, the exogenous random variables are critical for the supply chain and market boundaries of fertilizer plants and will remain so going forward in 2018. Random variables including demand, natural-gas prices, and import price for fertilizer are highly uncertain and are subject to change.

The nitrogen-based fertilizer industry has a high fixed-cost and low marginal-cost with uncertainties from demand and market conditions. Adding excess entry in an industry with surplus capacity, there is likely to be tremendous pressure to be logistically efficient and to keep input costs low by tapping into the lowest cost source of natural-gas while maximizing the "market share effect". Recent developments of low natural-gas prices have caused a few announcements about firm's intentions to expand or to build a new fertilizer in an industry that has not seen new construction in more than two decades. In addition, the industry has significant surplus capacity that further increases the possibility of an intense price war at the regional level. Going forward, only fertilizer plants with technological advantages as well as benefits in terms of easy/captive market, lower production cost, and a locational advantage will be able to survive. Opening new plants with the existing surplus capacity may prove to be detrimental for current fertilizer plants and to push them out of business.

For public agencies, the major implication will be on the planning side. Under the scenario that new plants open, some state agencies may have to provide an additional incentive in terms of lower electricity cost of other subsidies to allow existing and older fertilizer plants to continue. Other states may provide an incentive to compete for the location of fertilizer plants because a slight change in the location of a new fertilizer plant (by 50 miles) may result in lower electricity cost (second major input cost after natural-gas price). A change in the structure of the supply chain may also warrant a different location for currently used warehouses. Newer locations may need to be given licenses to store fertilizer, etc. Changing the transportation mode for a region as the most economical mode for example, from railroad to truck may prove to be a major addition to existing seasonal traffic of trucks on county and state roads. Such an addition of traffic can be understood from example of Grand Forks, ND plant producing urea. Shipments from this plant are expected to utilize trucks in the immediate vicinity; earlier, these shipments, may have been delivered by rail.

6.5. Contribution

It is only due to the combination of techniques utilized that such a data-intensive, stochastic optimization using the linear and mixed-integer approaches could be done. Results could be visualized and utilized for further analysis and insight. It will be a major contribution for the field of supply chains when data intensive analysis can be done with a statistical package, such as SAS, and then, preliminary results can be visualized for quick verification in GIS instead of going through a million plus rows of tabular data. No existing study in any individual field of academics was found to account for the full picture of supply chain of fertilizer logistics for North America while taking into account demand for fertilizer type at the county level and fertilizer production at the plant level. This dissertation makes use of skills that are traditionally not in common domain of the supply chain studies. However, with developing hardware and software resources, it is only appropriate utilize combination of software skills and to use a multitude of approaches from variety of theoretical background.

The major contribution of dissertation is the stochastic representation of the problem and its impact on the structure of the supply chain for the nitrogen-based fertilizer industry. The model provides flexibility and multiple options to assess the impact of changes in the fertilizer industry through variations in the market boundary, shadow prices, the utilization rate of fertilizer plants, the likely probability distribution for production at fertilizer plants, and the distribution fit for output production parameters. Various results are provided for the base case, two stochastic scenarios, and two stochastic sensitivities; thus giving interested readers multiple results use when analyzing any part of the supply chain structure and reaching the most conclusive decision. This dissertation in essence, provides a feasibility study for expanding existing plants or opening new plants. Had such feasibility study conducted on smaller geographic level as part of an individual study, market forces at play for the larger geographical level would have been ignored. Data manipulation and processing with post-optimized results provides significant insight that would have been ignored in the absence of GIS techniques. Optimized results, when presented with slight analytical steps of the GIS itself, lead to a quicker and clearer picture than a tabular data (for example Figure 5.9). There is no doubt that, in the future GIS techniques to make maps will be as common as using spreadsheets in conjunction with traditional statistical packages such as SAS 9.3 OR. Some major resultant outputs from the spatial stochastic optimization model are as follows:

1. Market boundaries.
2. Stochastic nature of the market boundaries addressed.
3. Impact of random variables on the market boundaries.
4. Distribution of product shipments from fertilizer plants and the probability distributions of product.

In light of the conservative assumptions made about import prices, it is clear that, despite lower natural-gas prices and enough surplus capacity, imports are likely to exist. Additionally, there should be some resilience from transportation mode like barge and railroad related firms from U.S.-Gulf to inland shipping nodes. Therefore, new fertilizer plants would not only compete with existing plants, but will also face consistent competition for imports from U.S.-

Gulf and Canada. . Technological advantage in production and economies of scale for fertilizer plant would be significant factor beside the type of fertilizer made at the plant.

Most of supply chain studies are aimed at a professional audience defined solely in mathematical equations, whereas results, when presented in graphical form, become much compact, thereby supplying more information. Graphical results are easy to understand by larger audience, most of which may not be interested in specific parameters but in overall bigger picture of state of problems. Using data-intensive approach with utilizing the best available statistical optimization and simulation packages, it was possible to account for distances between the supply (origin) and demand (destination) points for fertilizer plants producing anhydrous ammonia, urea, and UAN. These distances were derived from a national repository of various public databases from geographical information systems (GIS) divisions at departments of transportation. Although optimization is common to statistical packages, visualization is of optimized results is not.

Visualization of data is common for GIS group but customized data-intensive stochastic optimization as required by U.S. nitrogen-based fertilizer industry (with numerous constraints for supply and demand), is not. A combination SAS-OR and GIS was, thus, used in this dissertation where in extensive data conversion and manipulation was done to allow for the free flow of exchanging inputs and outputs between statistical optimization package (SAS 9.3) and GIS package (ArcMap 10.2). This exchange of data allowed for spatial stochastic optimization in statistical software and verification and for the visualization of results in GIS software, something that could not have been done within either methods alone. No such study considering the actual spatial aspect of locations and distances among fertilizer plants, along with individual plant capacities with all the crop-growing counties as demand points, has been conducted. In addition to mapping the structure of the supply chain, this dissertation also provides insight for individual plant-level, after the optimization process.

Post-optimization processing as done in this dissertation provides greater insight about the operation and feasibility of a fertilizer plant under different market conditions. In order to account for changing market conditions, a distribution of input parameters, instead of a few discrete values, was used. The results obtained by processing optimization solution provide insight that is not available with any stand-alone statistical and GIS software. It is this combination of data-intensive spatial stochastic optimization with statistical package and utilizing GIS for mapping a large, but important, set of results that makes the work done in this dissertation crucial for addressing the problem at hand. With time, a similar methodology may be applied to other industries for comprehensive analysis of problems.

Fertilizer-industry related studies are mostly confined to production efficiency related to the methods utilized from chemistry stand point. Due to the complexity of various types of nitrogen-based fertilizers being produced, their cost of production varying by location, the cost of shipments between plants (for conversion) and the cost of shipments between fertilizer plants and consumption points, this dissertation presents a novel way of addressing the structures of the supply chain and market boundaries for all fertilizer plants in United States. Although actual market conditions may be different at the micro-regional level, this dissertation provides a macro-level, overall view of the supply chain for the nitrogen-based fertilizer industry from start to end, by type of fertilizer, and by mode of transportation. In addition, this dissertation also provides the most likely structural changes for the supply chain and market boundaries of fertilizer plants in light of recent developments affecting the industry: cheaper natural-gas from shale-oil exploration domestically, and recent announcements to expand existing plants or construct new fertilizer plants. This dissertation provides invaluable scenarios analysis for both private firms and academia. Some of the private firms that this dissertation may interest are firms engaged in the ownership of and production of nitrogen-based fertilizer plants; transportation service providers such as railroad and trucking companies; and third-party logistics, firms engaged in warehouse operations at the regional level for storage and distribution of fertilizer (such as farmer co-operatives); and the farmers.

Some academic and government agencies that may interest this dissertation are policy planners in the transportation sector (changing structure of the supply chain, for example, from rail as a mode to trucks, adds a significant amount of truck traffic to the region), regulatory bodies that provide promotional incentives for fertilizer plants to become viable and bring development to their localities, and regulatory bodies involving transportation of anhydrous ammonia (a hazardous material). Academia from agribusiness should also gain significant knowledge from analyzing the associated results in light of the changes caused by the fertilizer industry's market conditions. For example, the equipment needed for fertilizer varies by fertilizer type as well as crop type and soil conditions.

6.6. Future Work

Assumptions made in this dissertation regarding the most likely market variables in 2018 are very conservative. Distributions for variables that were treated as random were used for the stochastic linear simulation and stochastic mixed-integer simulation. The optimized results were then processed and analyzed further to derive the most probable market boundaries for fertilizer plants and the distribution for production at plants. It may be useful to extend this study to further analyze the effect of change with one parameter or in combination to discover which random variables affect the market boundaries of fertilizer plants and by what extent. This change in fertilizer plant's market boundary can be achieved by regressing values from the output distributions against the values from the input distribution, by the indexed (simulation number) value. A similar approach may also be used to determine which random parameters affect the total miles traveled (or the last miles traveled) for each fertilizer type. It may be interesting to first derive the total average distance traveled for a ton of anhydrous to reach its destination. Such analysis can provide greater insight about which counties consume fertilizer from faraway places (Farmers in such areas would be paying more for their transportation cost.), thus is there an incentive for closer fertilizer plants to lower their price? If yes, then by how much?

Another improvement for this study would be inclusion of a pipeline network with details for loading and unloading points in the pipeline network. This information would specially be helpful when long term benefits of transporting of hazardous material such as anhydrous ammonia is to be considered. Currently, such data are not available to the public (for security reasons). The location of loading and unloading can provide a cost benefit analysis with slight modification in the current model used for this dissertation.

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APPENDIX A. MODEL INPUTS

Table A.1. Description list of nitrogen-based fertilizer plants in United States and Canada that are treated as origin nodes along with their set id for identification and reference purposes in this study.

Firm	City	State	County	Zipcode(ID set (i))
Honeywell International Inc	Hopewell	VA	Prince George	23860
PCS Nitrogen Fertilizer, L.P.	Augusta	GA	Richmond	30901
TradeMark Nitrogen Corporation	Tampa	FL	Hillsborough	33619
LSB Industries, Inc.	Cherokee	AL	Colbert	35616
U.S. Nitrogen LLC	Mosheim	TN	Greene	37809
CF Industries, Inc.	Yazoo City	MS	Yazoo	39194
Mississippi Power	Kemper County	MS	Kemper	39358
Agrium U.S. Inc.	North Bend	OH	Hamilton	45052
PCS Nitrogen Fertilizer, L.P.	Lima	OH	Allen	45804
Ohio Valley Resources, LLC	Rockport	IN	Spencer	47635
Syngest Inc.	Menlo	IA	Guthrie	50164
Kock Nitrogen Company	Fort Dodge	IA	Webster	50501
Green Valley Chemical Corporation	Creston	IA	Union	50801
CF Industries, Inc.	Port Neal	IA	Woodbury	51054
OCI - (Iowa Fertilizer Company)	Wever	IA	Lee	52658
Northern Plains Nitrogen	Grand Forks	ND	Grand Forks	58203
CHS	Jamestown	ND	Stutsman	58481
Dakota Gasification Co.	Beulah	ND	Mercer	58523
Rentech Nitrogen, LLC	East Dubuque	IL	Jo Daviess	61025
Agrium U.S. Inc.	New Madrid	MO	Pike	63869
Coffeyville Resources, LLC	Coffeyville	KS	Montgomery	67337
Kock Nitrogen Company	Dodge City	KS	Ford	67801
Kock Nitrogen Company	Beatrice	NE	Gage	68310
CF Industries, Inc.	Donaldsonville	LA	Ascension	70346
PCS Nitrogen Fertilizer, L.P.	Geismar	LA	Ascension	70734
Russian Plant	Iberville	LA	Iberville	70765
The Mosaic Company	Faustina	LA	Saint James	70792
Kock Nitrogen Company	Enid	OK	Garfield	73701
CF Industries, Inc.	Woodward	OK	Woodward	73801
CF Industries, Inc.	Verdigris	OK	Rogers	74019
LSB Industries, Inc.	Pryor	OK	Mayes	74362
OCI North America	Beaumont	TX	Jefferson	77627
Agrium U.S. Inc.	Borger	TX	Hutchinson	79007
Summit Energy/CHS	Penwell	TX	Ector	79776
Dyno Nobel, Inc.	Cheyenne	WY	Laramie	82001
Southeast Idaho Energy	American Falls	ID	Power	83211
J.R. Simplot Company	Helm	CA	Fresno	93627
Agrium U.S. Inc.	W. Sacremento	CA	Yolo	95691
Dyno Nobel, Inc.	St. Helens	OR	Columbia	97051
Agrium U.S. Inc.	Kennewick	WA	Benton	99337
Agrium U.S. Inc.	Kenai	AK	Kenai Penisula	99611

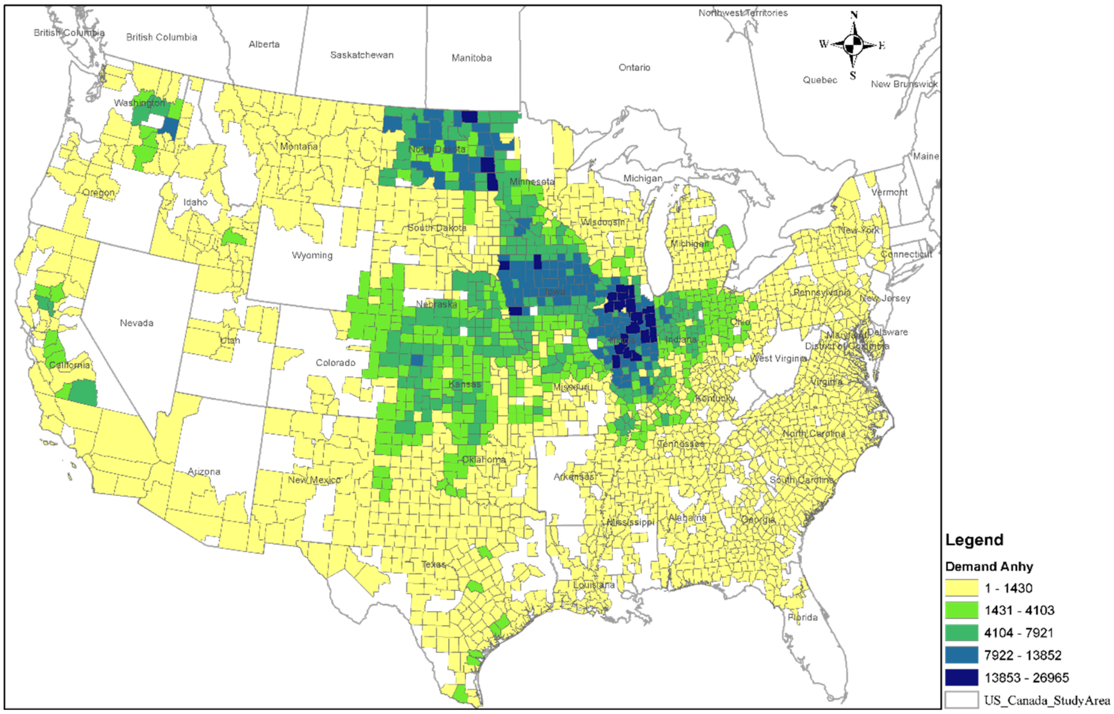

Figure A.1. Demand for anhydrous ammonia at counties (demand nodes) shown as graduating colors.

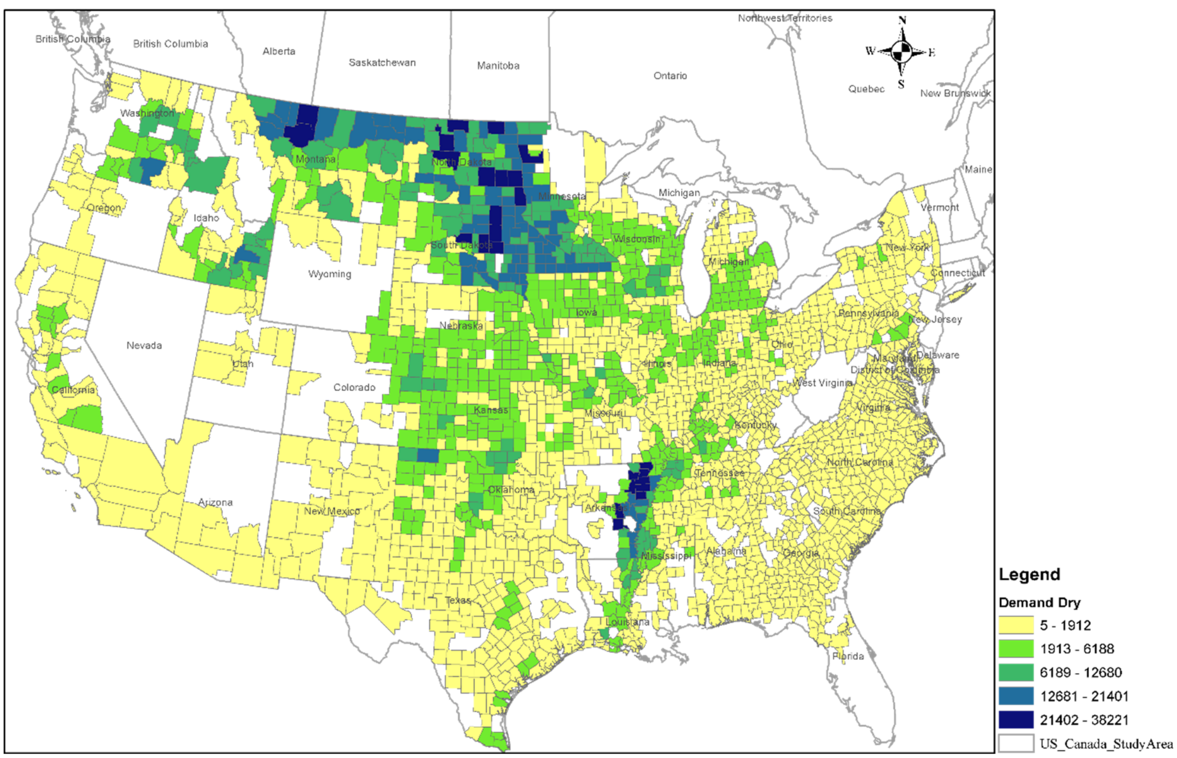

Figure A.2. Demand for urea at counties (demand nodes) shown as graduating colors.

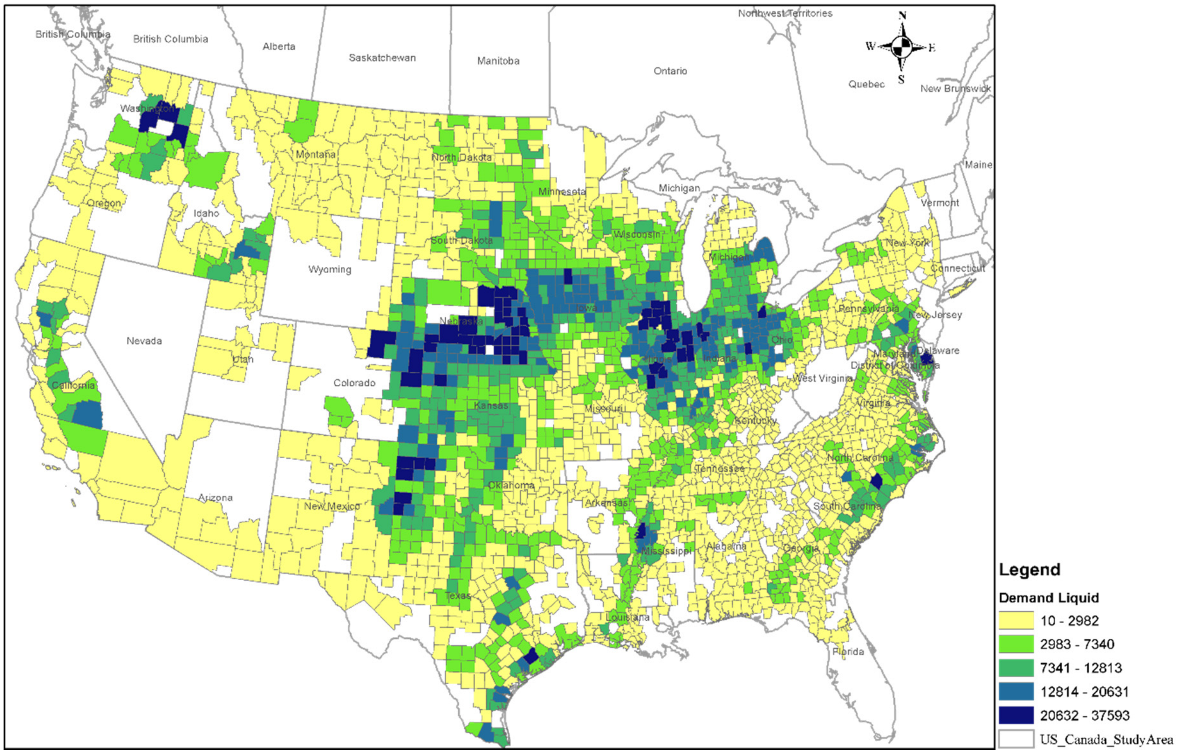

Figure A.3. Demand for UAN at counties (demand nodes) shown as graduating colors.

APPENDIX B. BASE CASE

B.1. Distribution of Origination Destination Matrix for Base Case Linear

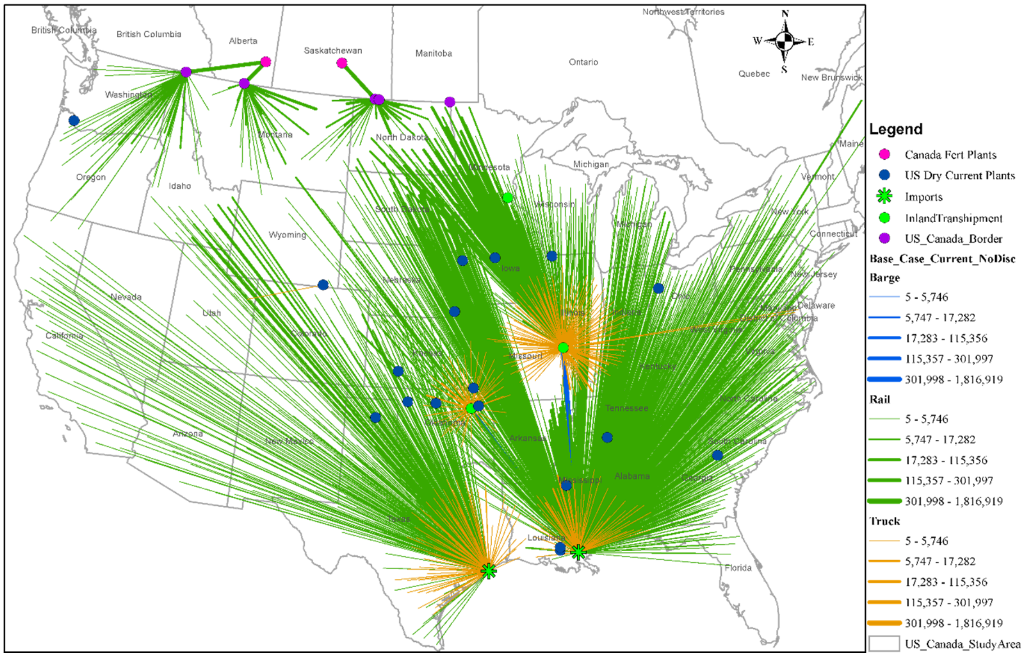

Figure B.1. Structure of supply chain for urea for base case by mode (Rail=Green, Truck=Orange, Barge=Blue).

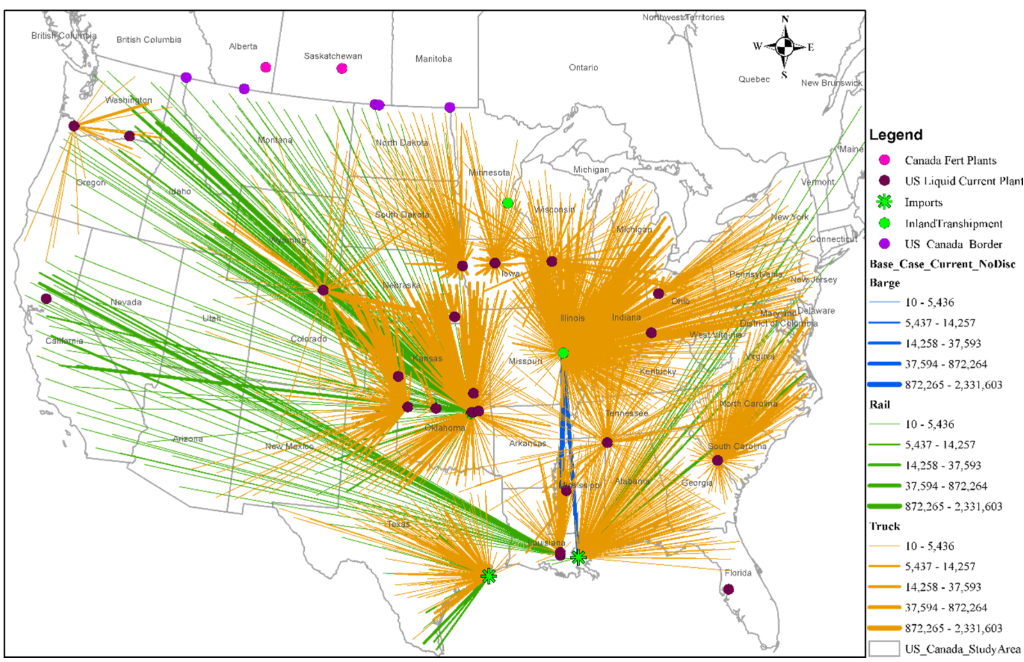

Figure B.2. Structure of supply chain for UAN for base case by mode (Rail=Green, Truck=Orange, Barge=Blue).

B.2. Shadow Prices Base Case

Figure B.3. Shadow prices for urea in base case.

Figure B.4. Shadow prices for UAN in base case.

B.3. Market Boundaries for Selective Plants Base Case

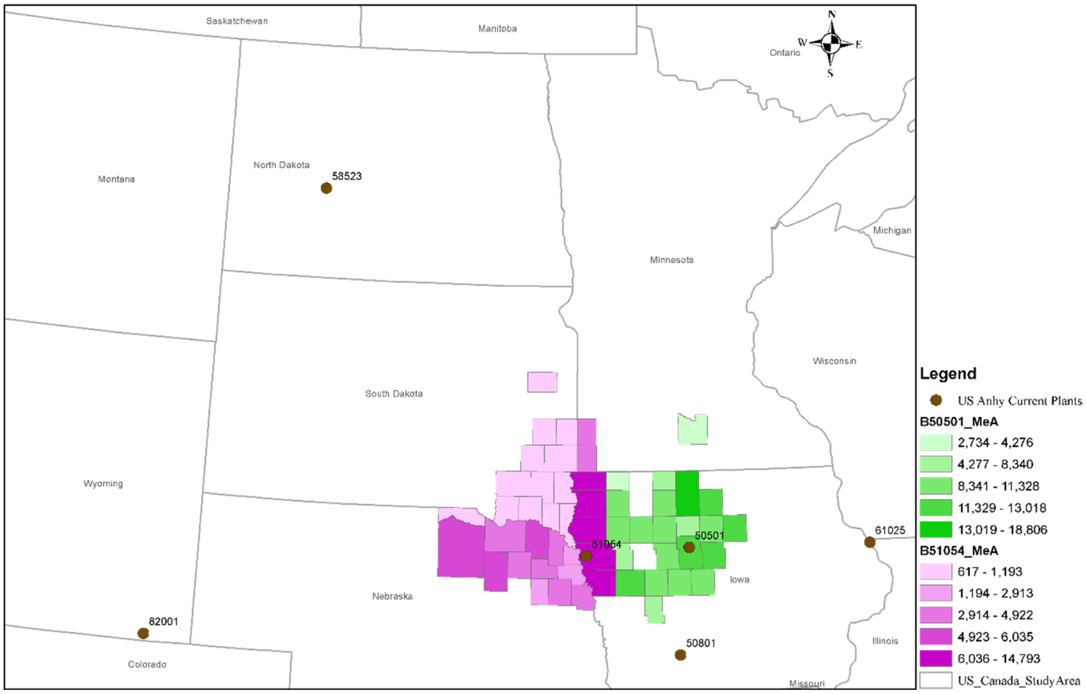

Figure B.5. Market boundaries for plant j= 50501, j= 51054 for anhydrous ammonia.

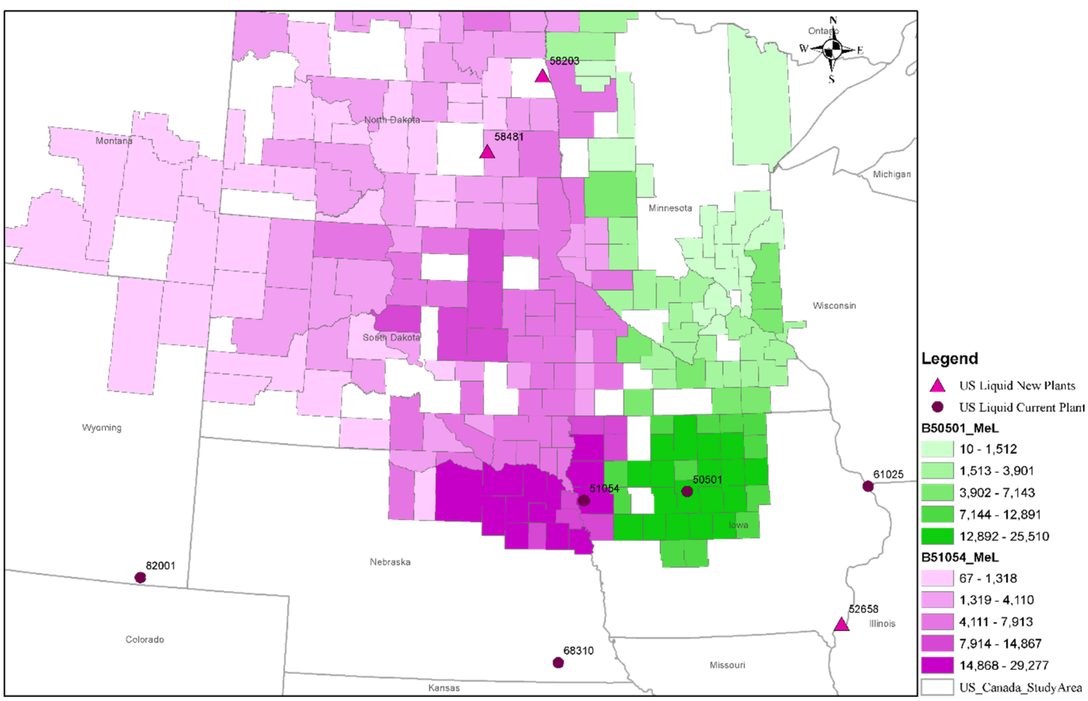

Figure B.6. Market boundaries for plant j= 50501, j= 51054 for UAN.

APPENDIX C. STOCHASTIC LINEAR FUTURE CASE 2018

C.1. Distribution of Origination Destination Matrix for Stochastic Linear Future Case 2018

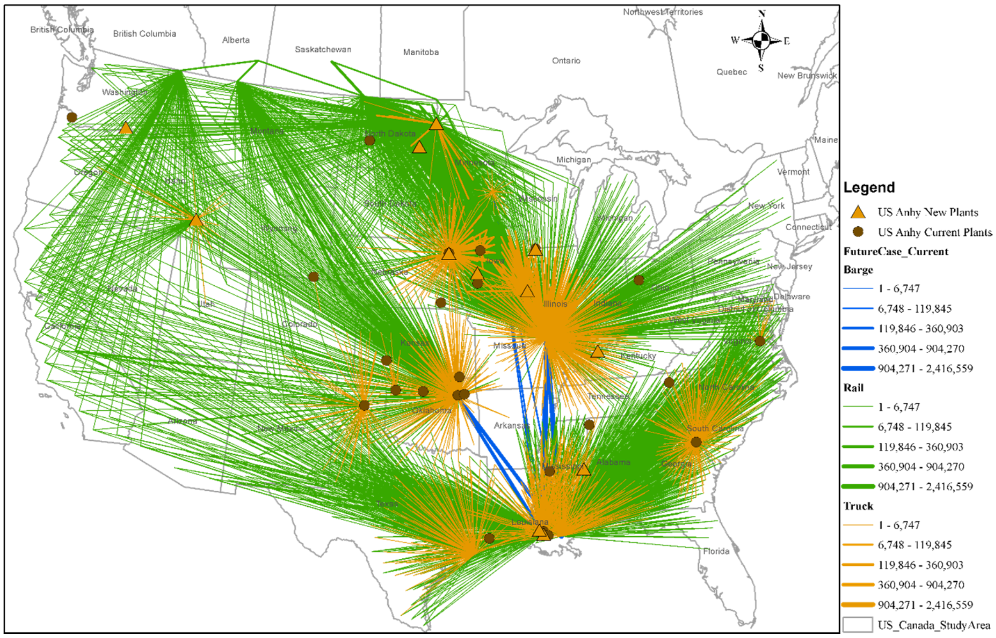

Figure C.1. Structure of supply chain for anhydrous ammonia for future case linear by mode (Rail=Green, Truck=Orange, Barge=Blue).

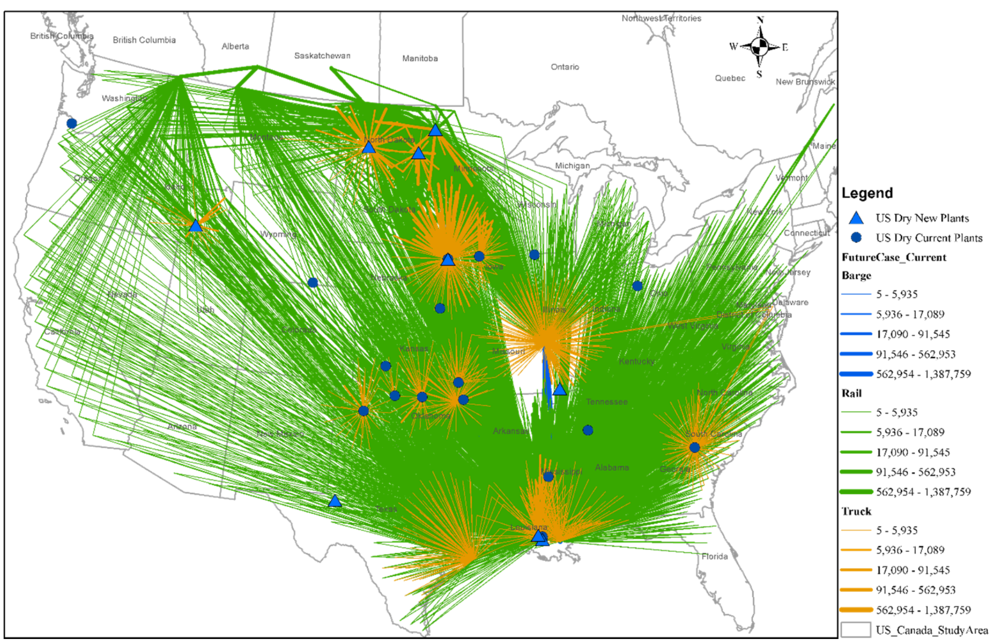

Figure C.2. Structure of supply chain for urea for stochastic linear future case 2018 by mode (Rail=Green, Truck=Orange, Barge=Blue).

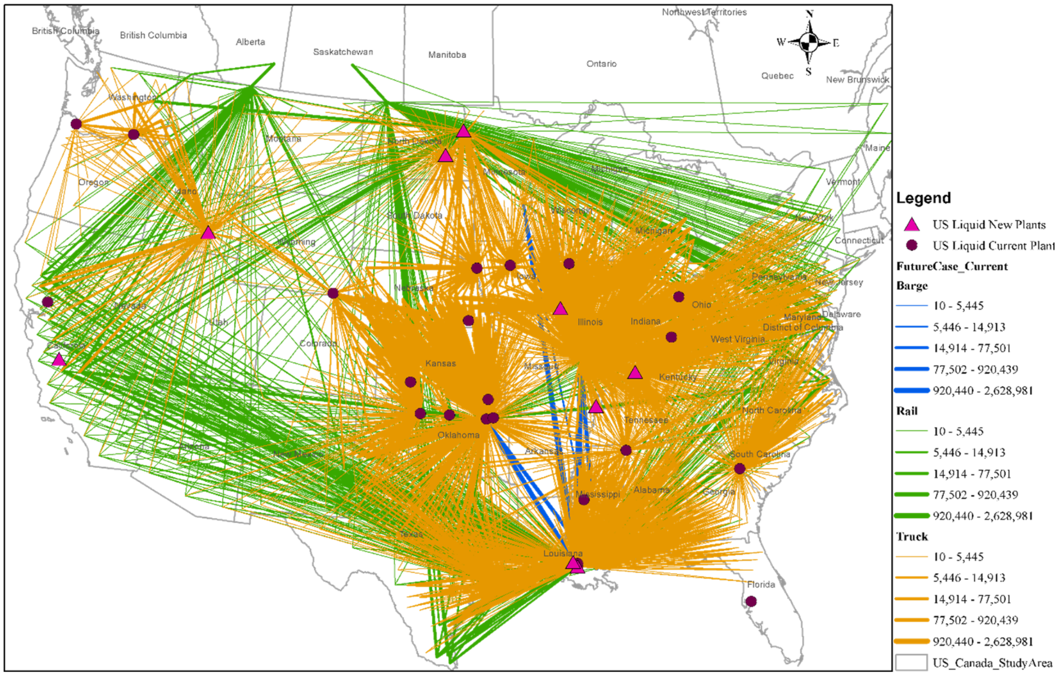

Figure C.3. Structure of supply chain for UAN for stochastic linear future case 2018 by mode (Rail=Green, Truck=Orange, Barge=Blue).

C.2. Shadow Prices for Stochastic Linear Future Case 2018

Figure C.4. Shadow prices for anhydrous ammonia in stochastic linear future case 2018.

Figure C.5. Shadow prices for urea in stochastic linear future case 2018.

Figure C.6. Shadow prices for UAN in stochastic linear future case 2018.

C.3. Market Boundaries for Selective Plants by Probability of Shipping for 1000 Iterations in Stochastic Linear Future Case 2018

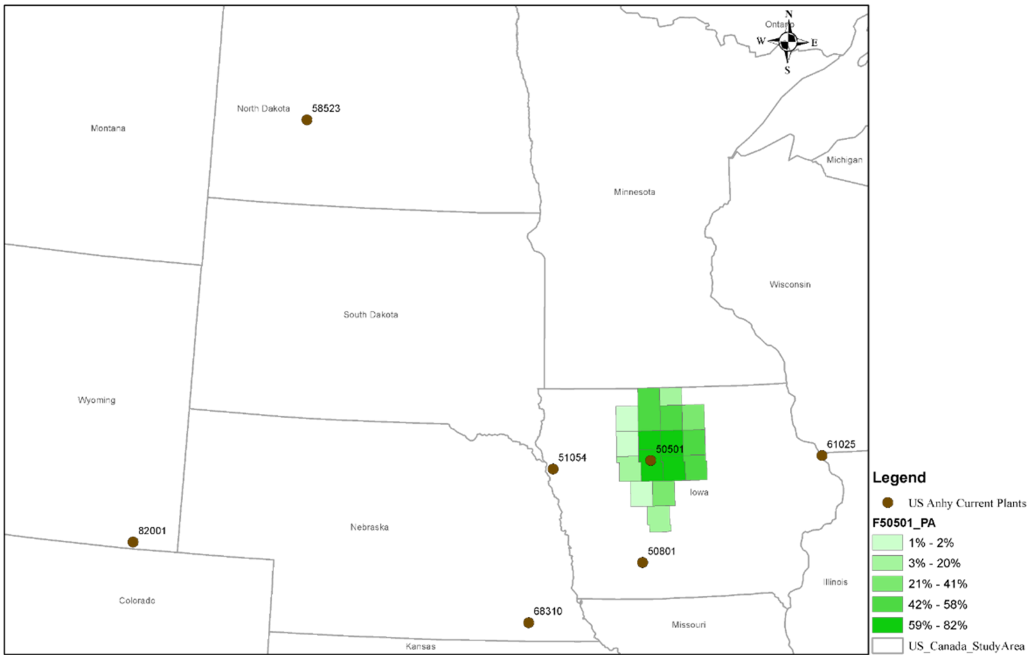

Figure C.7. Market boundaries for plant j= 50501 for anhydrous ammonia (probability of shipping for 1000 iterations) in stochastic linear future case 2018.

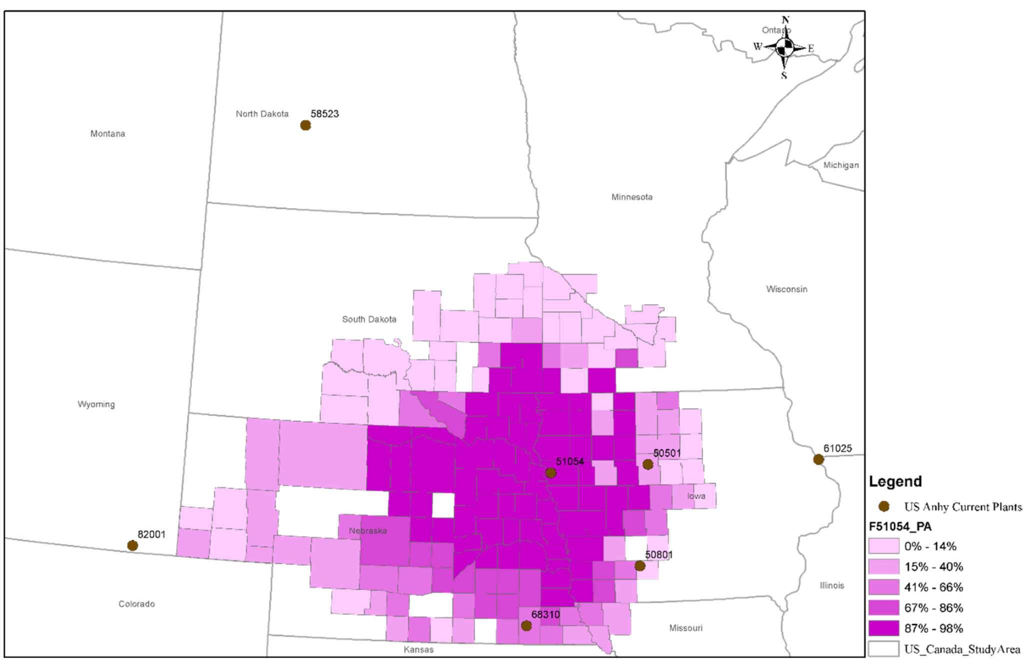

Figure C.8. Market boundaries for plant j= 51054 for anhydrous ammonia (probability of shipping for 1000 iterations) in stochastic linear future case 2018.

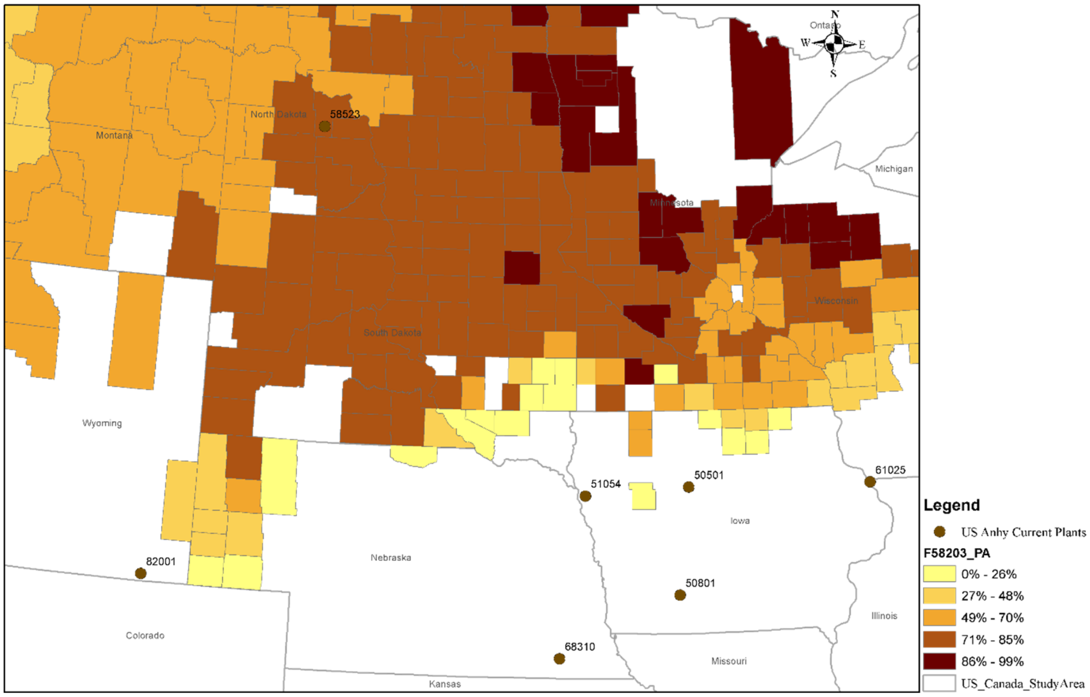

Figure C.9. Market boundaries for plant j=58203 for anhydrous ammonia (probability of shipping for 1000 iterations) in stochastic linear future case 2018.

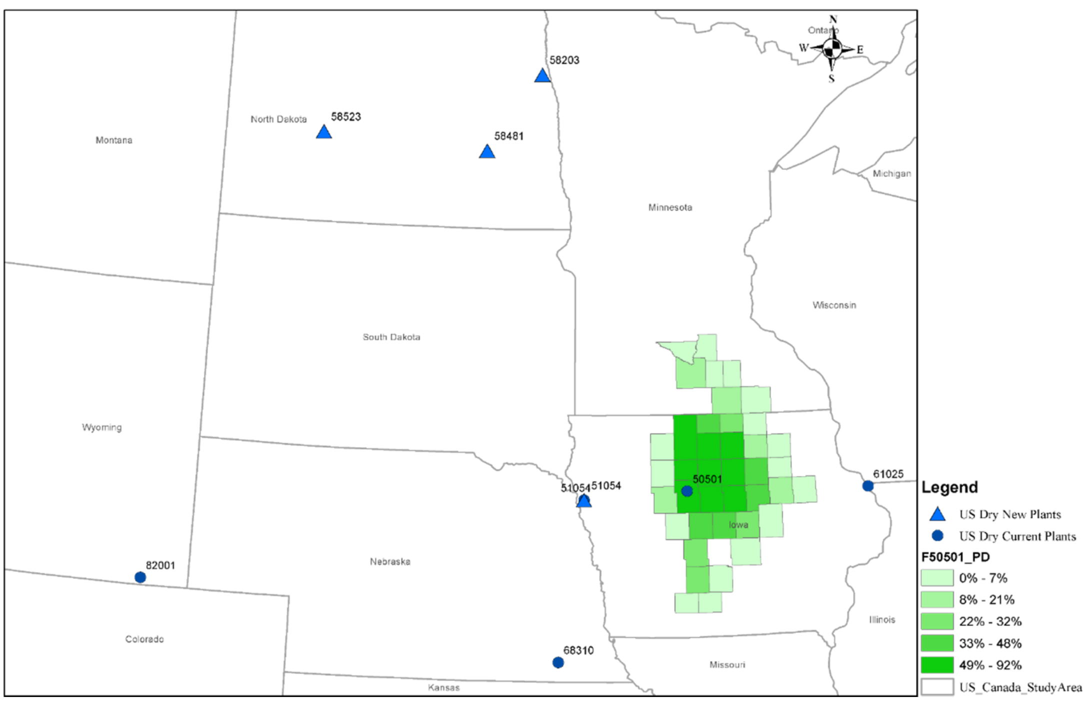

Figure C.10. Market boundaries for plant j=50501 for urea (probability of shipping for 1000 iterations) in stochastic linear future case 2018.

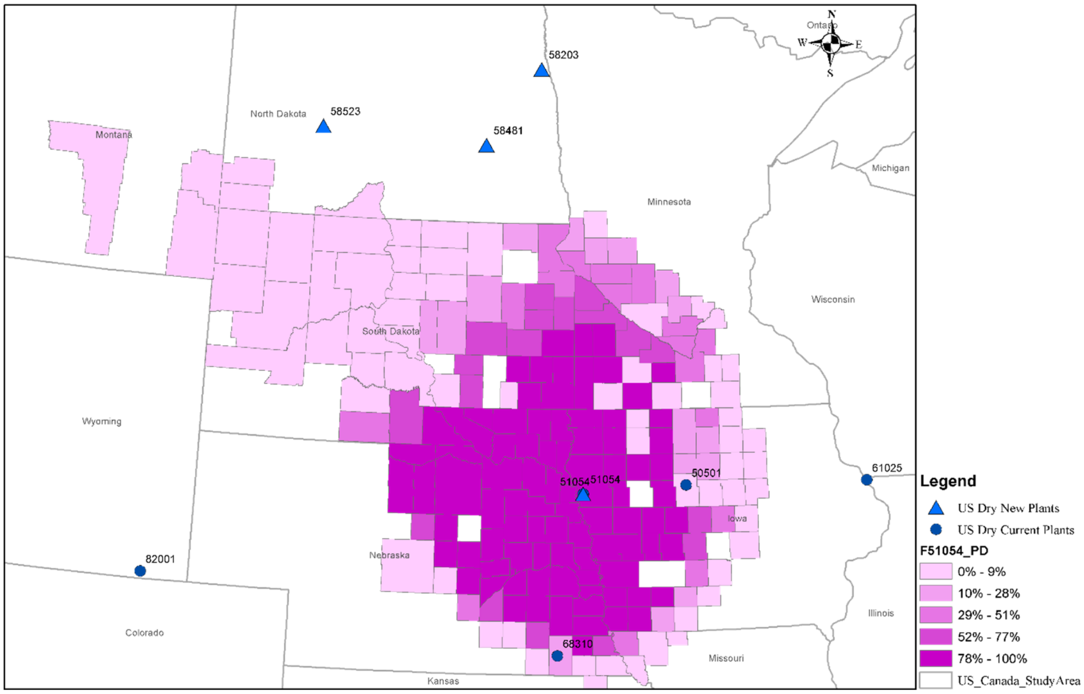

Figure C.11. Market boundaries for plant j=51054 for urea (probability of shipping for 1000 iterations) in stochastic linear future case 2018.

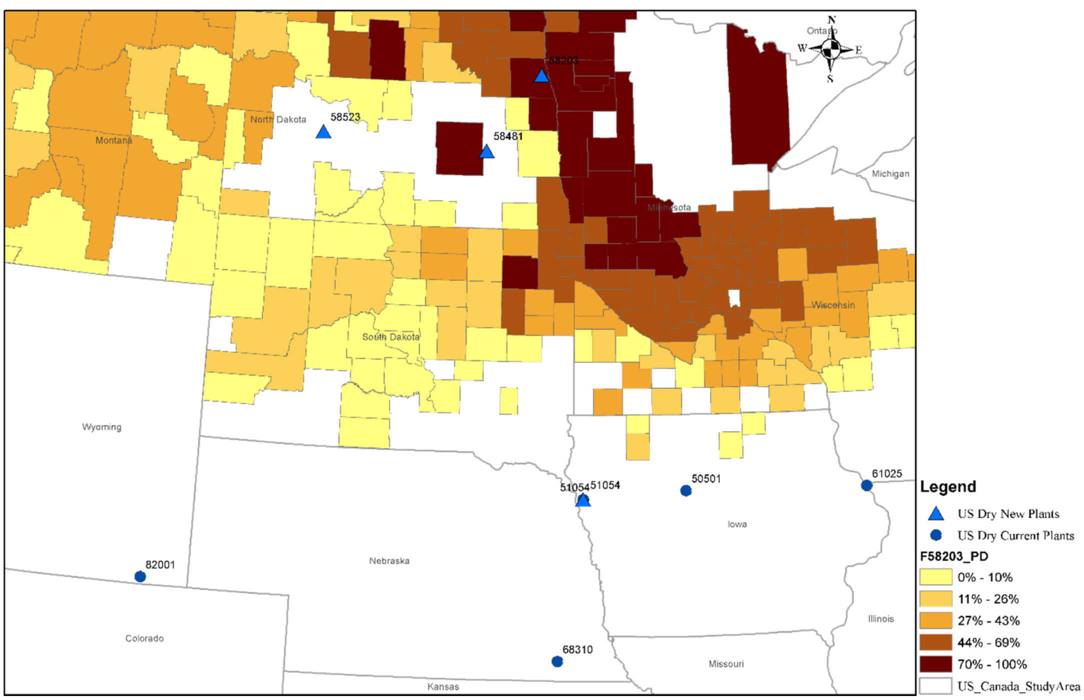

Figure C.12. Market boundaries for plant j=58203 for urea (probability of shipping for 1000 iterations) in stochastic linear future case 2018.

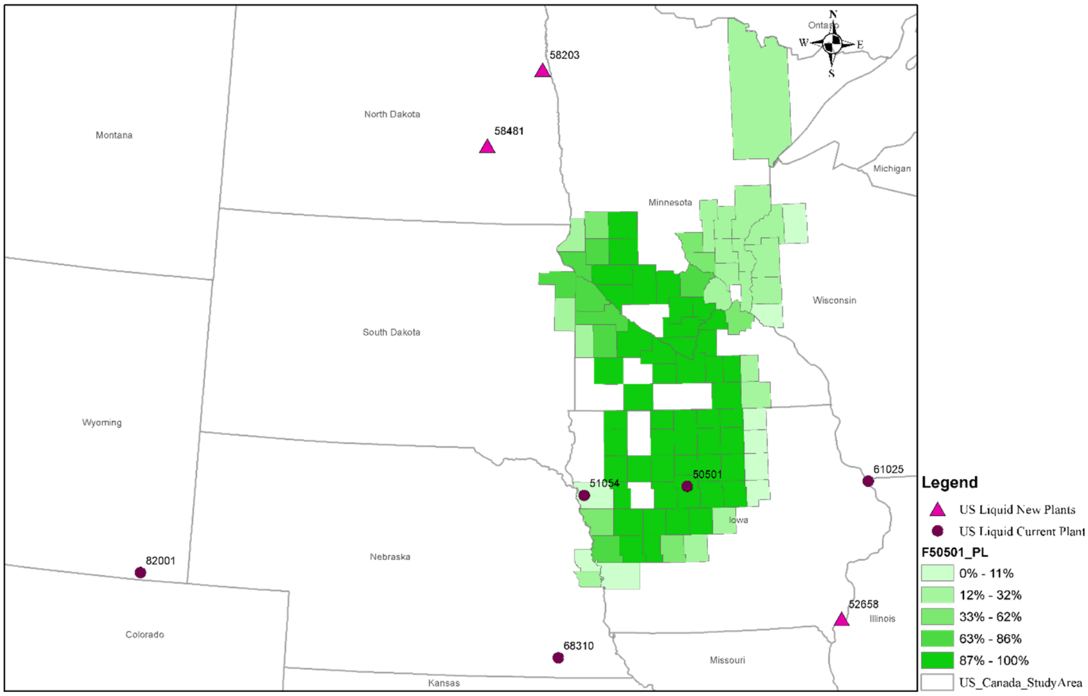

Figure C.13. Market boundaries for plant j=50501 for UAN (probability of shipping for 1000 iterations) in stochastic linear future case 2018.

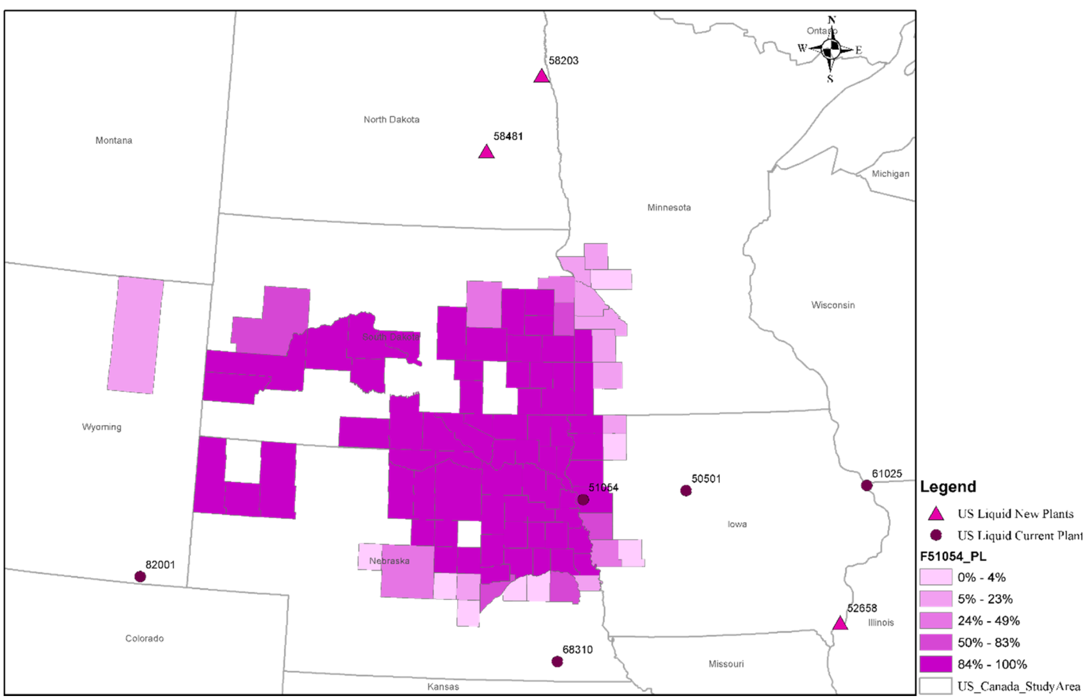

Figure C.14. Market boundaries for plant j=51054 for UAN (probability of shipping for 1000 iterations) in stochastic linear future case 2018.

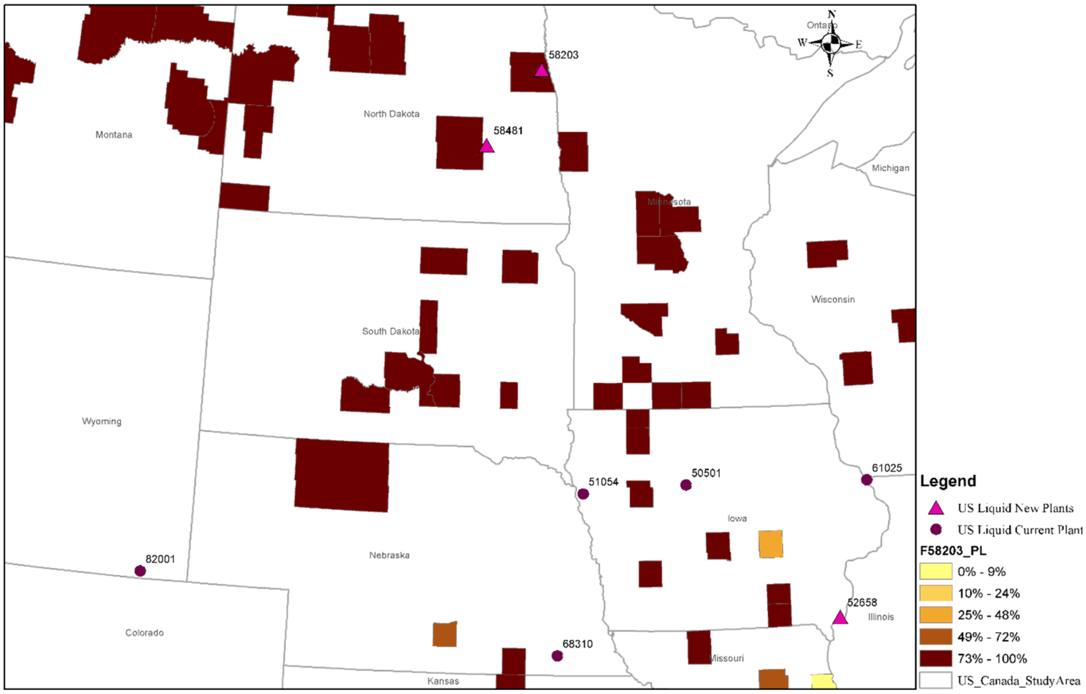

Figure C.15. Market boundaries for plant j=58203 for UAN (probability of shipping for 1000 iterations) in stochastic linear future case 2018.

C.4. Market Boundaries for Selective Plants by Mean Quantity of Shipping for 1000 Iterations in Stochastic Linear Future Case 2018

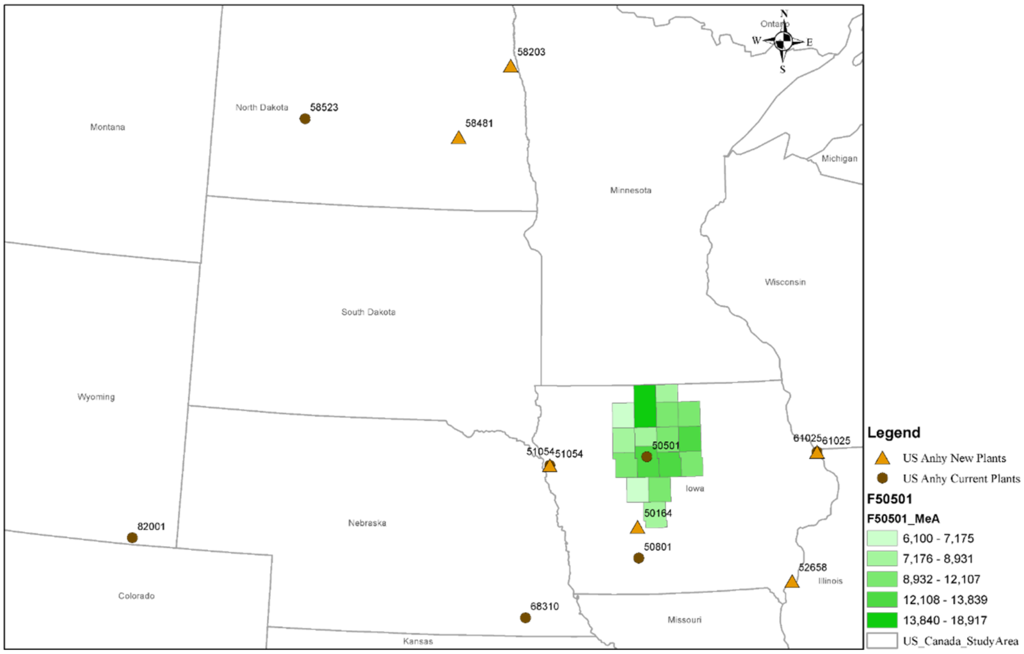

Figure C.16. Market boundaries for plant j=50501 for anhydrous ammonia (mean quantity of shipping for 1000 iterations) in stochastic linear future case 2018.

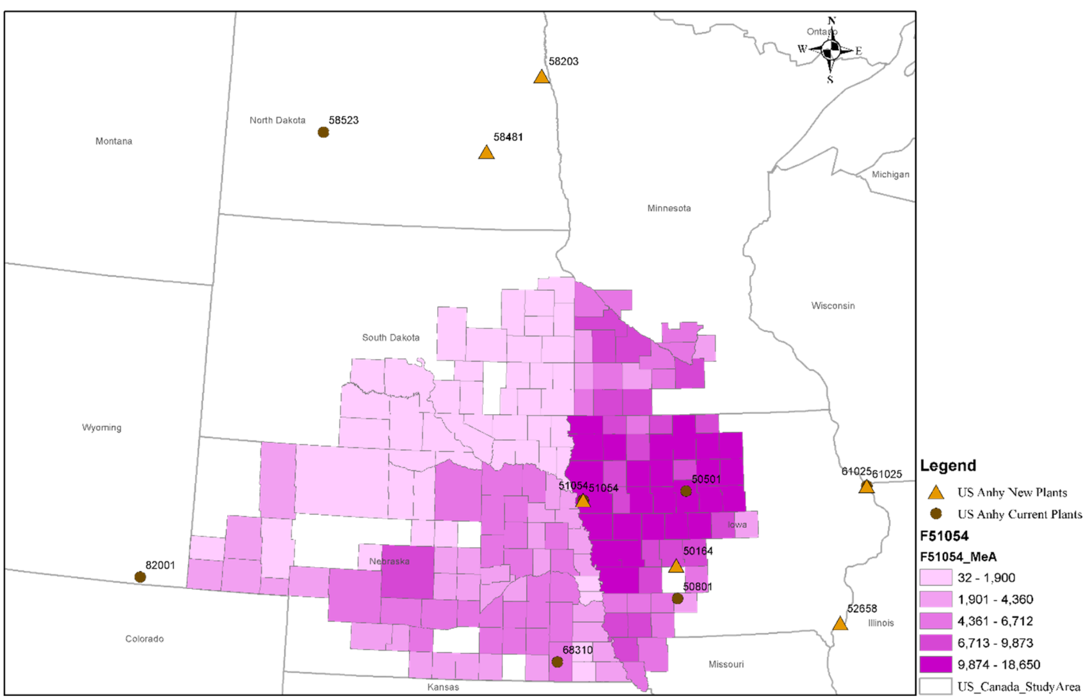

Figure C.17. Market boundaries for plant j=51054 for anhydrous ammonia (mean quantity of shipping for 1000 iterations) in stochastic linear future case 2018.

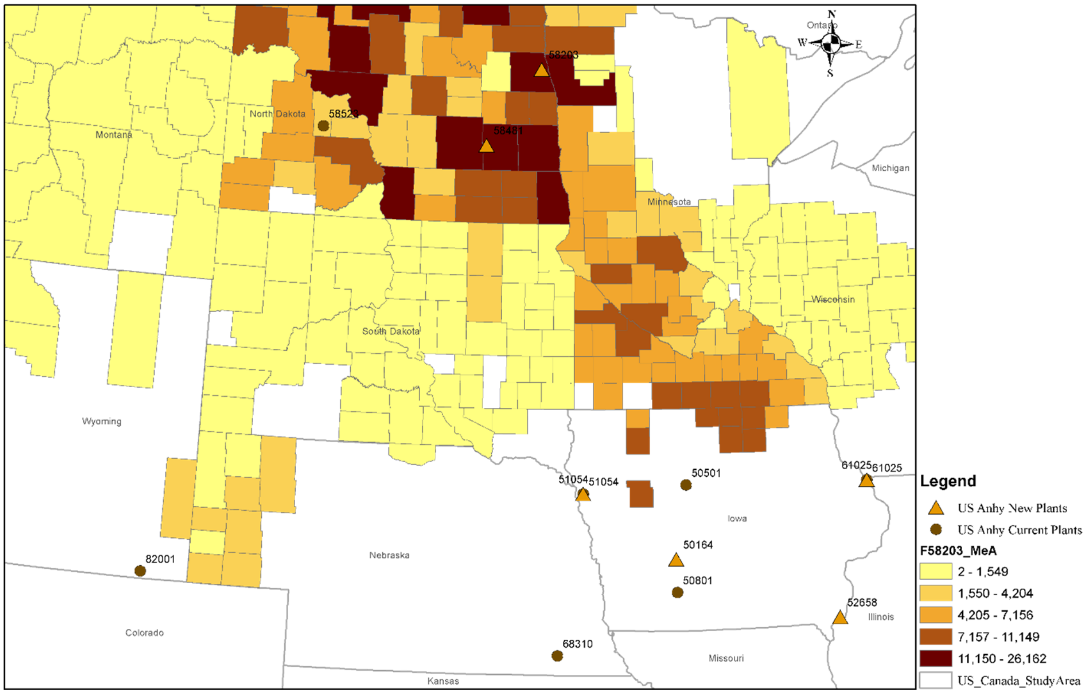

Figure C.18. Market boundaries for plant j=58203 for anhydrous ammonia (mean quantity of shipping for 1000 iterations) in stochastic linear future case 2018.

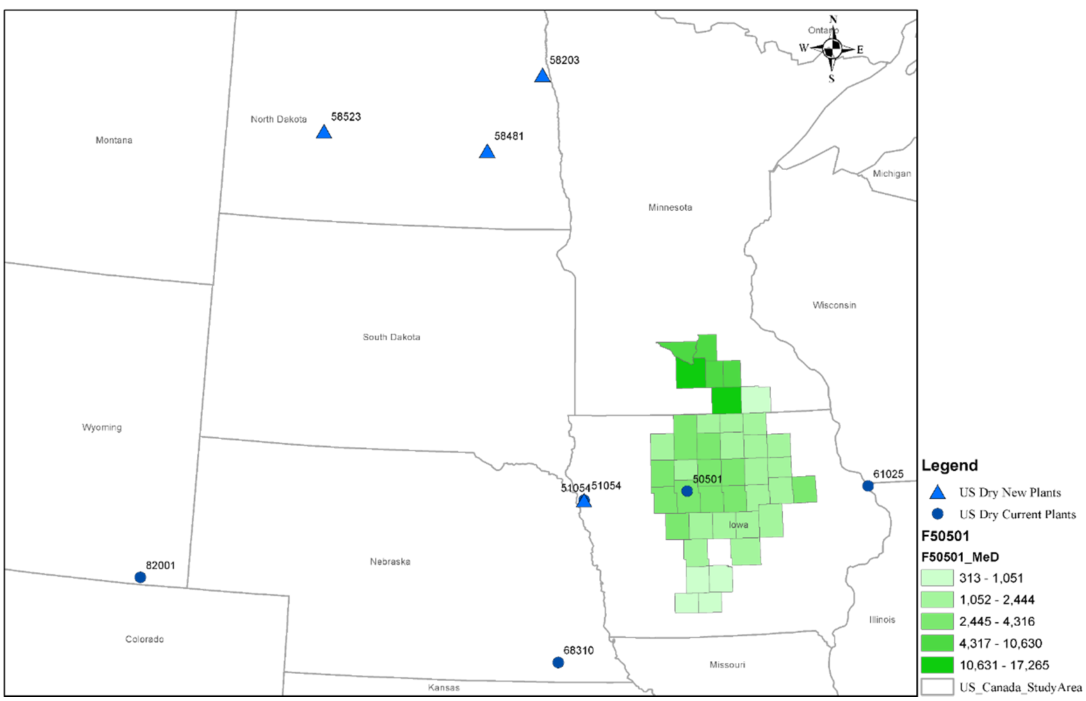

Figure C.19. Market boundaries for plant j=50501 for urea (mean quantity of shipping for 1000 iterations) in stochastic linear future case 2018.

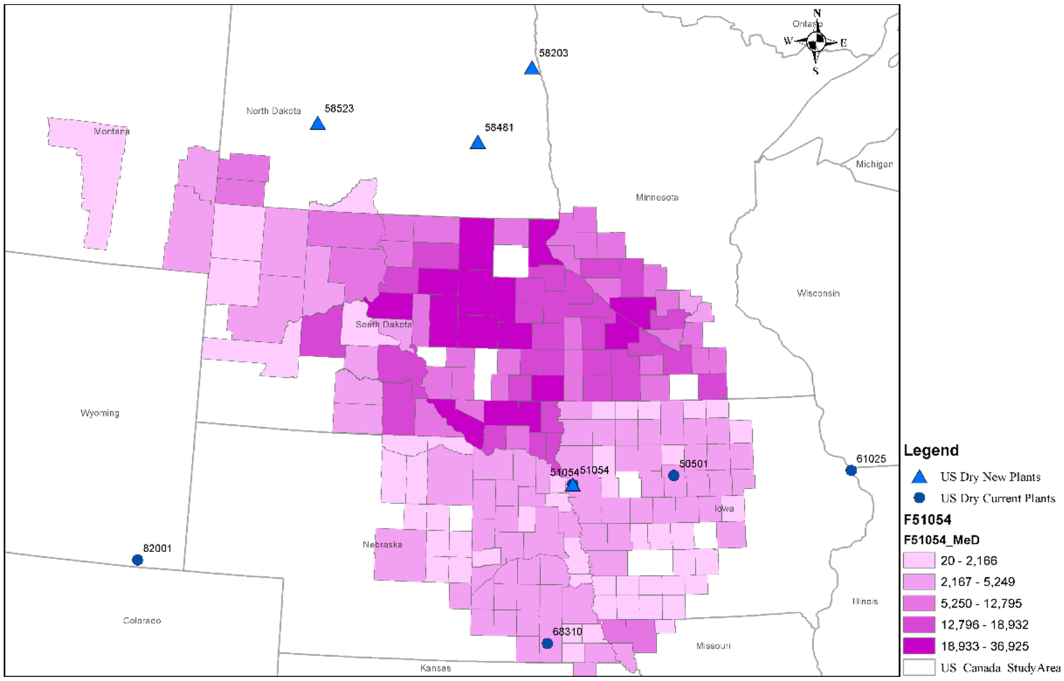

Figure C.20. Market boundaries for plant j=51054 for urea (mean quantity of shipping for 1000 iterations) in stochastic linear future case 2018.

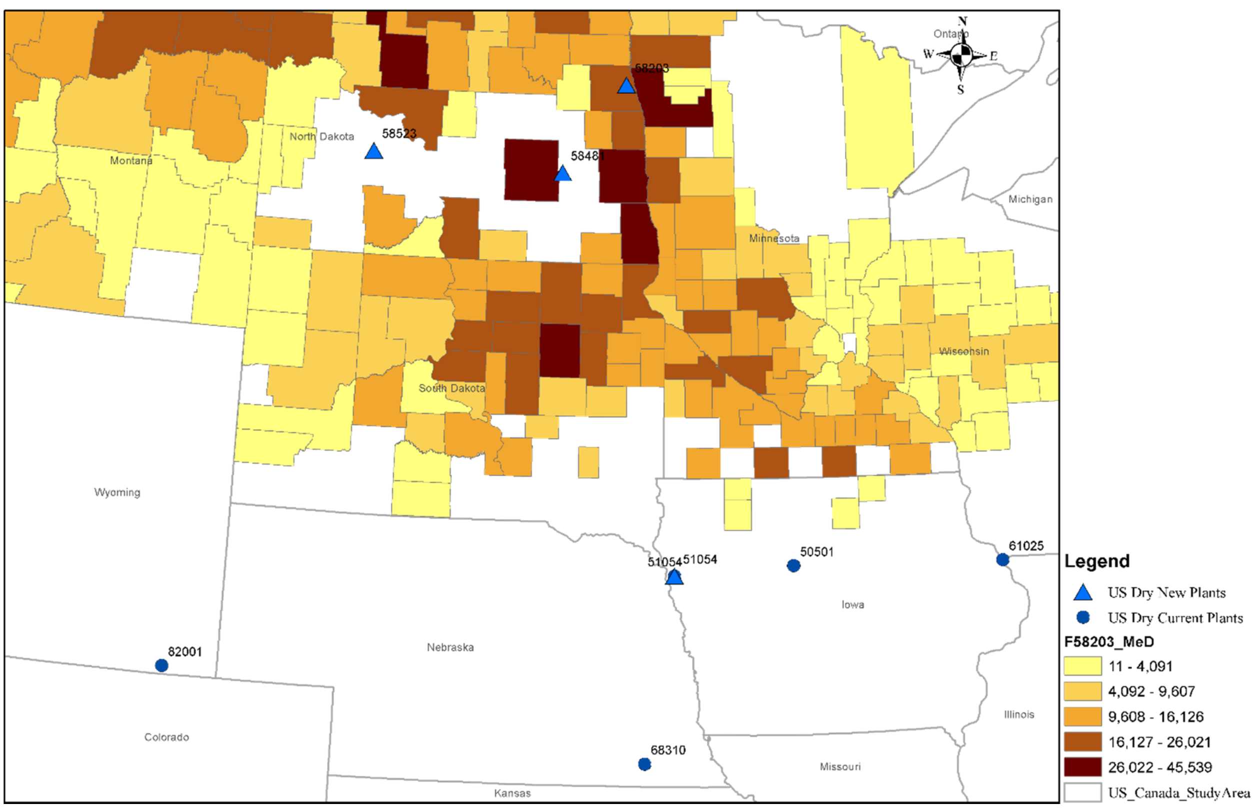

Figure C.21. Market boundaries for plant j=58203 for urea (mean quantity of shipping for 1000 iterations) in stochastic linear future case 2018.

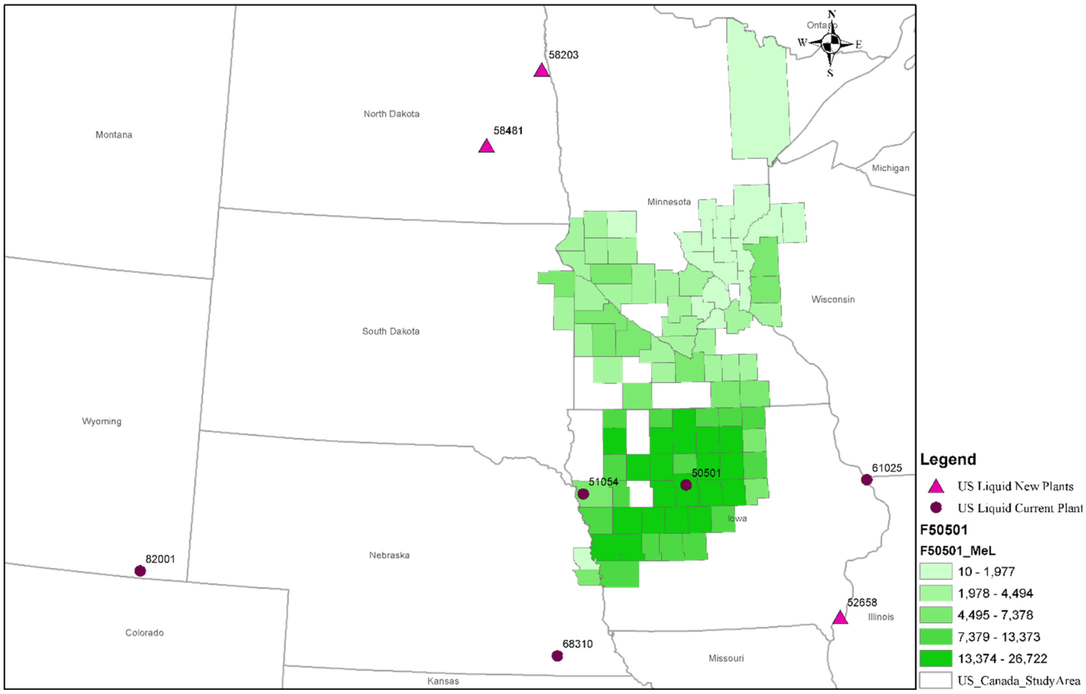

Figure C.22. Market boundaries for plant j=50501 for UAN (mean quantity of shipping for 1000 iterations) in stochastic linear future case 2018.

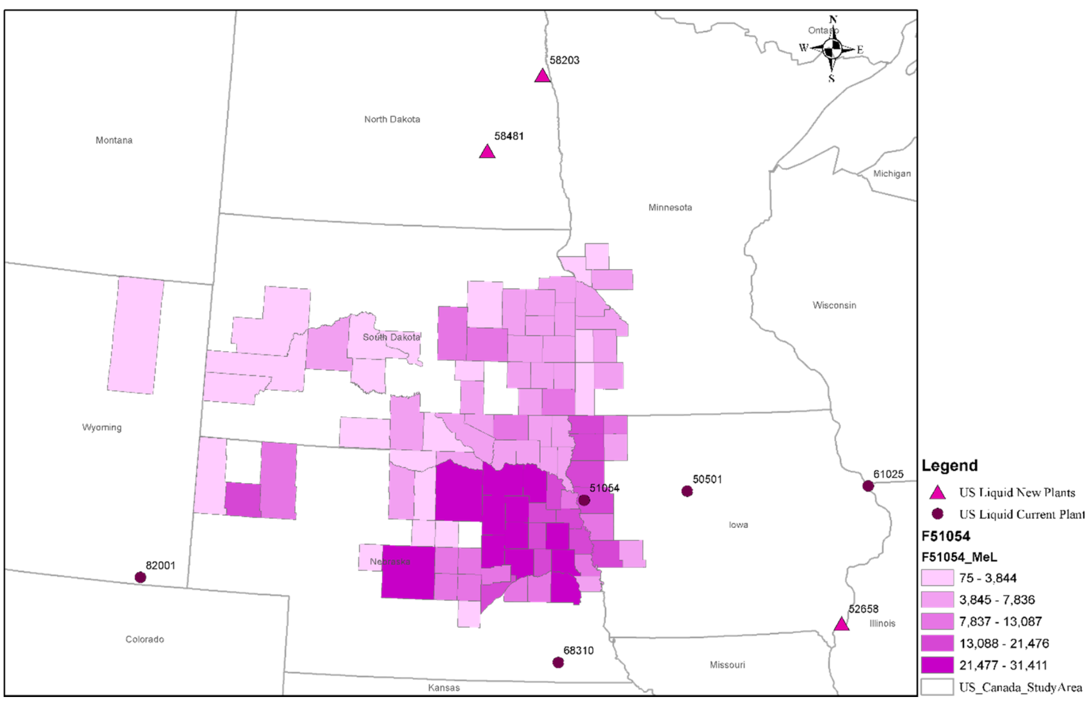

Figure C.23. Market boundaries for plant j=51054 for UAN (mean quantity of shipping for 1000 iterations) in stochastic linear future case 2018.

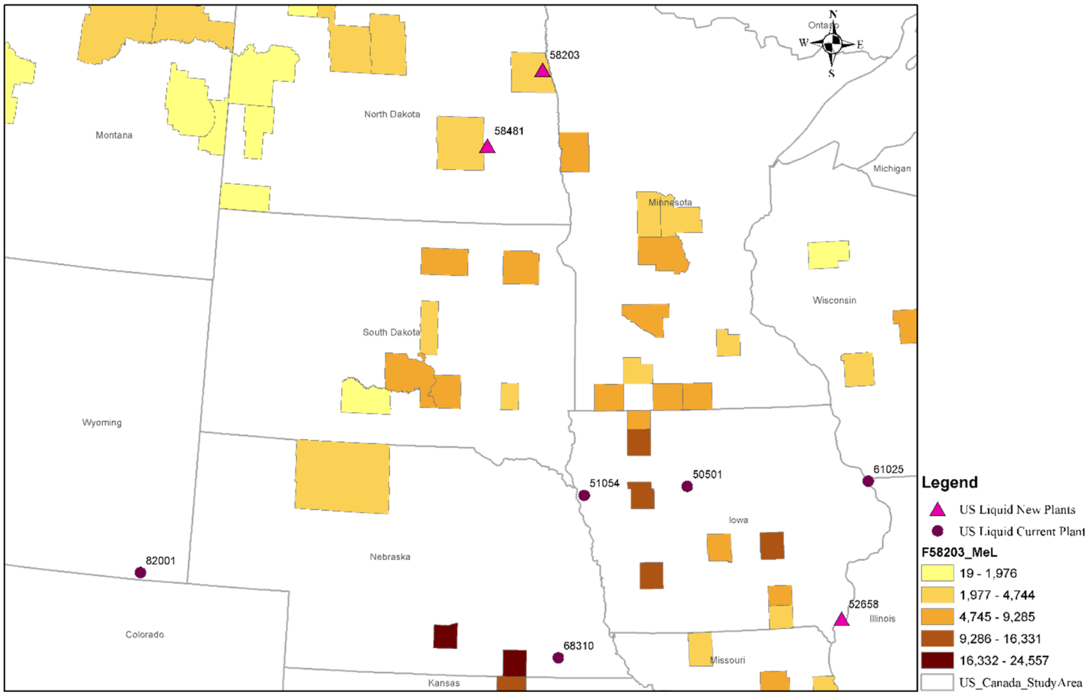

Figure C.24. Market boundaries for plant j=58203 for UAN (mean quantity of shipping for 1000 iterations) in stochastic linear future case 2018.

C.5. CDFs by Nodes in Stochastic Linear Future Case 2018

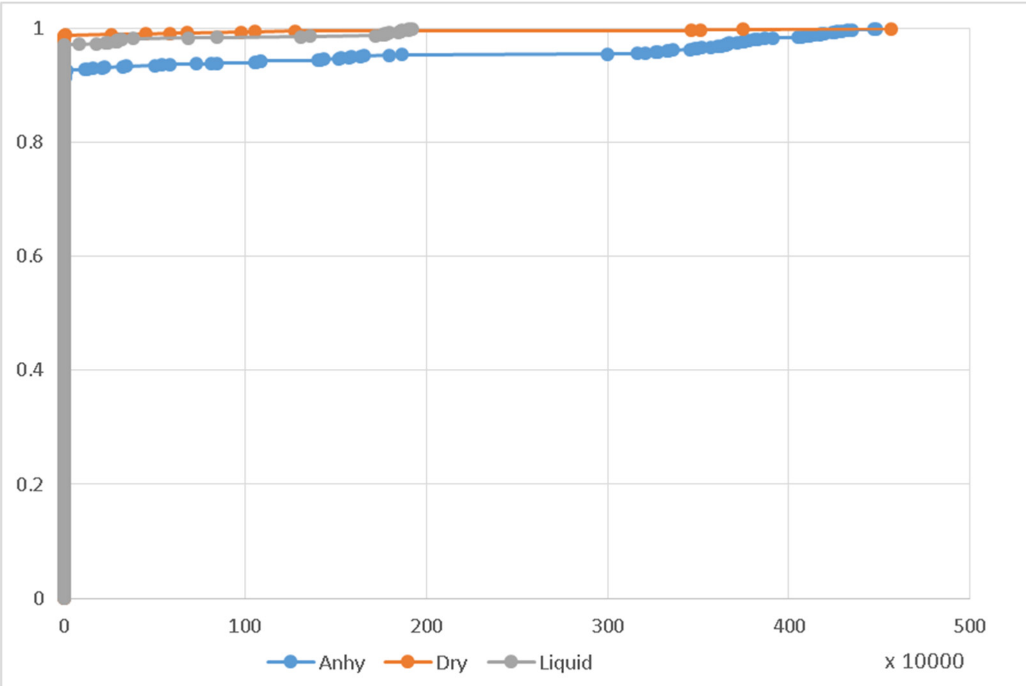

Figure C.25. Cumulative probability for 2200374 (New Orleans, LA) in stochastic linear future case.

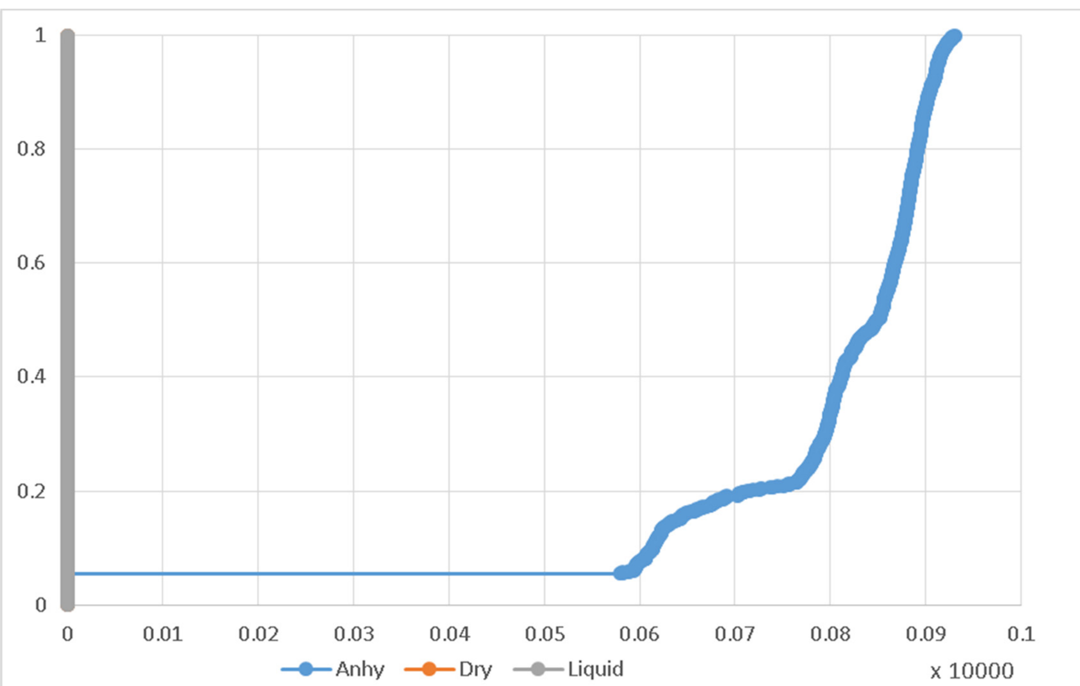

Figure C.26. Cumulative probability for 23860 (Hopewell, VA) in stochastic linear future case.

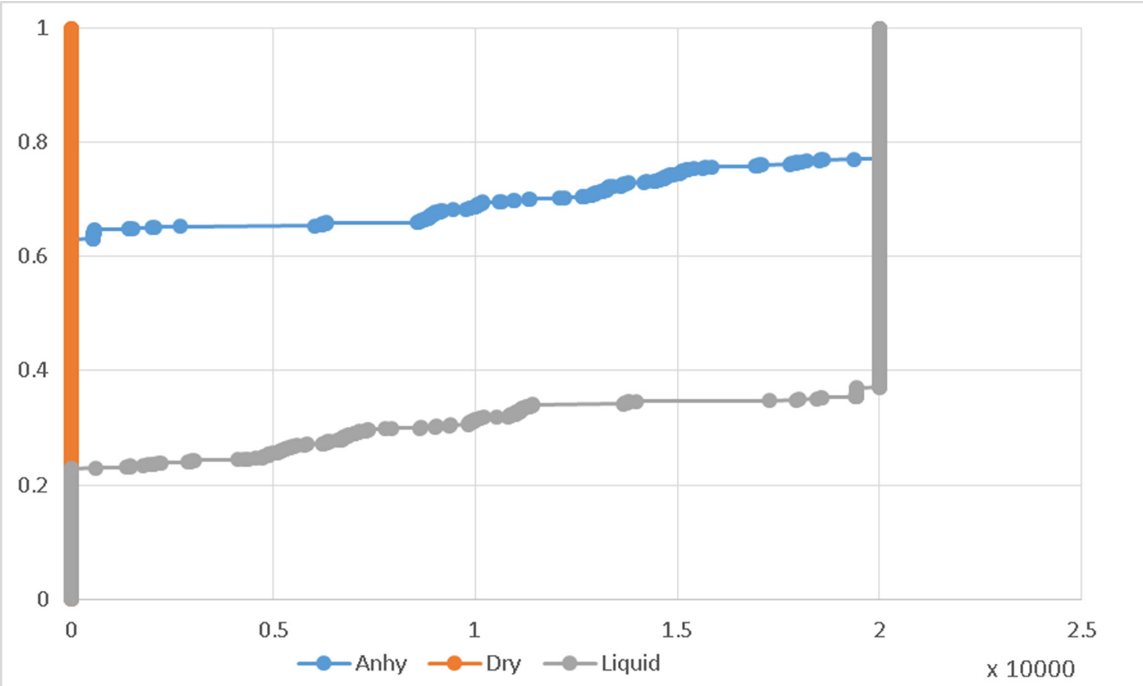

Figure C.27. Cumulative probability for 2700093 (Minneapolis, MN) in stochastic linear future case.

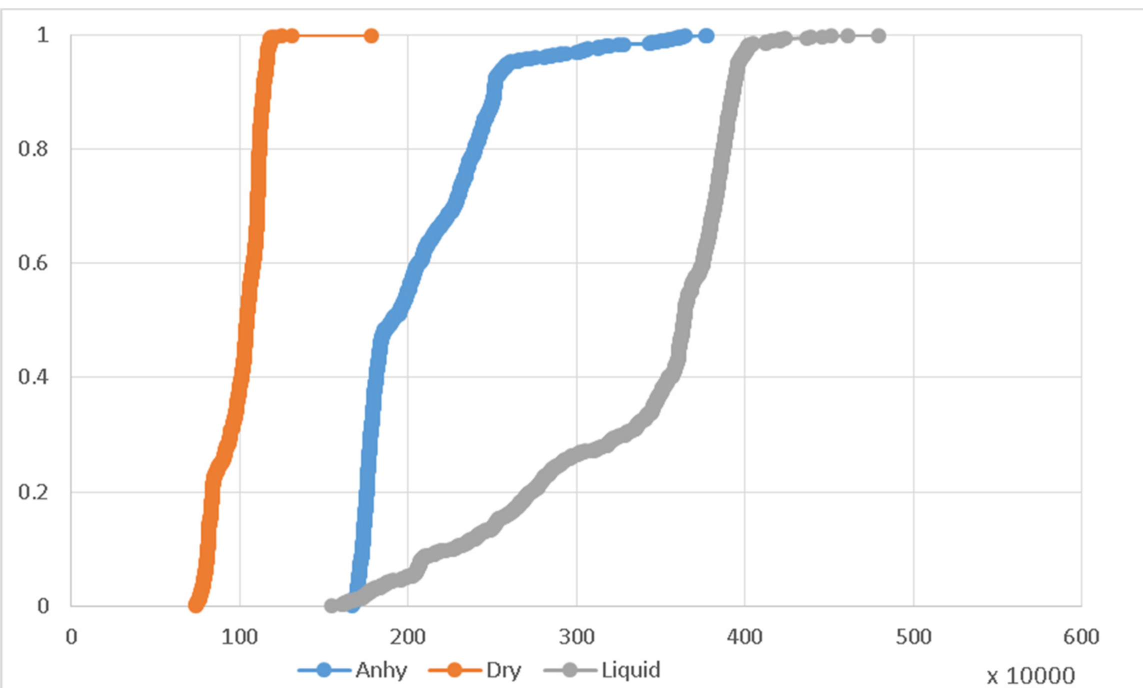

Figure C.28. Cumulative probability for 2900310 (St Louis, MO) in stochastic linear future case.

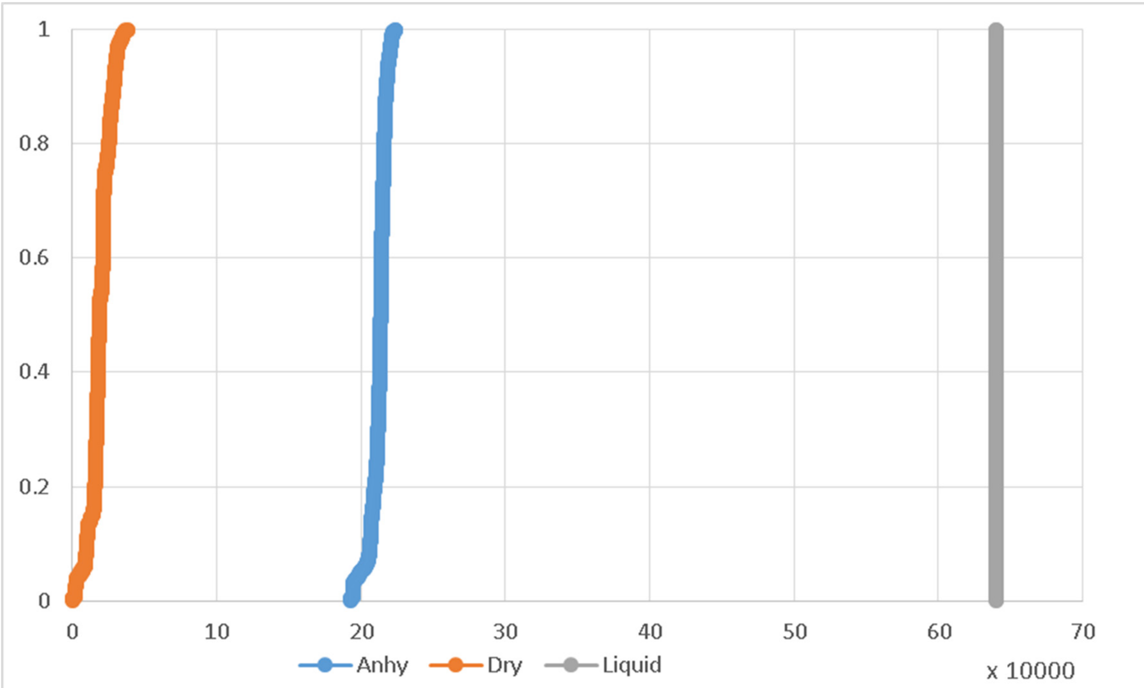

Figure C.29. Cumulative probability for 30901 (Augusta, GA) in stochastic linear future case.

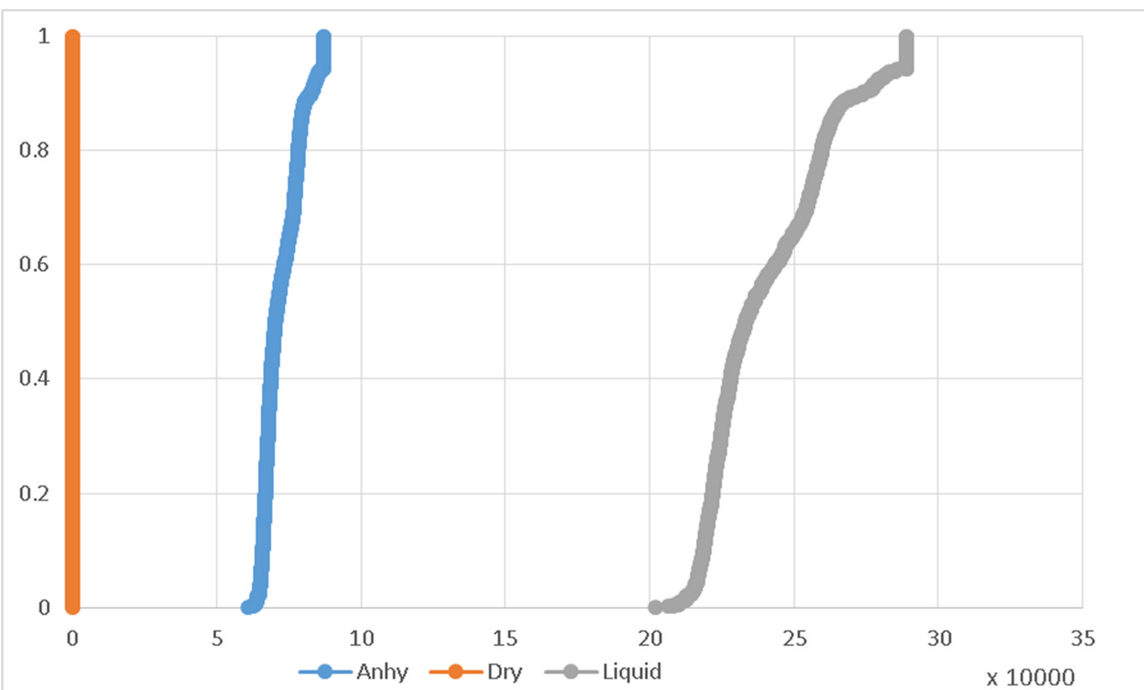

Figure C.30. Cumulative probability for 35616 (Cherokee, AL) in stochastic linear future case.

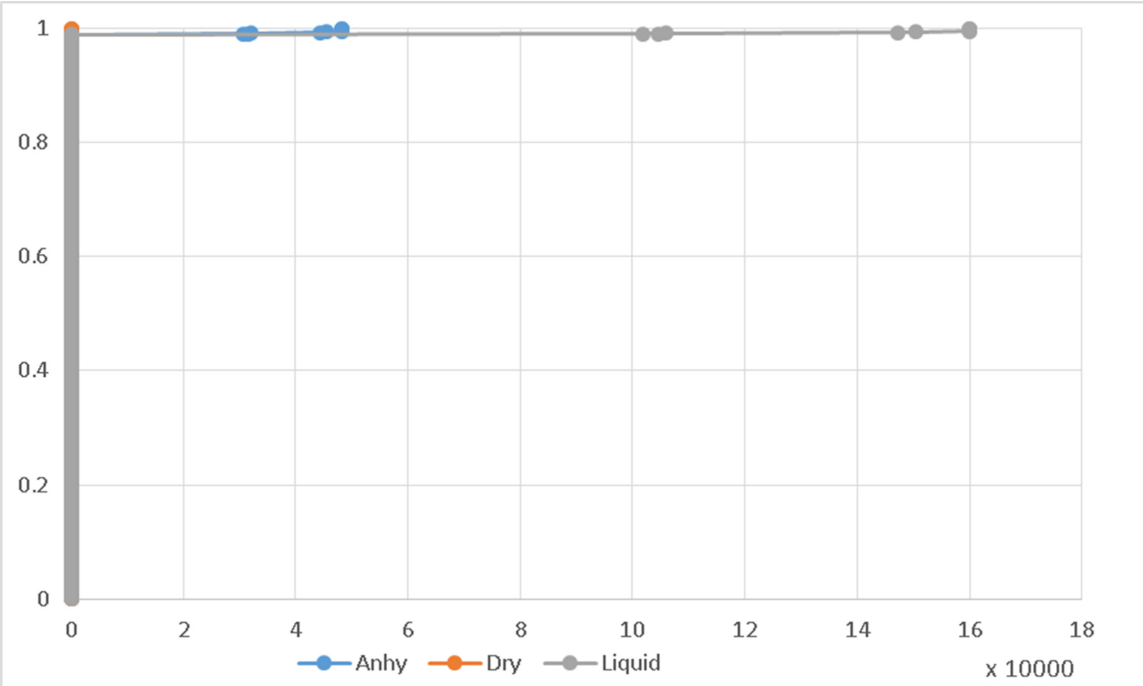

Figure C.31. Cumulative probability for 39194 (Yazoo City, MS) in stochastic linear future case.

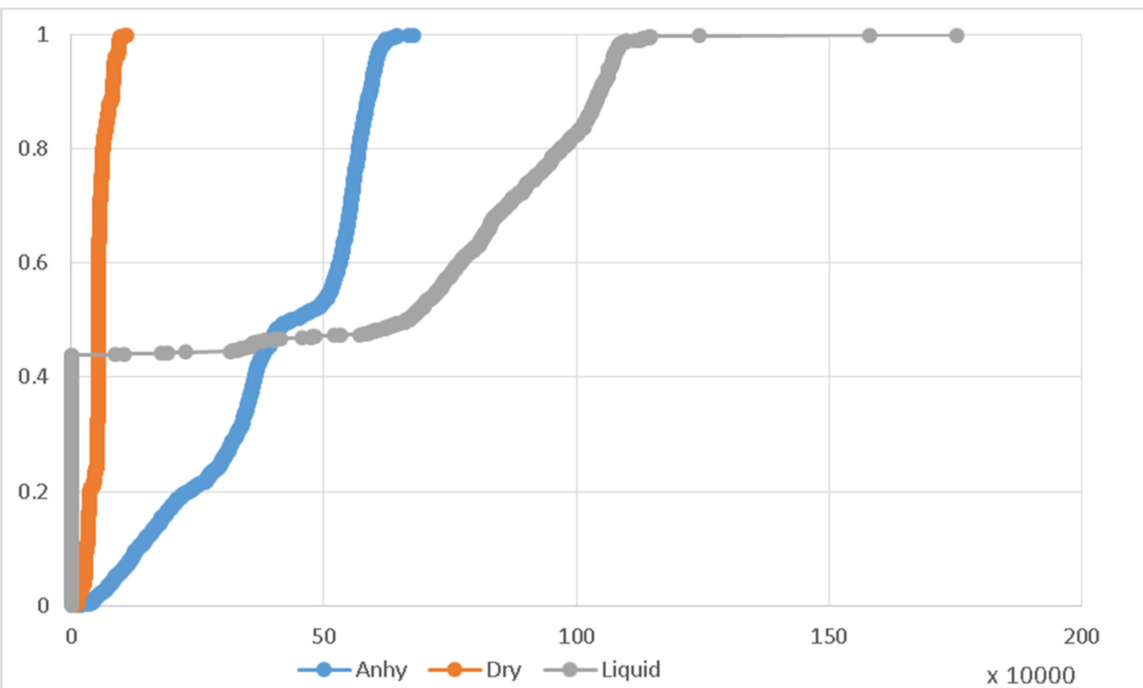

Figure C.32. Cumulative probability for 4000131 (Catoosa, OK) in stochastic linear future case.

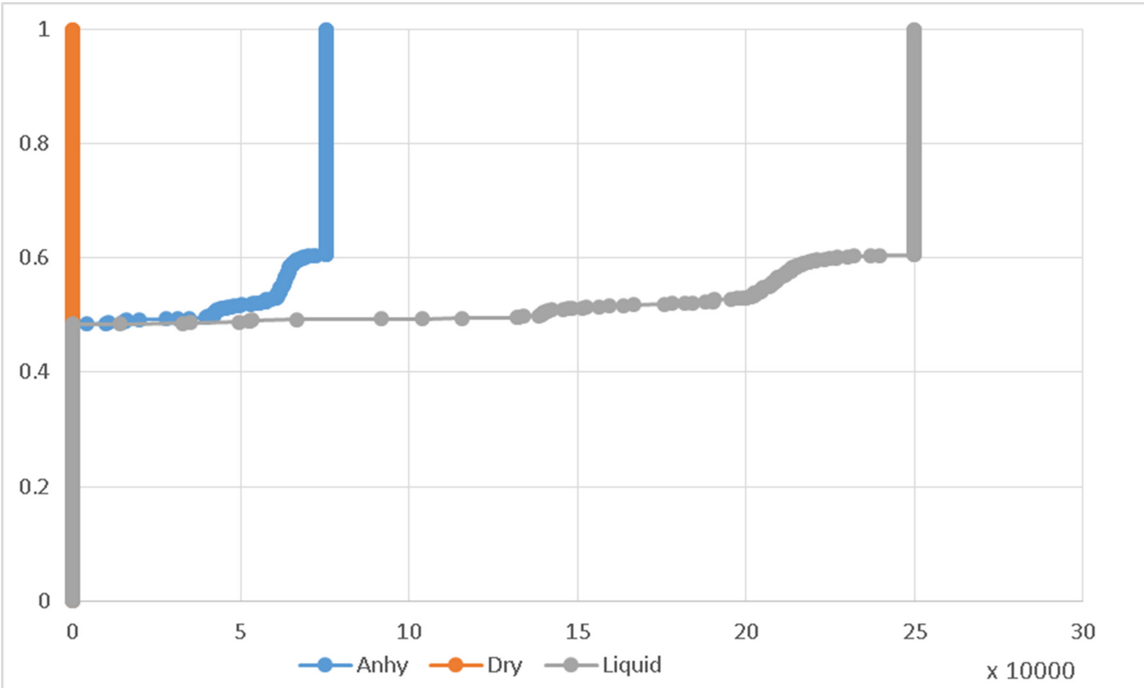

Figure C.33. Cumulative probability for 45804 (Lima, OH) in stochastic linear future case.

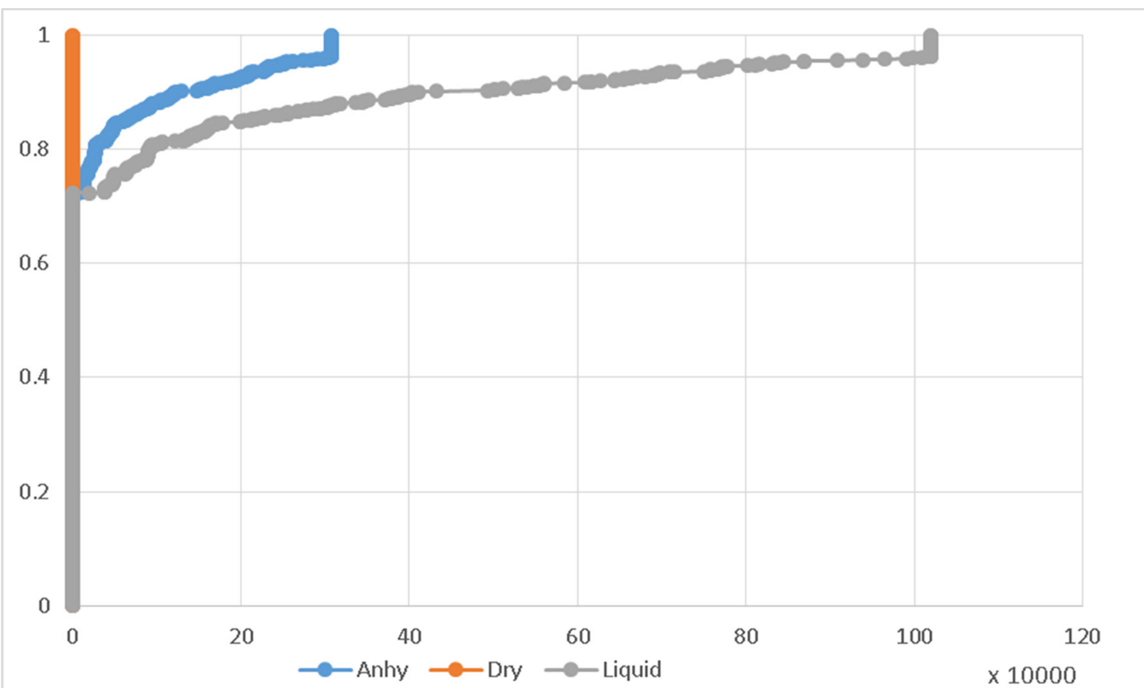

Figure C.34. Cumulative probability for 47635 (Rockport, IN) in stochastic linear future case.

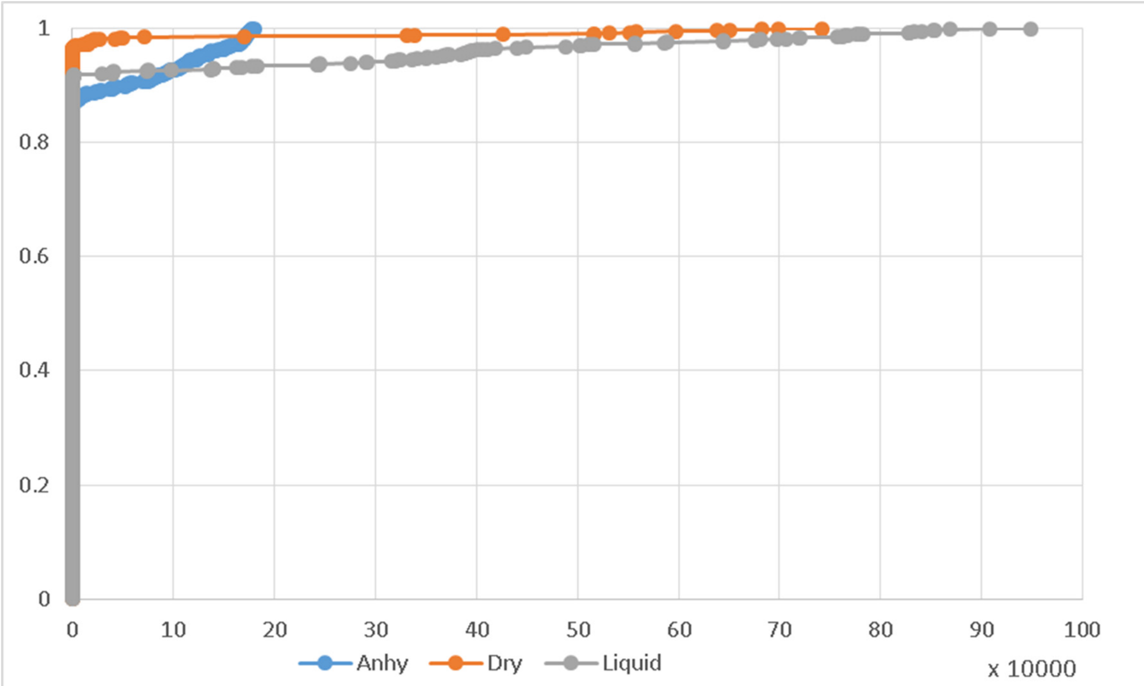

Figure C.35. Cumulative probability for 4800608 (Galveston, TX) in stochastic linear future case.

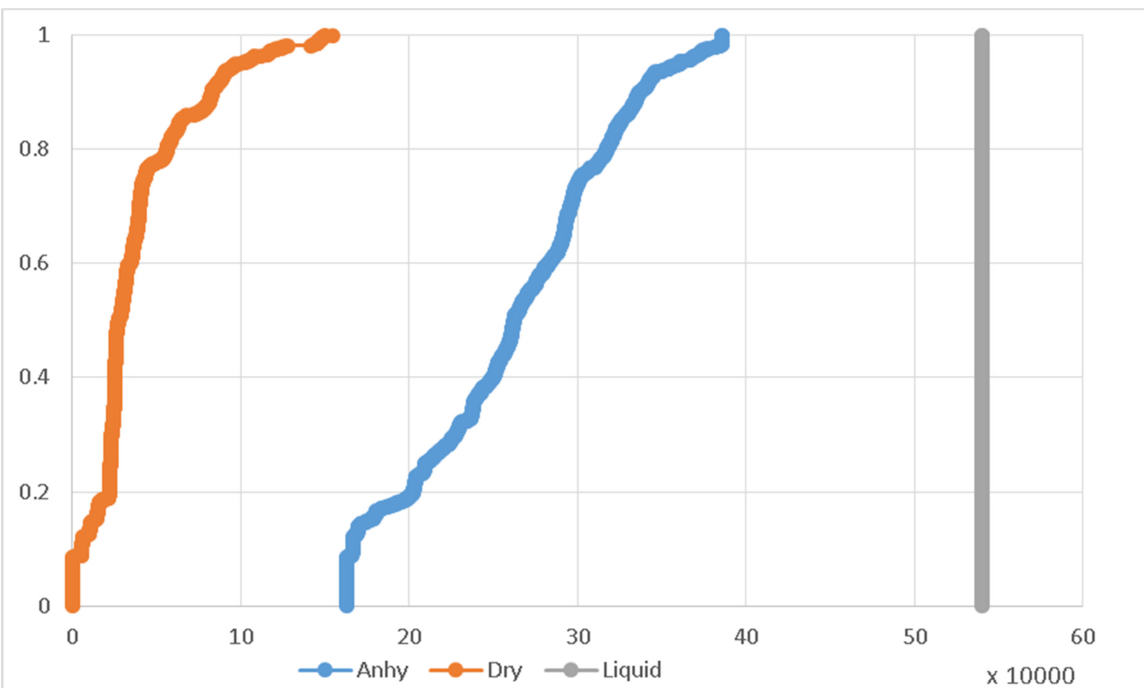

Figure C.36. Cumulative probability for 50501 (Fort Dodge, IA) in stochastic linear future case.

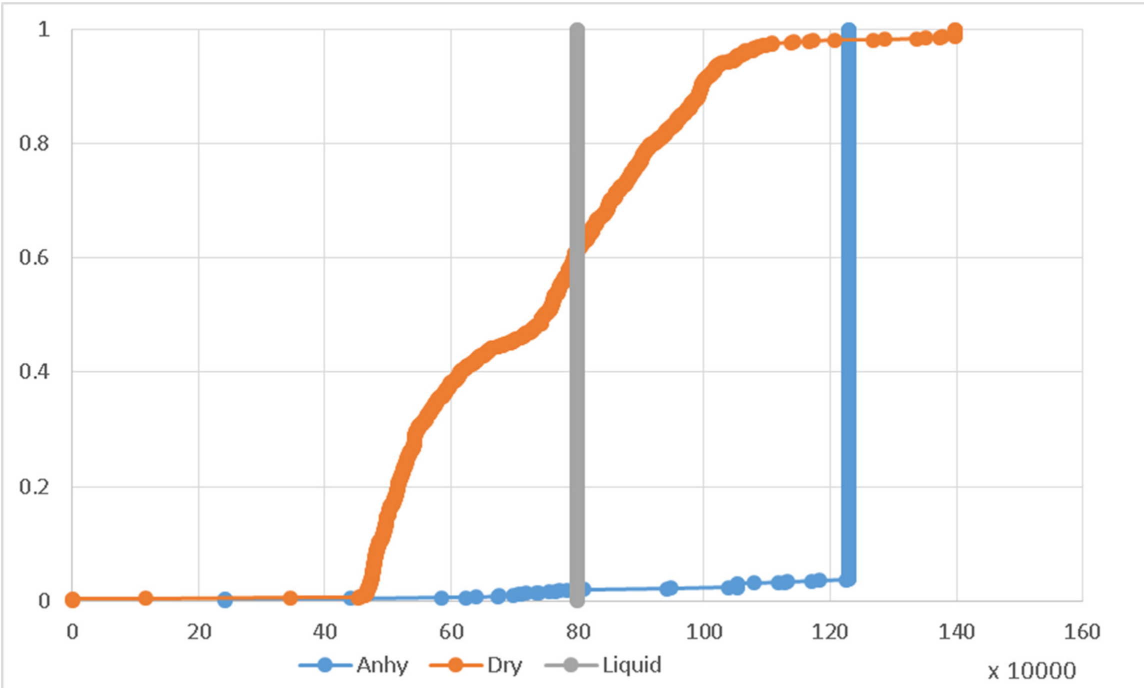

Figure C.37. Cumulative probability for 51054 (Port Neal, IA) in stochastic linear future case.

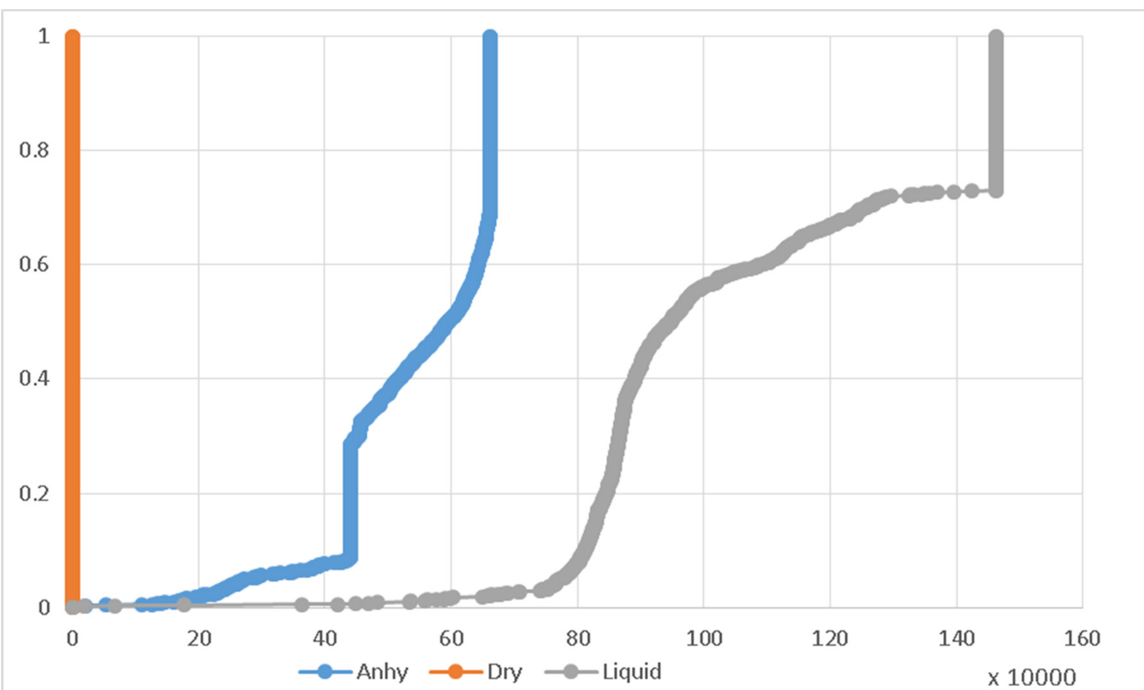

Figure C.38. Cumulative probability for 52658 (Wever, IA) in stochastic linear future case.

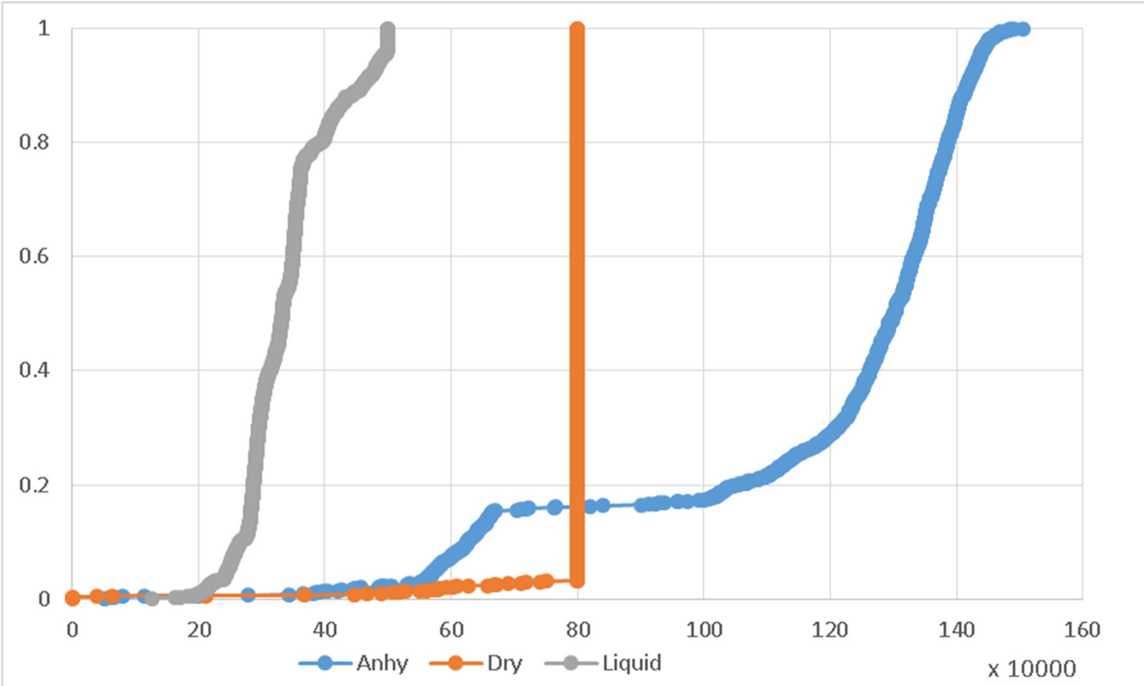

Figure C.39. Cumulative probability for 58203 (Grand Forks, ND) in stochastic linear future case.

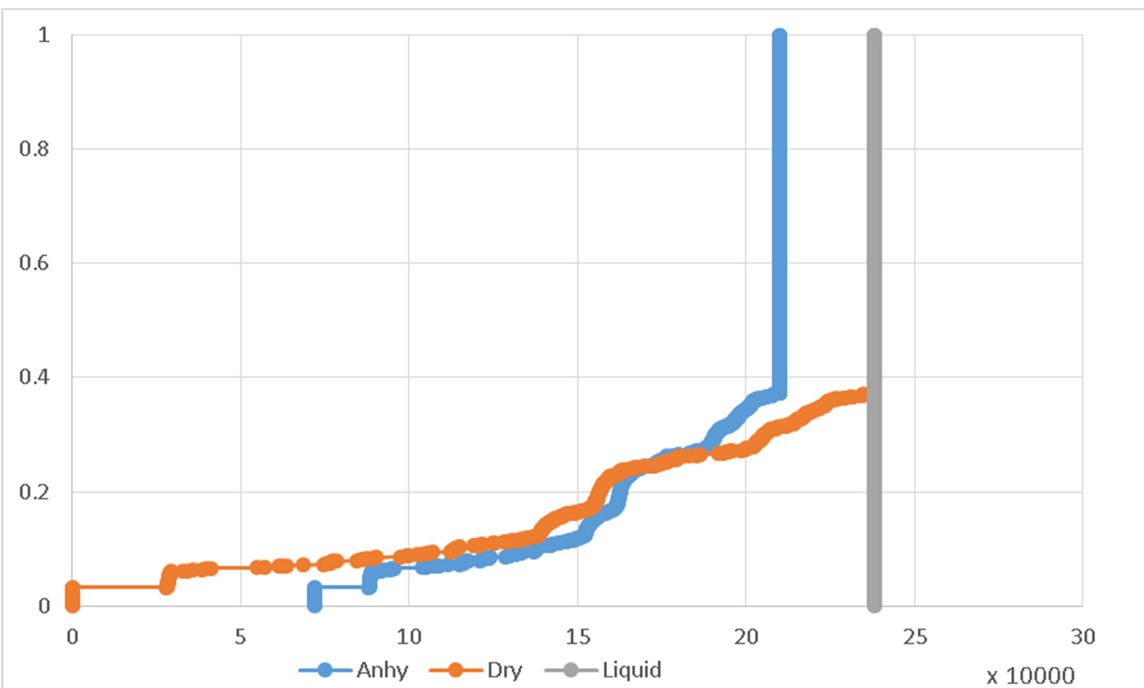

Figure C.40. Cumulative probability for 58481 (Jamestown, ND) in stochastic linear future case.

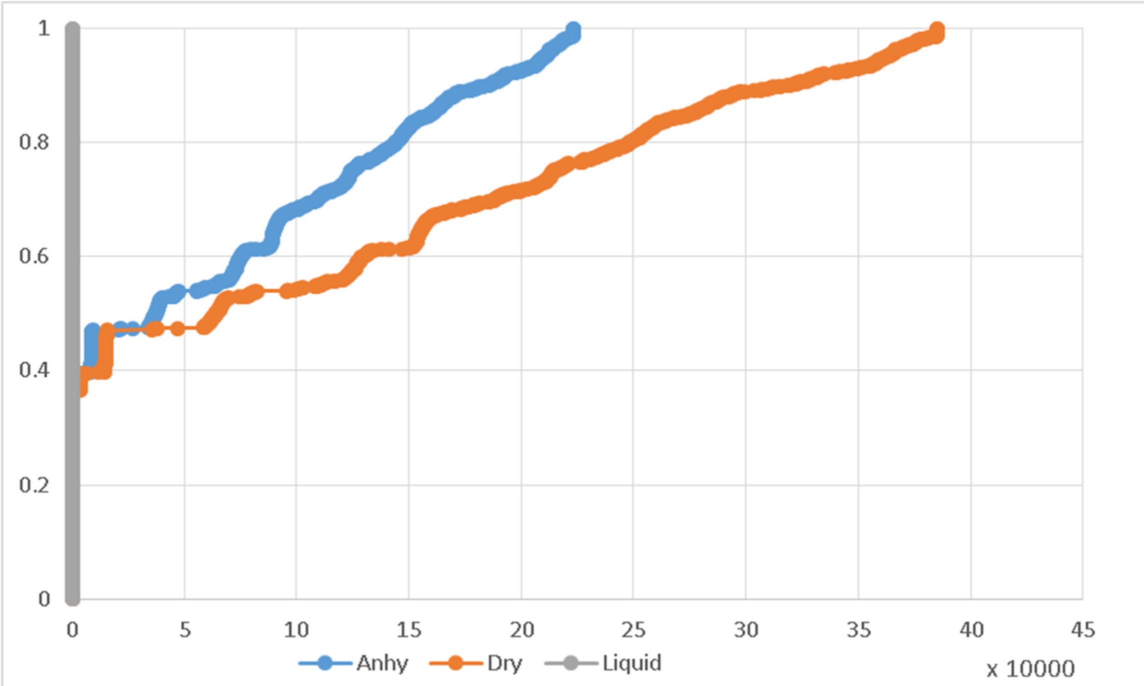

Figure C.41. Cumulative probability for 58523 (Beulah, ND) in stochastic linear future case.

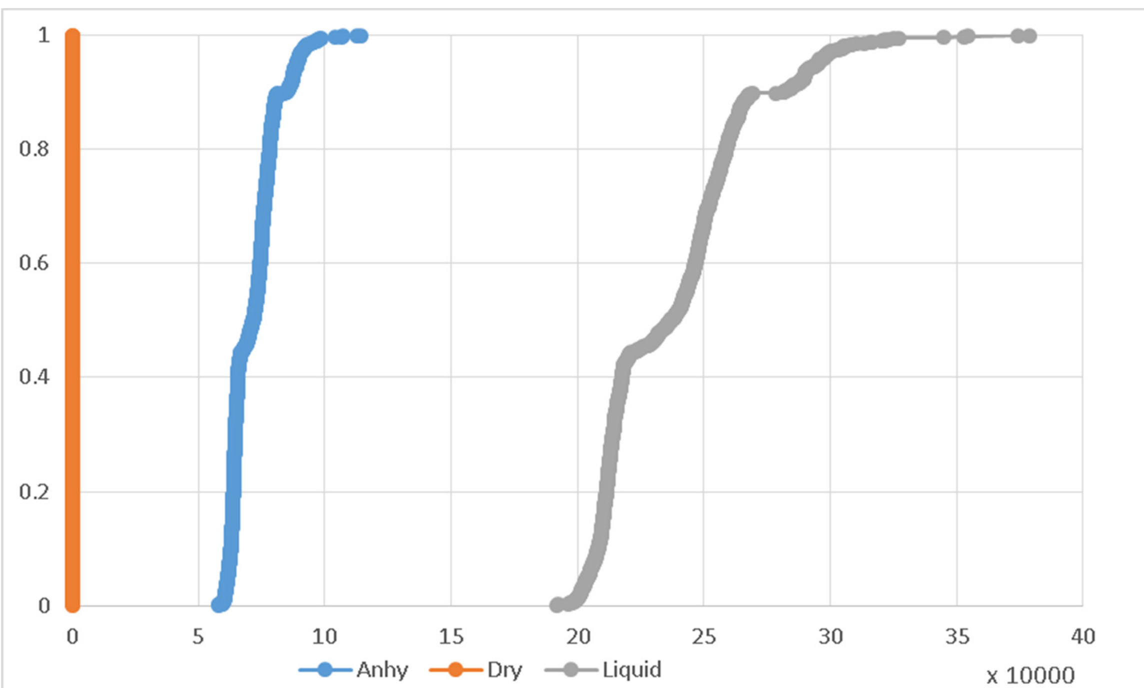

Figure C.42. Cumulative probability for 61025 (East Dubuque, IL) in stochastic linear future case.

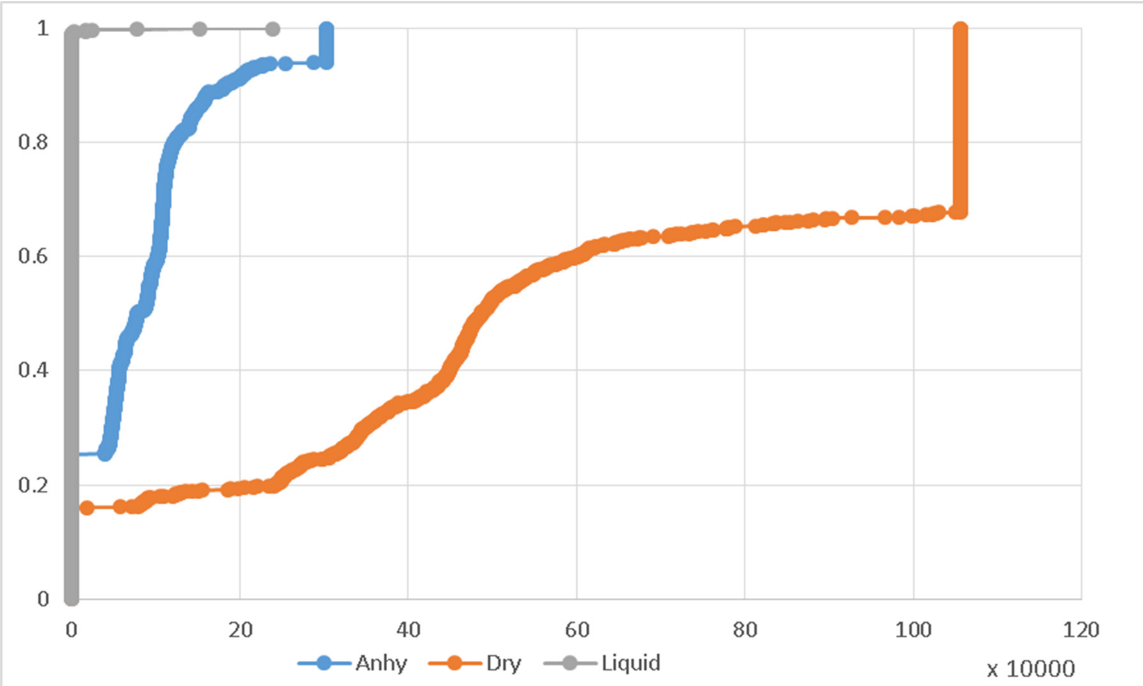

Figure C.43. Cumulative probability for 612 (Medicine Hat, AB) in stochastic linear future case.

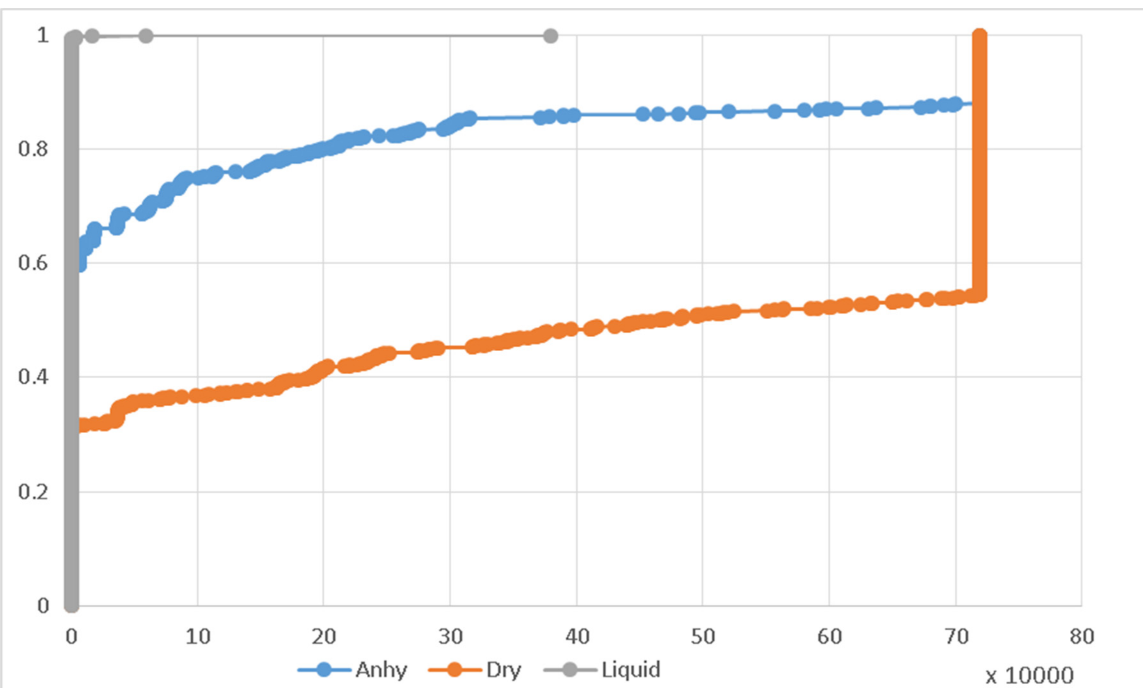

Figure C.44. Cumulative probability for 644 (Belle Plaine, SK) in stochastic linear future case.

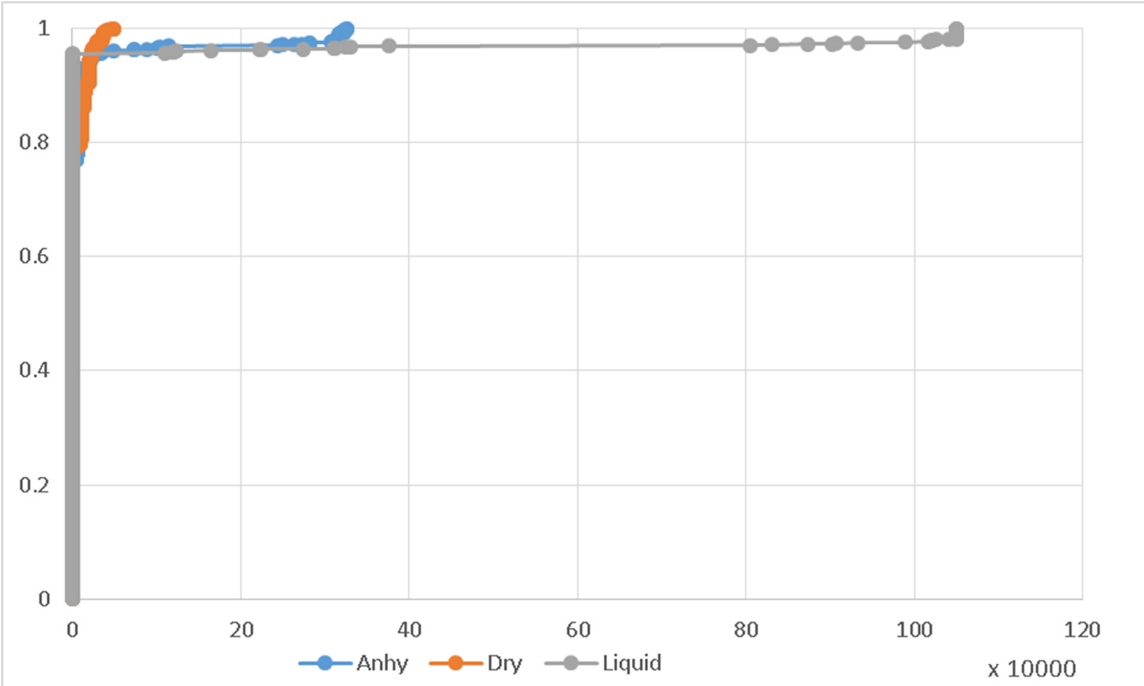

Figure C.45. Cumulative probability for 67337 (Coffeyville, KS) in stochastic linear future case.

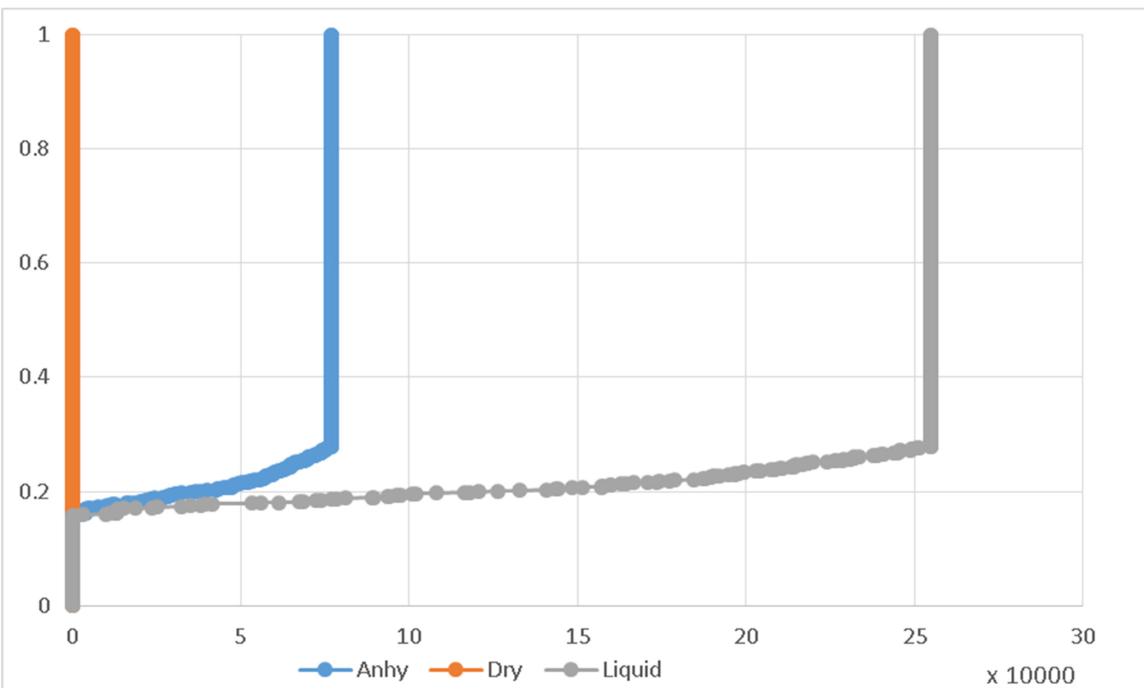

Figure C.46. Cumulative probability for 67801 (Dodge City, KS) in stochastic linear future case.

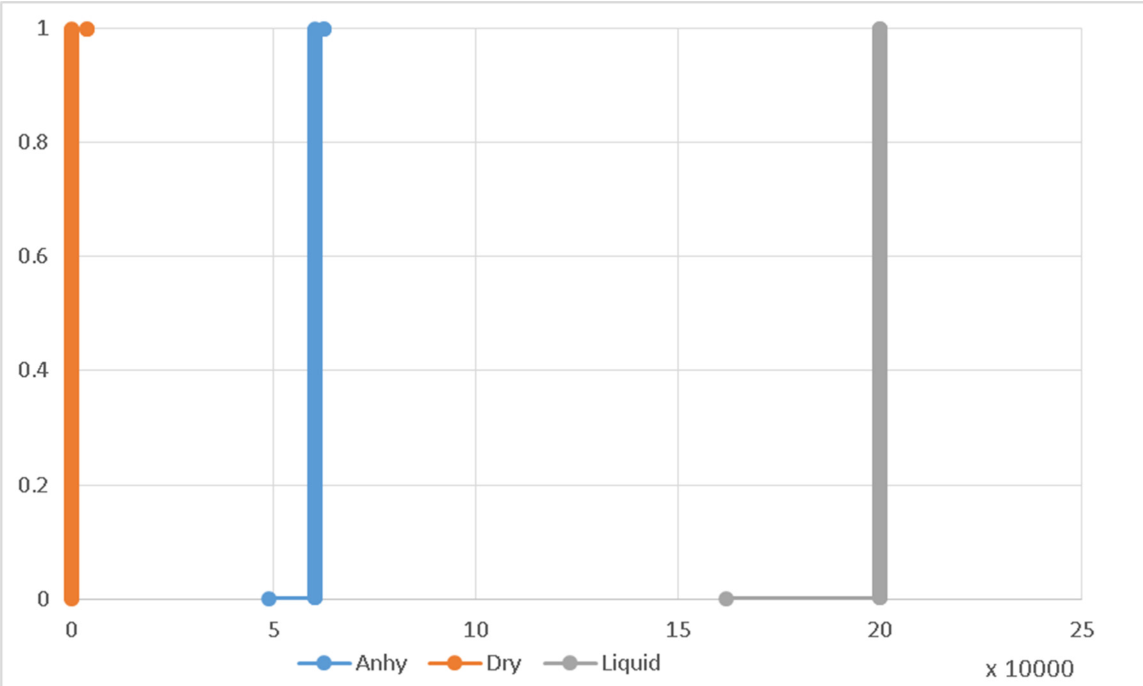

Figure C.47. Cumulative probability for 68310 (Beatrice, NE) in stochastic linear future case.

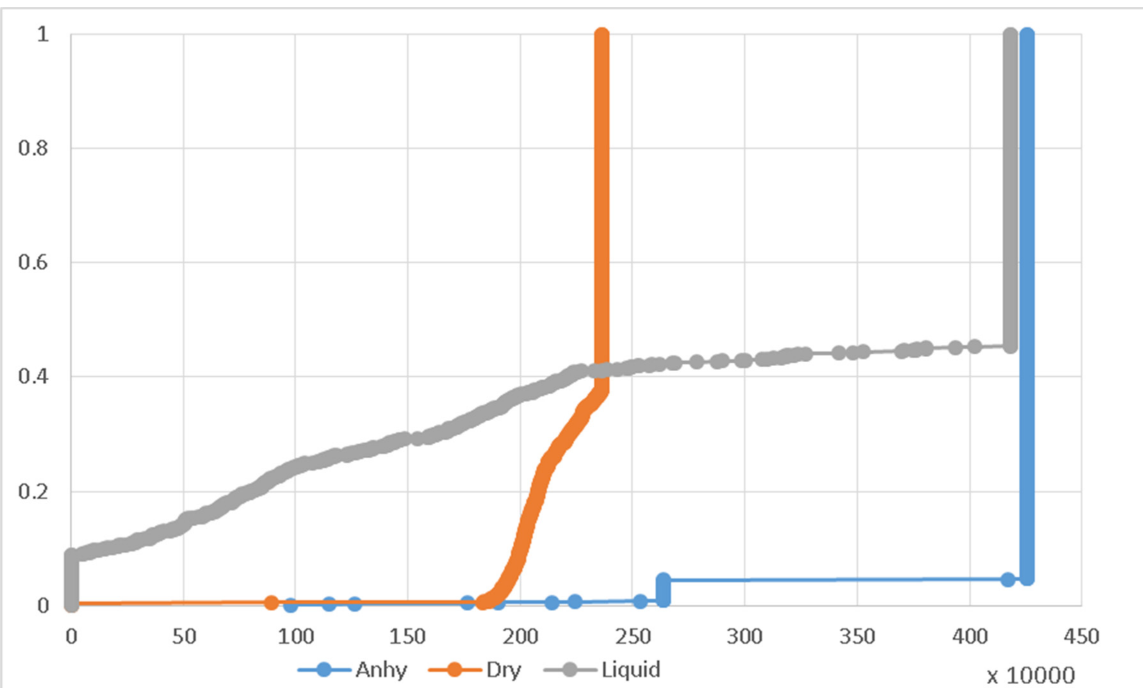

Figure C.48. Cumulative probability for 70346 (Donaldsonville, LA) in stochastic linear future case.

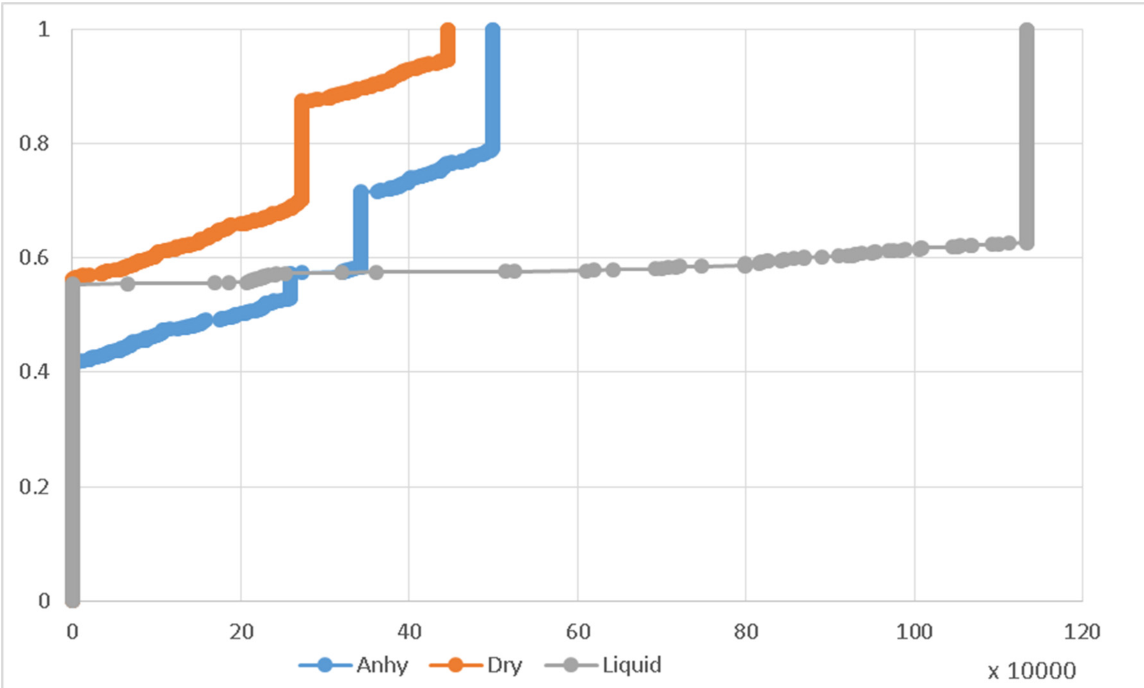

Figure C.49. Cumulative probability for 70734 (Geismar, LA) in stochastic linear future case.

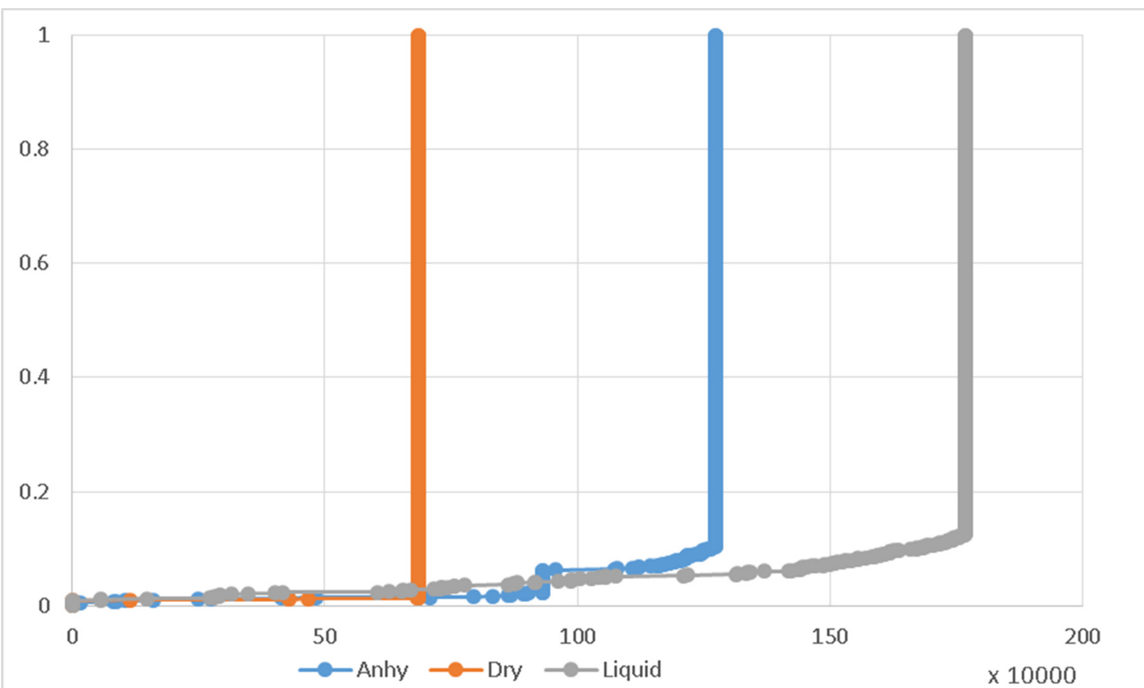

Figure C.50. Cumulative probability for 70765 (Iberville, LA) in stochastic linear future case.

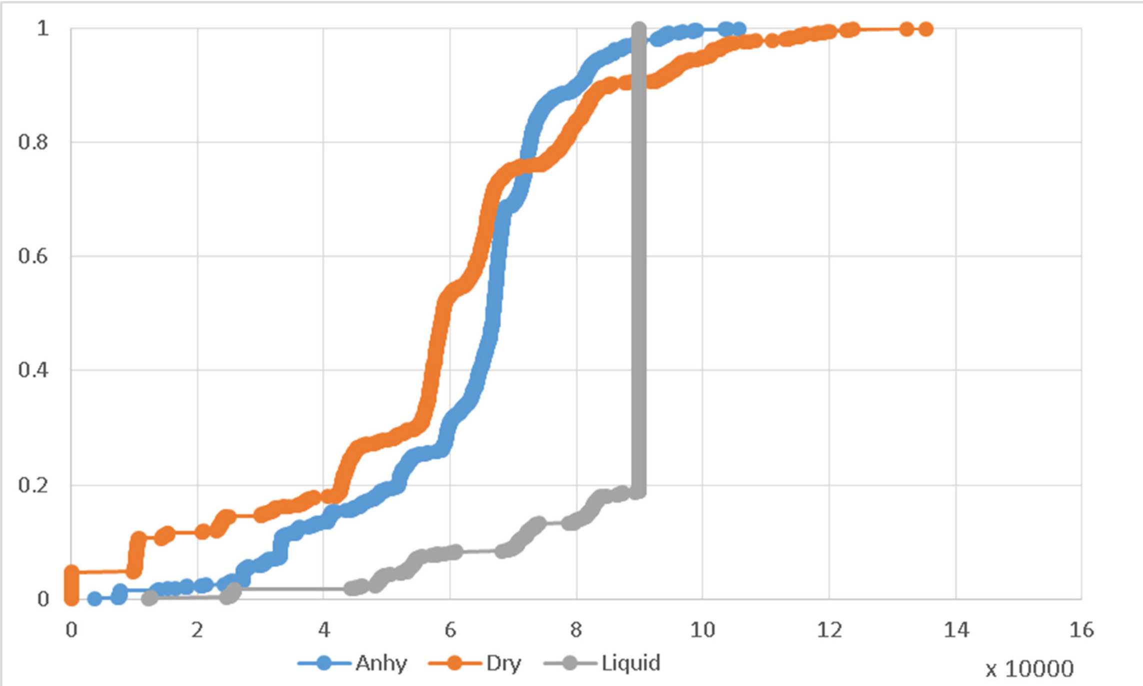

Figure C.51. Cumulative probability for 73701 (Enid, OK) in stochastic linear future case.

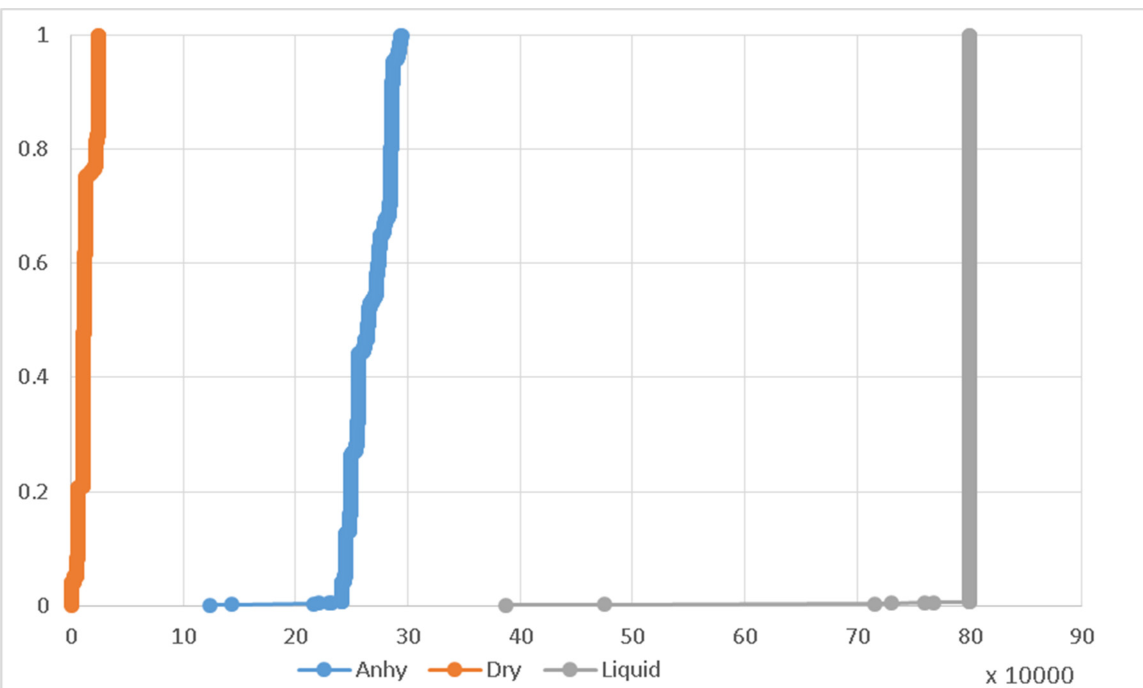

Figure C.52. Cumulative probability for 73801 (Woodward, OK) in stochastic linear future case.

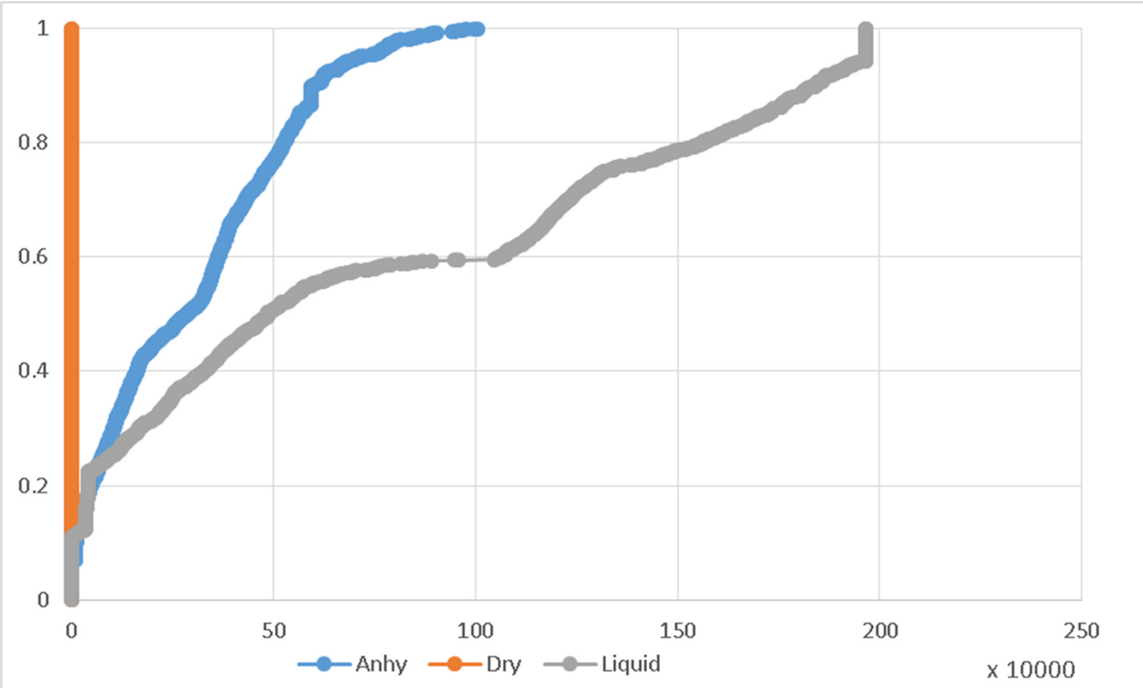

Figure C.53. Cumulative probability for 74019 (Verdigris, OK) in stochastic linear future case.

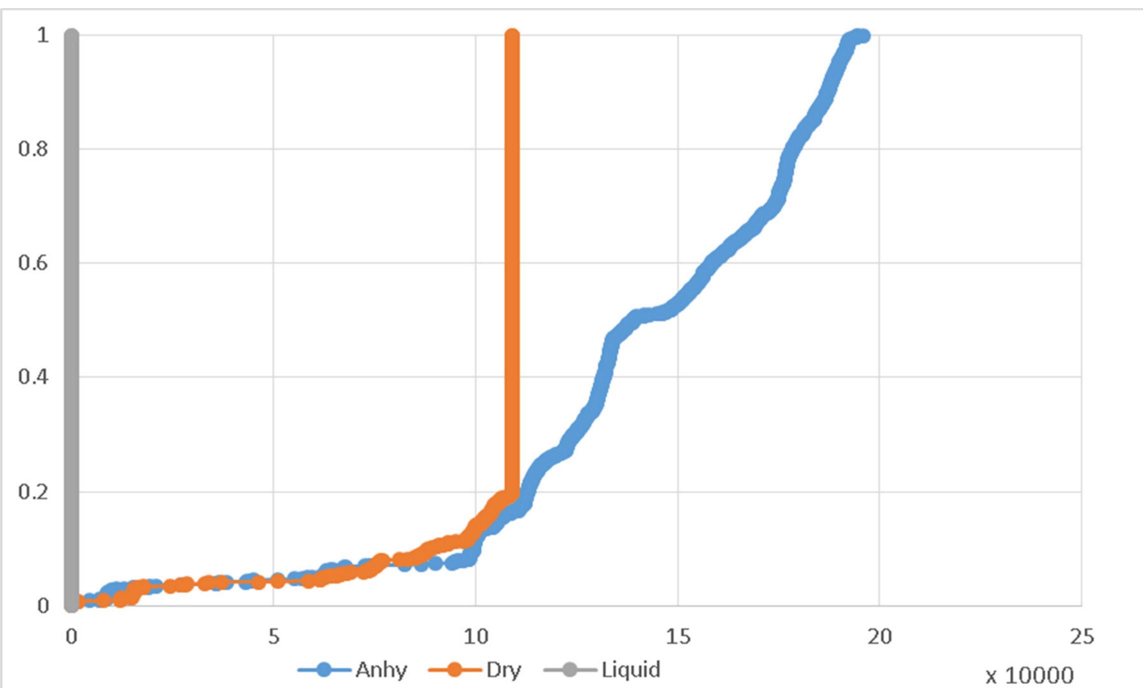

Figure C.54. Cumulative probability for 79007 (Borger, TX) in stochastic linear future case.

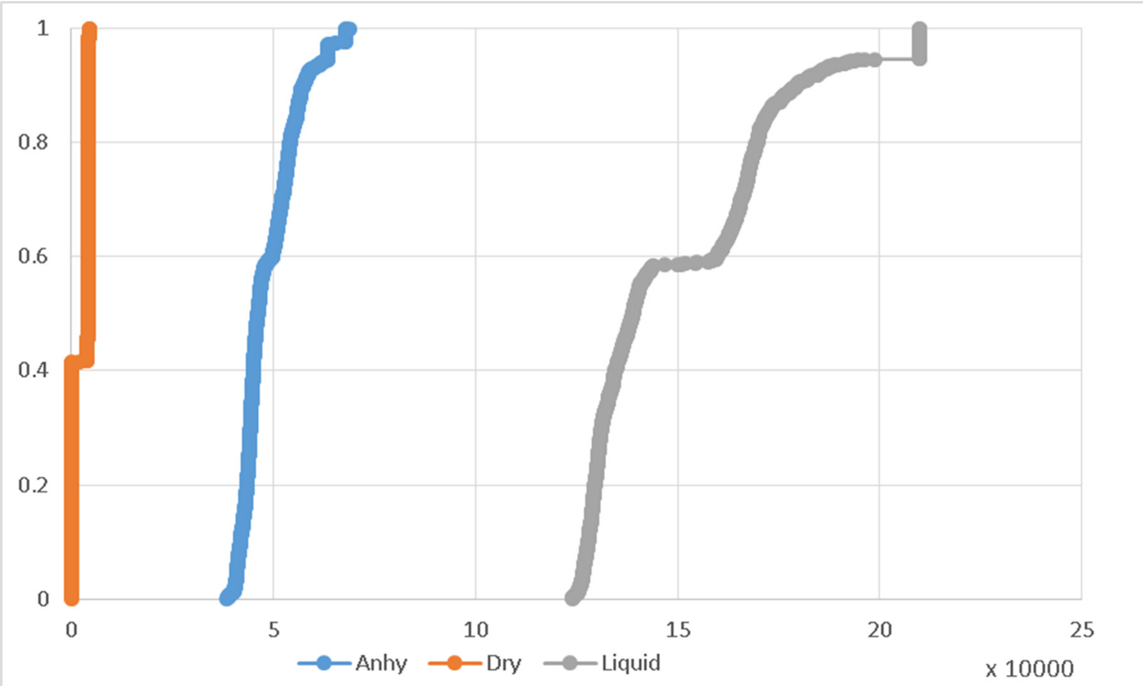

Figure C.55. Cumulative probability for 82001 (Cheyenne, WY) in stochastic linear future case.

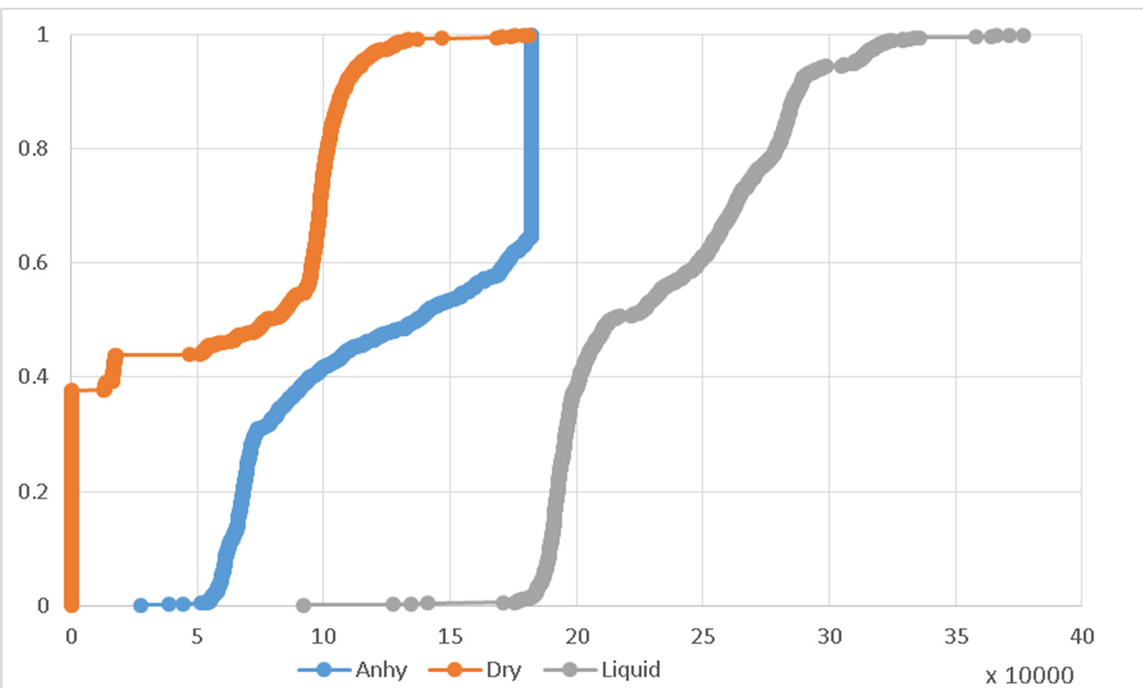

Figure C.56. Cumulative probability for 83211 (American Falls, ID) in stochastic linear future case.

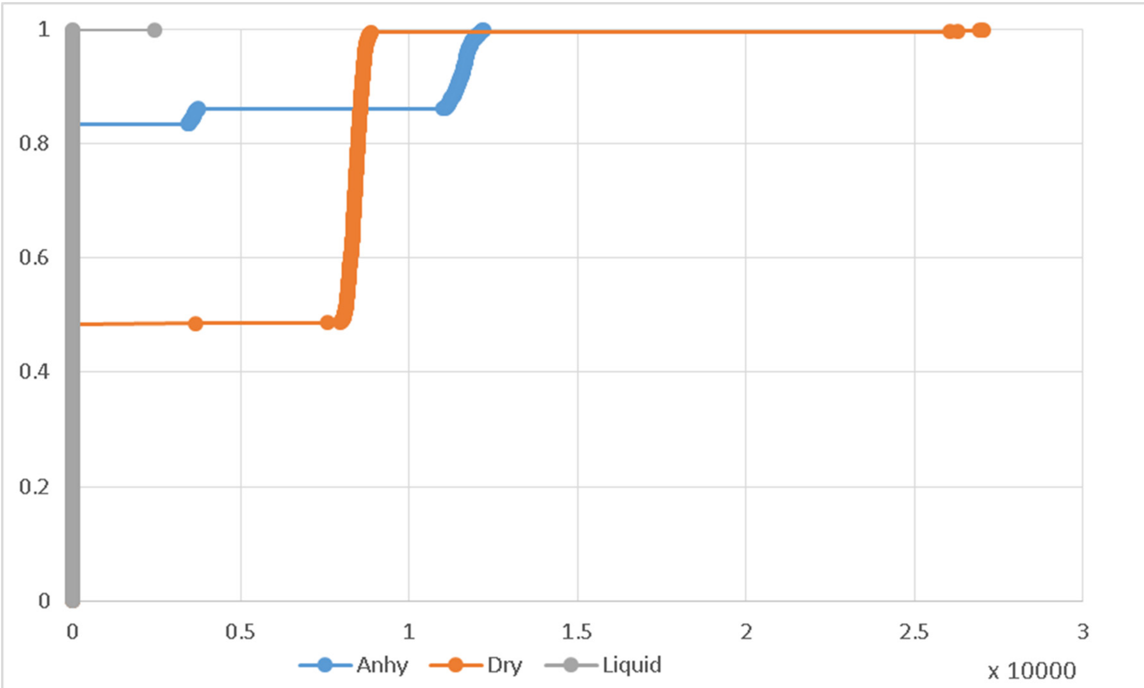

Figure C.57. Cumulative probability for 8800451 (Port of Entry (POE): Emerson, ND) in stochastic linear future case.

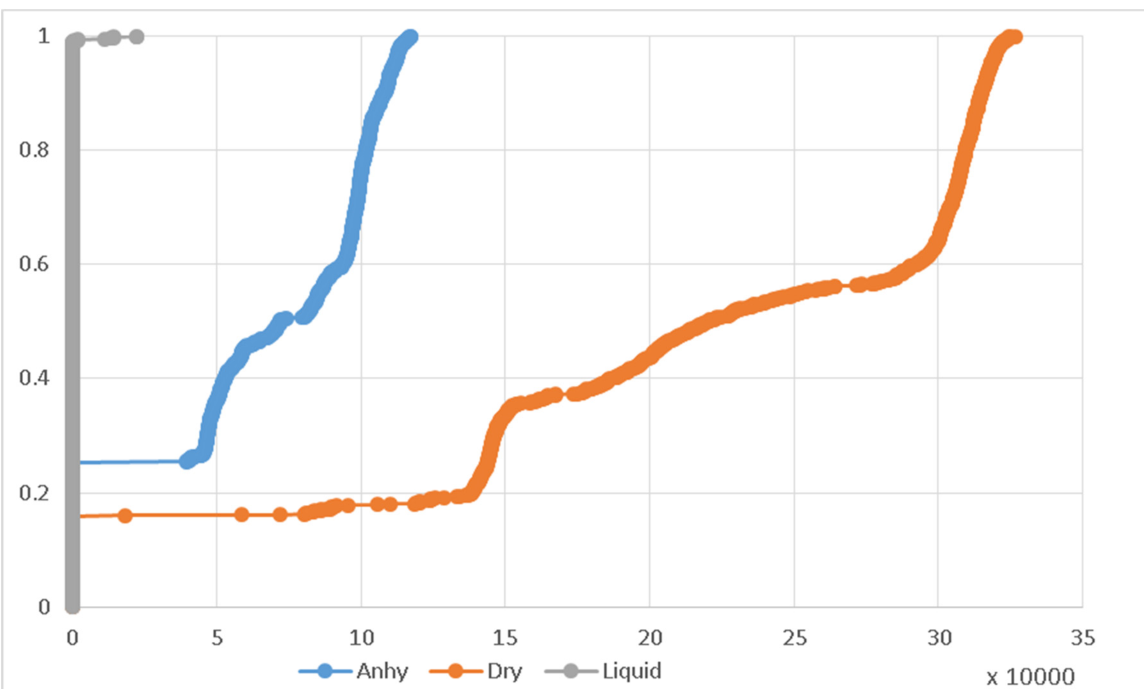

Figure C.58. Cumulative probability for 9163 (POE: Kingsgate, ID) in stochastic linear future case.

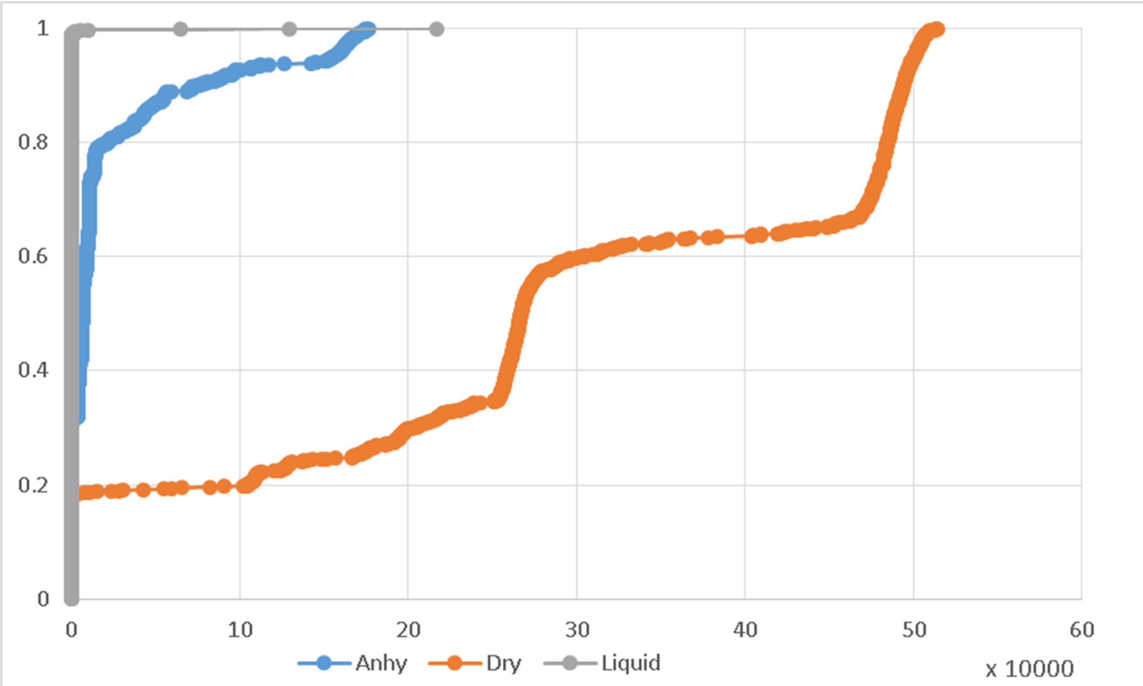

Figure C.59. Cumulative probability for 9303 (POE: Coutts, MT) in stochastic linear future case.

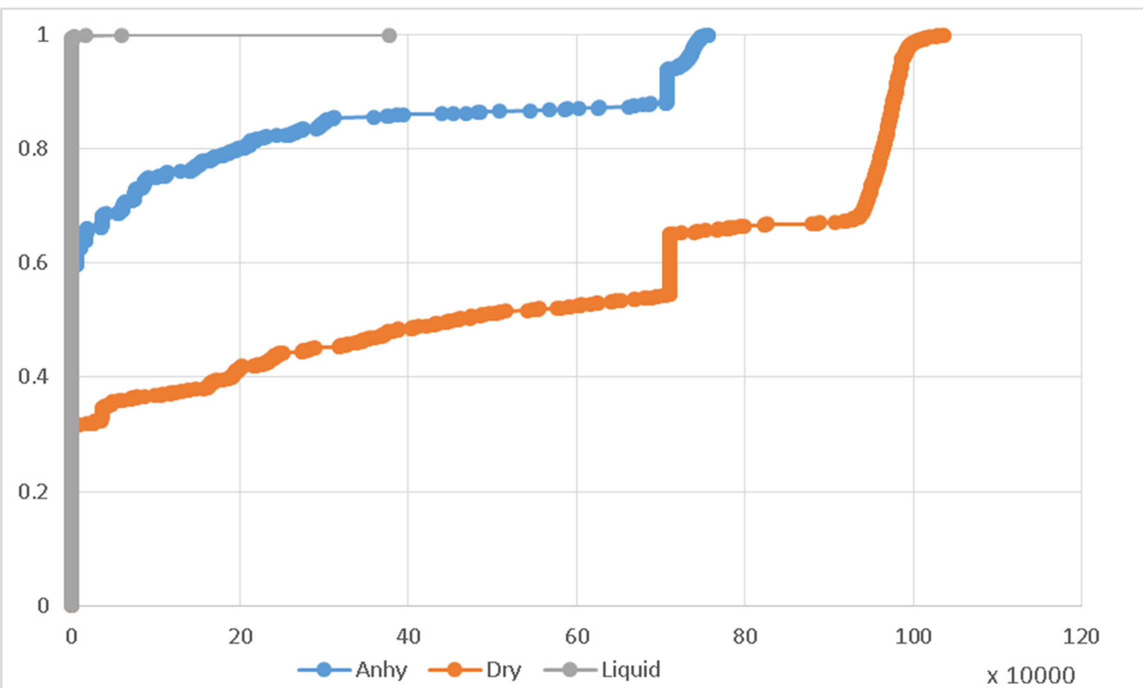

Figure C.60. Cumulative probability for 9384 (POE: Portal, ND) in stochastic linear future case.

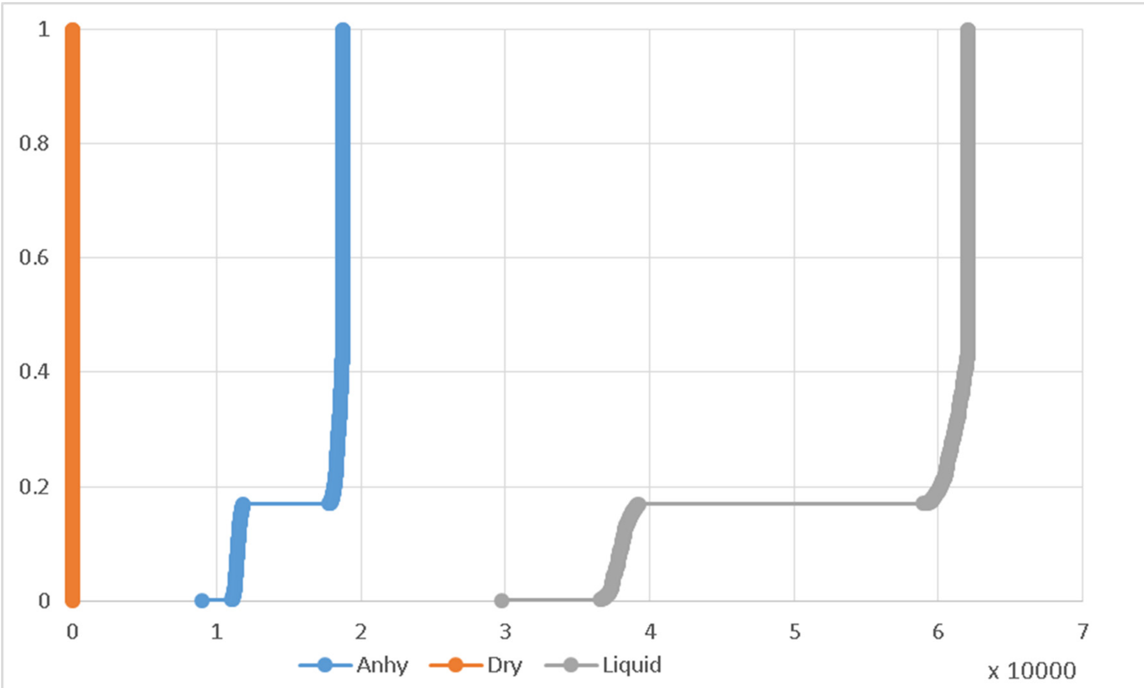

Figure C.61. Cumulative probability for 97051 (St. Helens, OR) in stochastic linear future case.

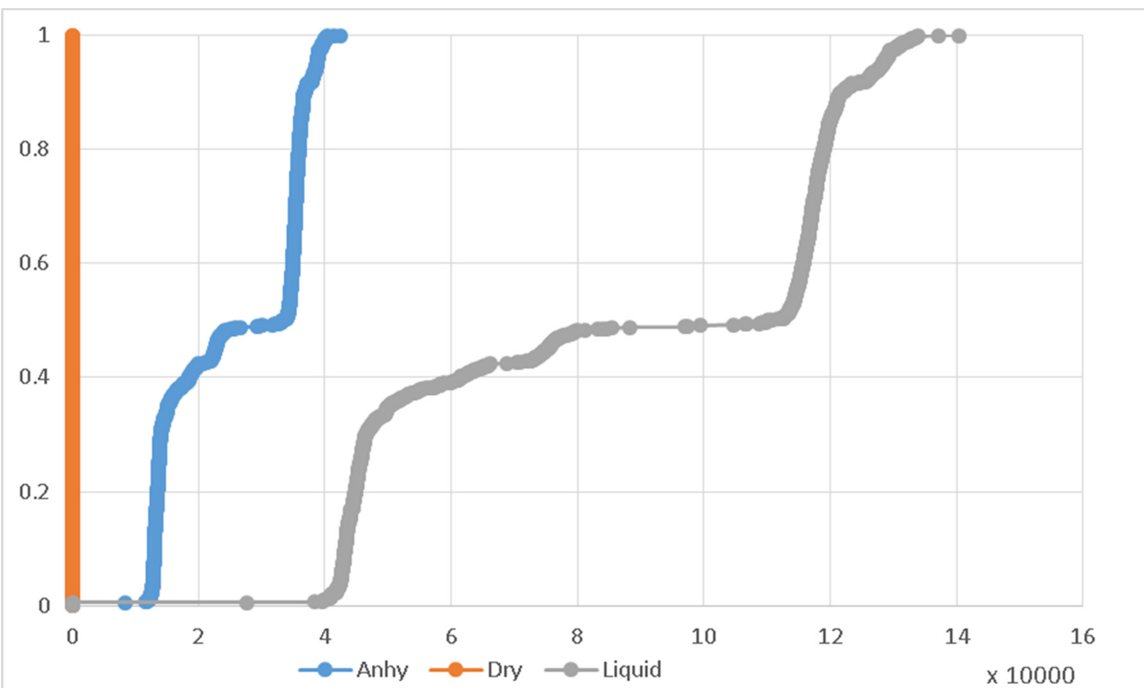

Figure C.62. Cumulative probability for 99337 (Kennewick, WA) in stochastic linear future case.

APPENDIX D. STOCHASTIC MIXED-INTEGER FUTURE CASE 2018

D.1. Distribution of Origination Destination Matrix for Stochastic Mixed-Integer Future Case 2018

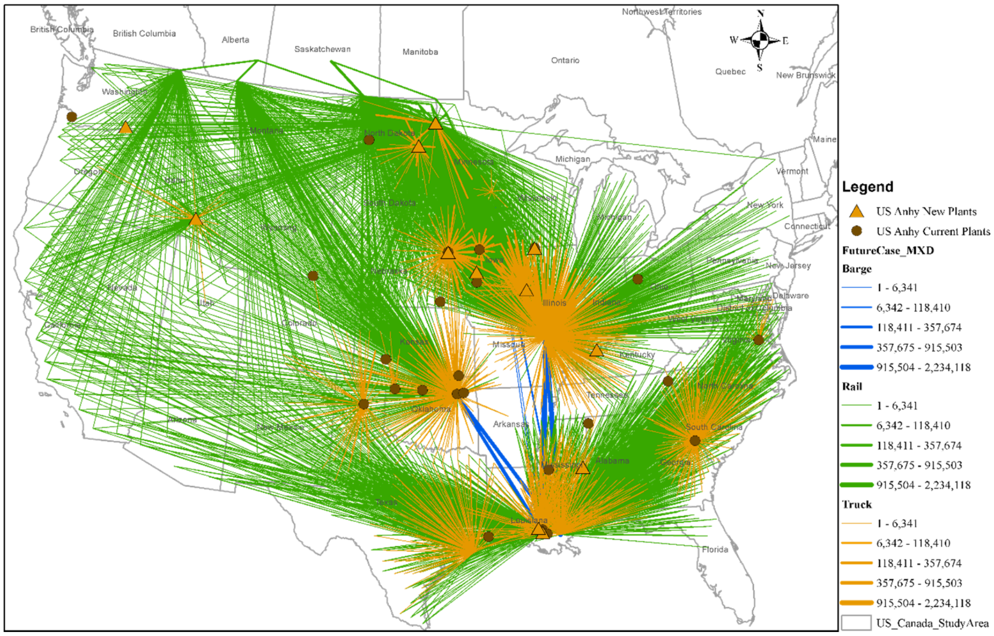

Figure D.1. Structure of supply chain for anhydrous ammonia for stochastic mixed-integer future case by mode (Rail=Green, Truck=Orange, Barge=Blue).

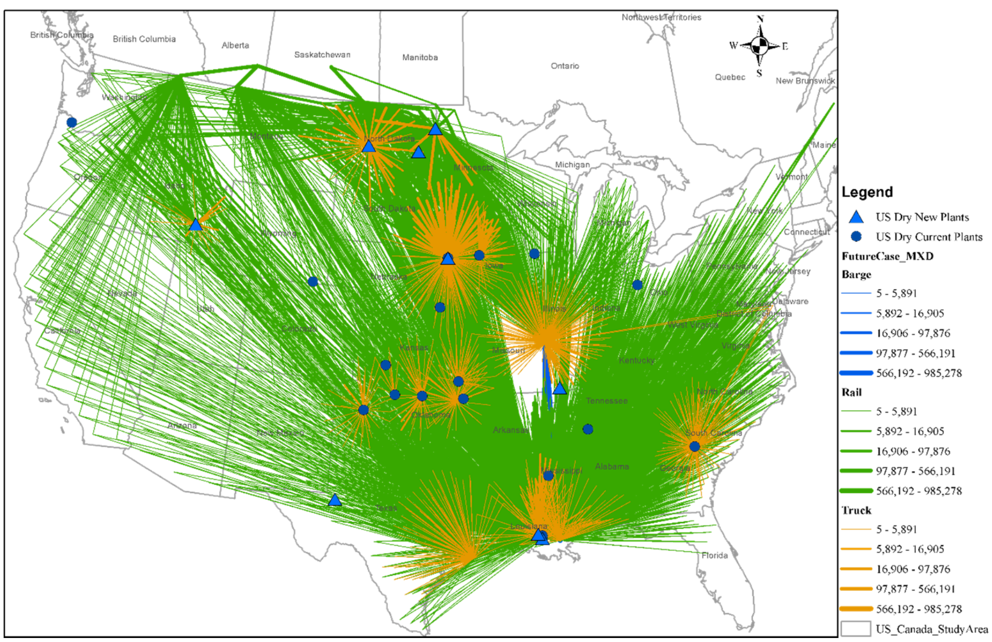

Figure D.2. Structure of supply chain for urea for stochastic mixed-integer future case by mode (Rail=Green, Truck=Orange, Barge=Blue).

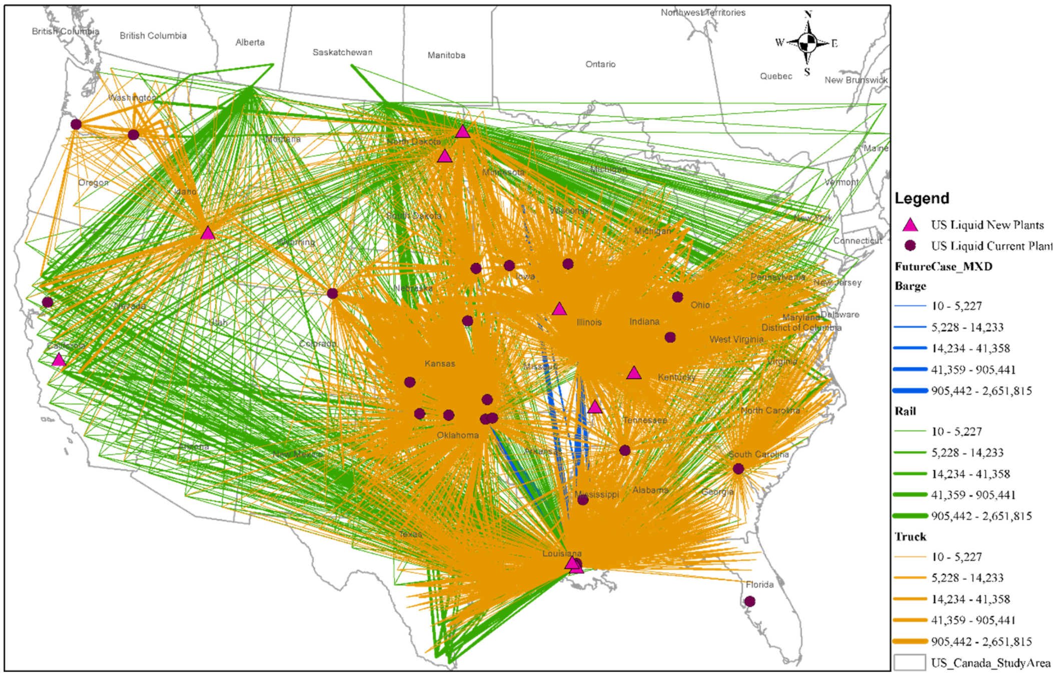

Figure D.3. Structure of supply chain for UAN for stochastic mixed-integer future case by mode (Rail=Green, Truck=Orange, Barge=Blue).

D.2. Market Boundaries for Selective Plants by Probability of Shipping for 1000 Iterations in Stochastic Mixed-Integer Future Case 2018

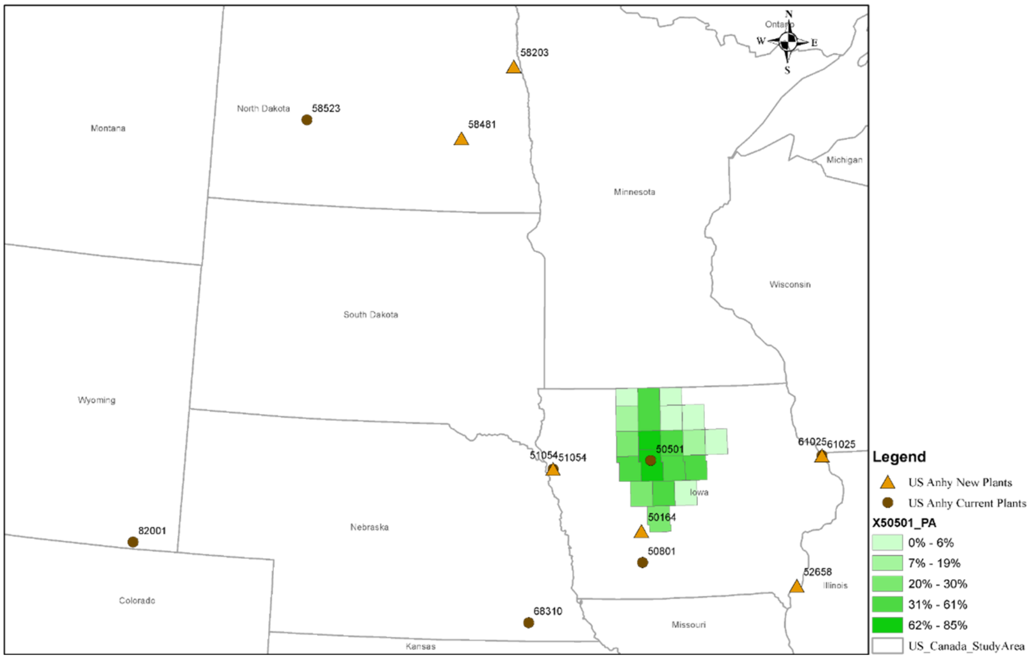

Figure D.4. Market boundaries for plant j=50501 for anhydrous ammonia (probability of shipping for 1000 iterations) in stochastic mixed-integer future case.

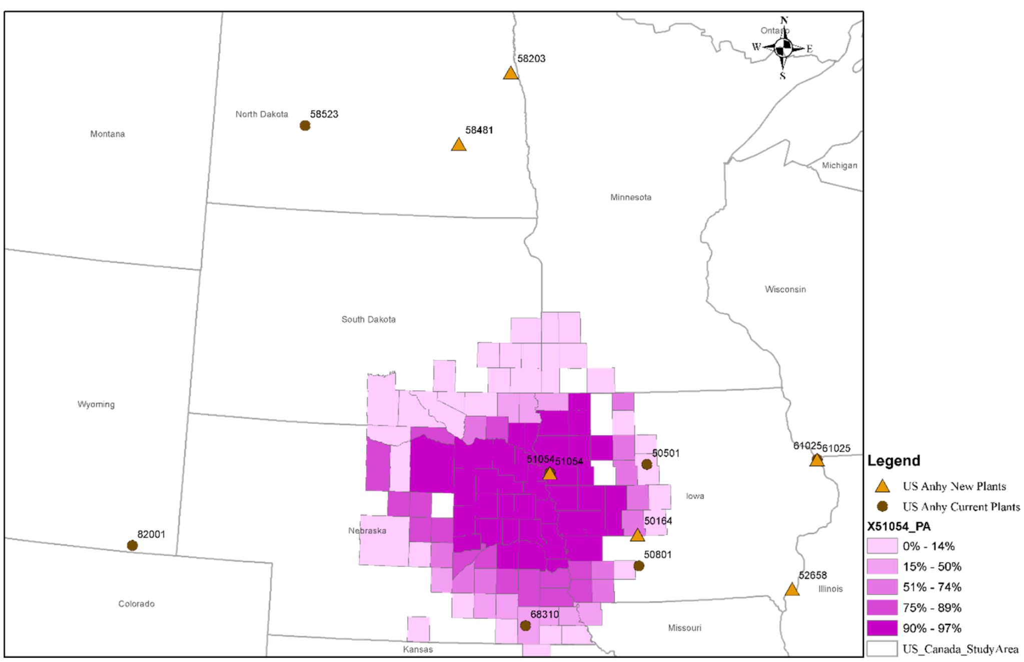

Figure D.5. Market boundaries for plant j=51054 for anhydrous ammonia (probability of shipping for 1000 iterations) in stochastic mixed-integer future case.

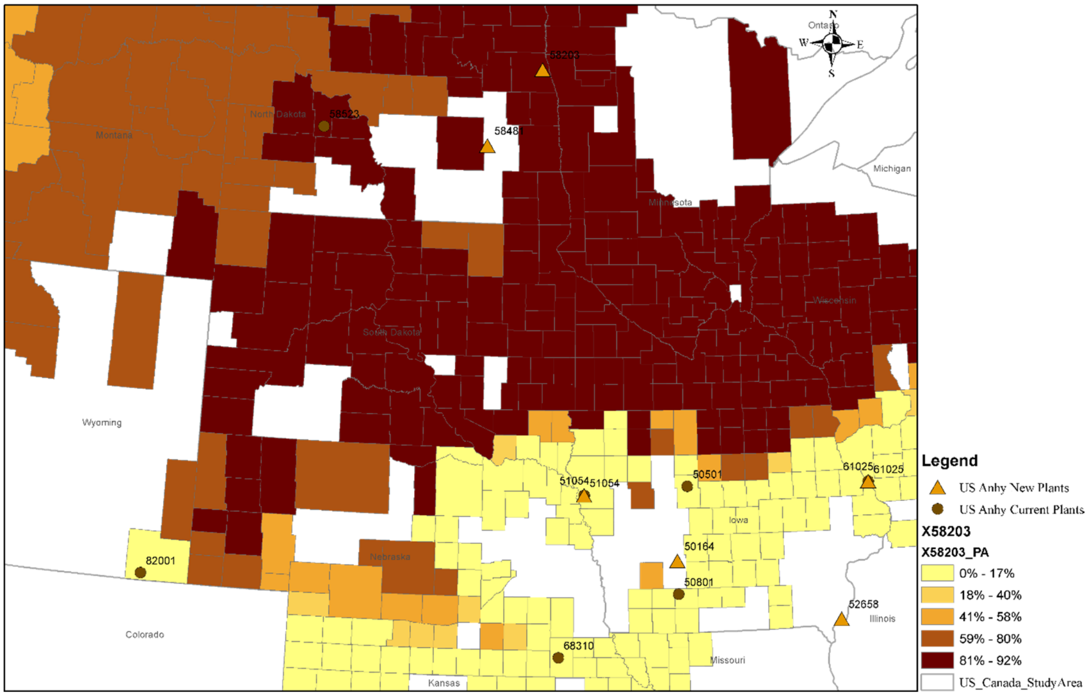

Figure D.6. Market boundaries for plant j=58203 for anhydrous ammonia (probability of shipping for 1000 iterations) in stochastic mixed-integer future case.

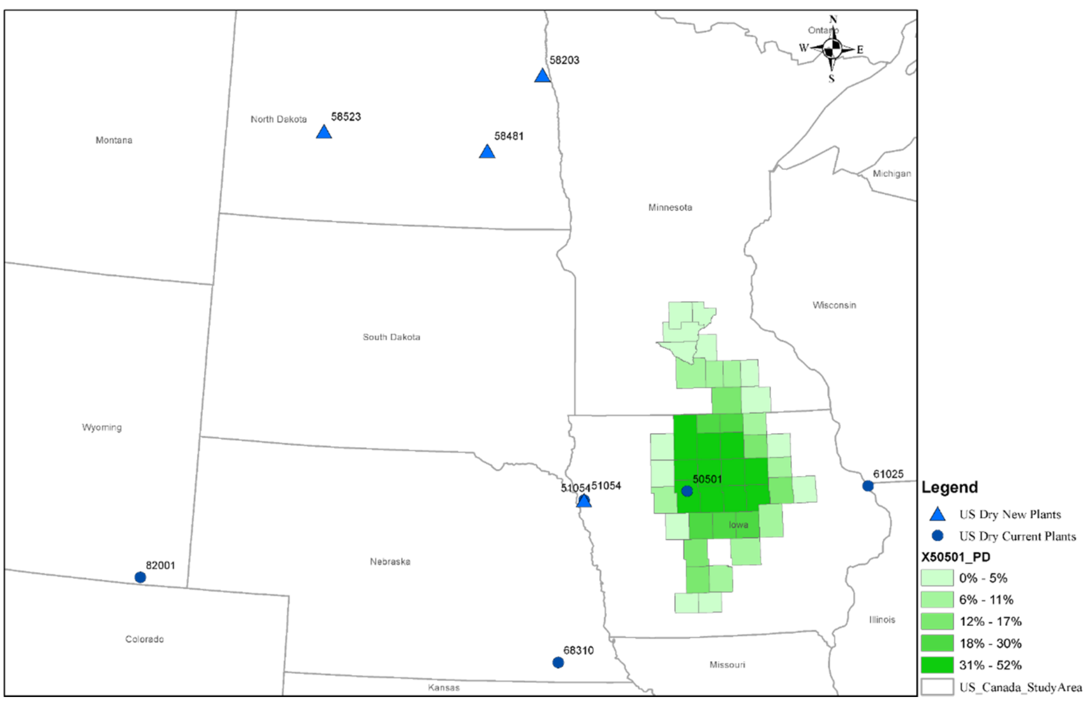

Figure D.7. Market boundaries for plant j=50501 for urea (probability of shipping for 1000 iterations) in stochastic mixed-integer future case.

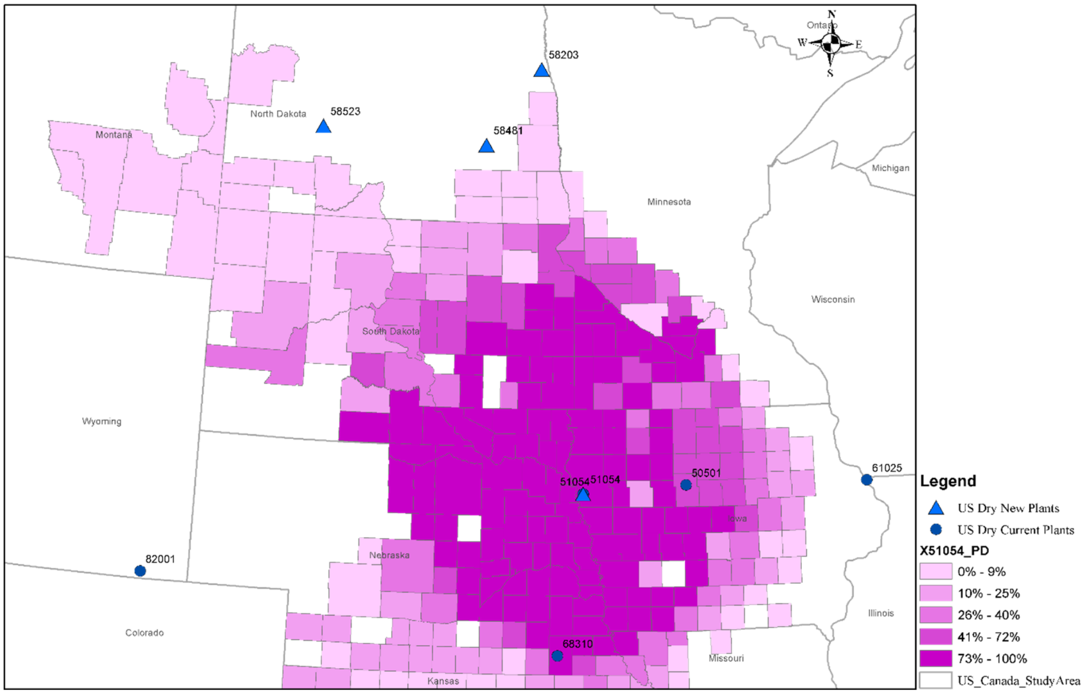

Figure D.8. Market boundaries for plant j=51054 for urea (probability of shipping for 1000 iterations) in stochastic mixed-integer future case.

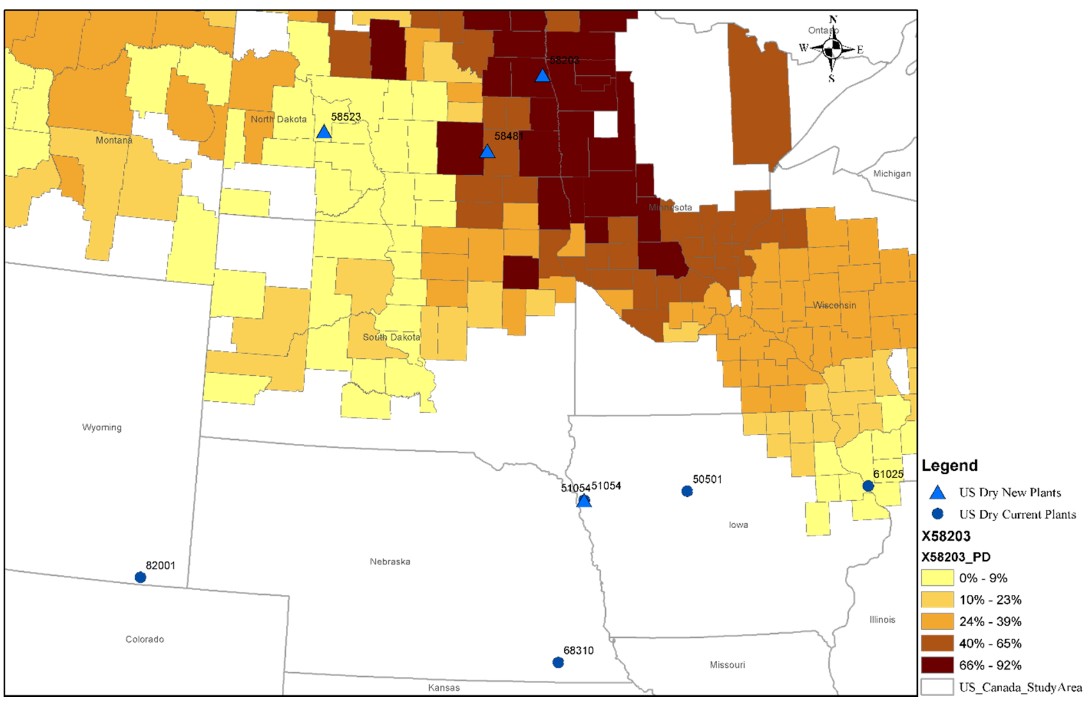

Figure D.9. Market boundaries for plant j=58203 for urea (probability of shipping for 1000 iterations) in stochastic mixed-integer future case.

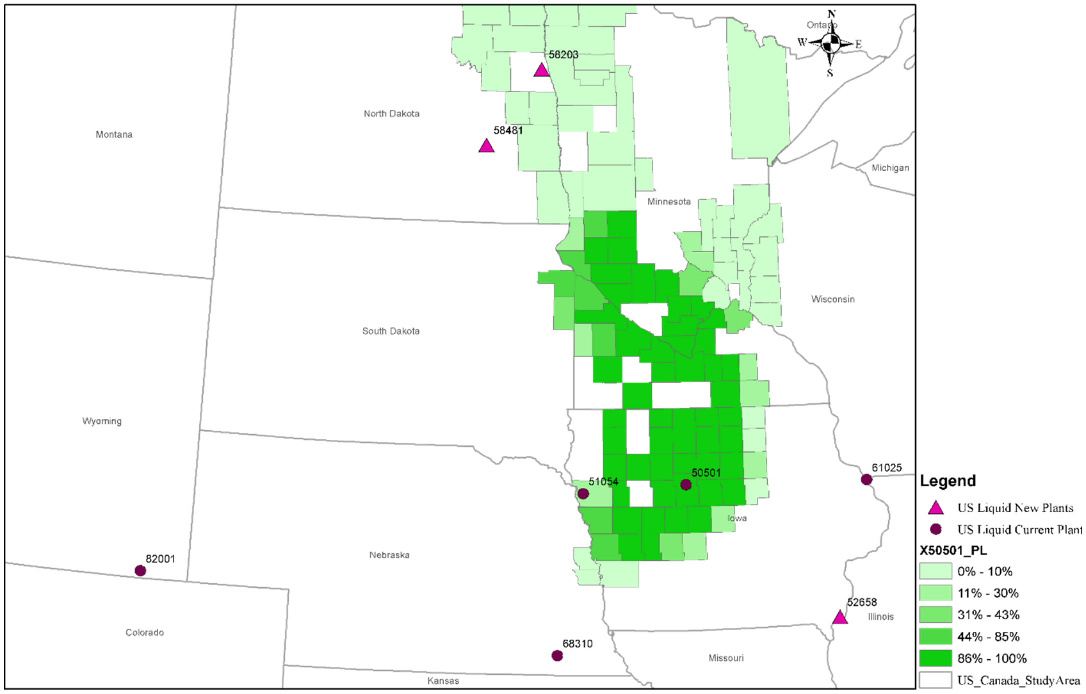

Figure D.10. Market boundaries for plant j=50501 for UAN (probability of shipping for 1000 iterations) in stochastic mixed-integer future case.

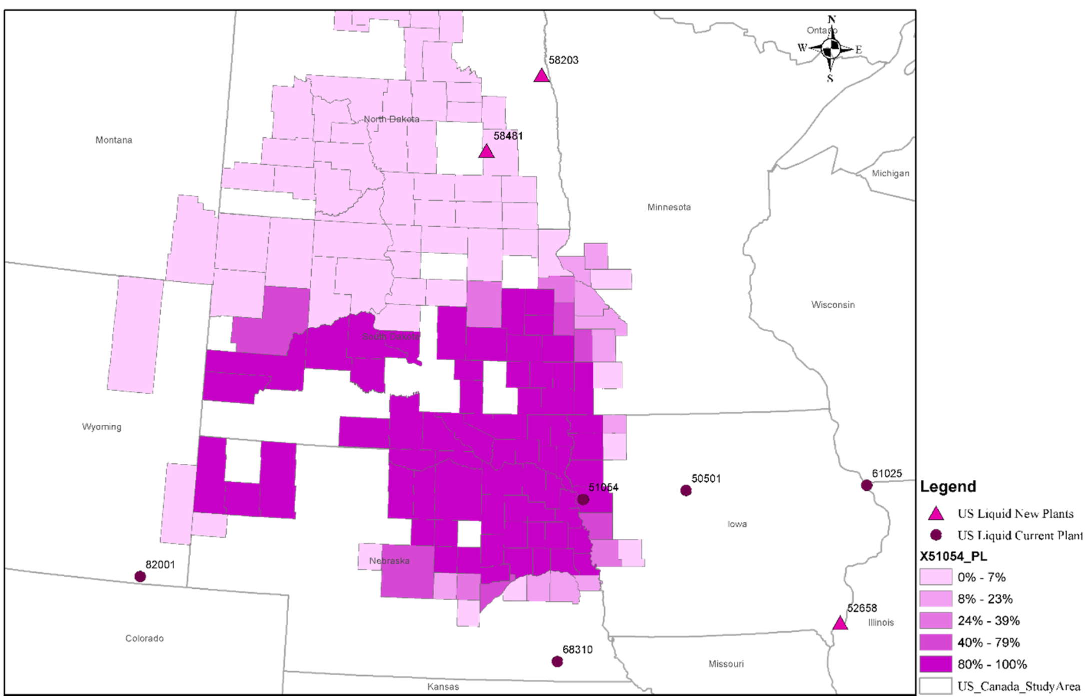

Figure D.11. Market boundaries for plant j=51054 for UAN (probability of shipping for 1000 iterations) in stochastic mixed-integer future case.

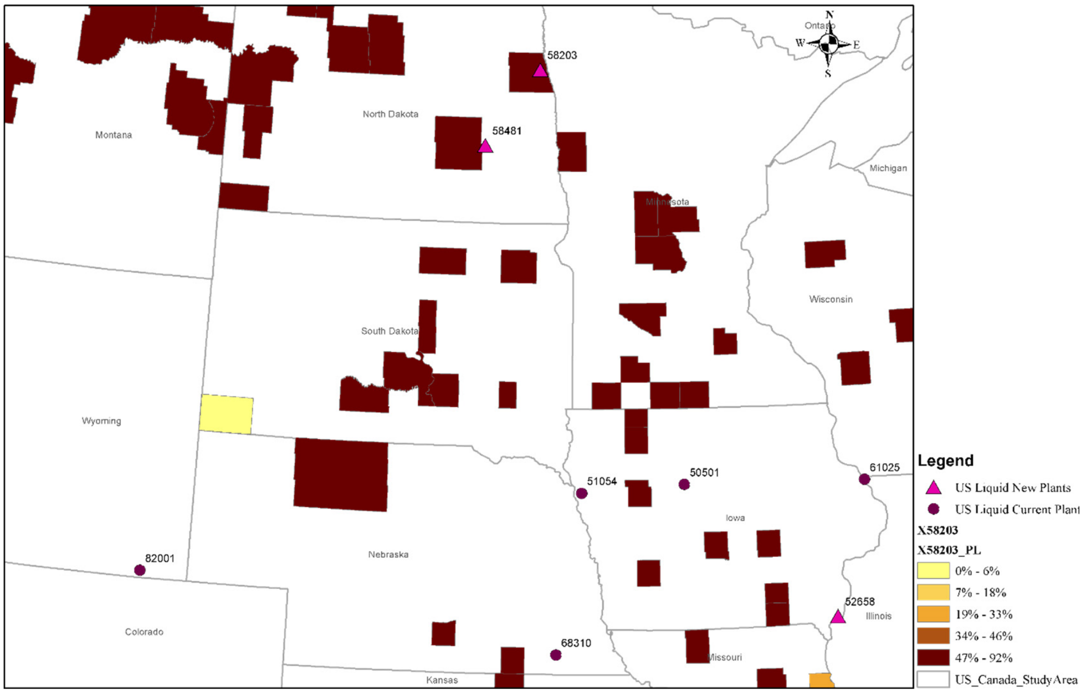

Figure D.12. Market boundaries for plant j=58203 for UAN (probability of shipping for 1000 iterations) in stochastic mixed-integer future case.

D.3. CDFs by Nodes in Stochastic Mixed-Integer Future Case 2018

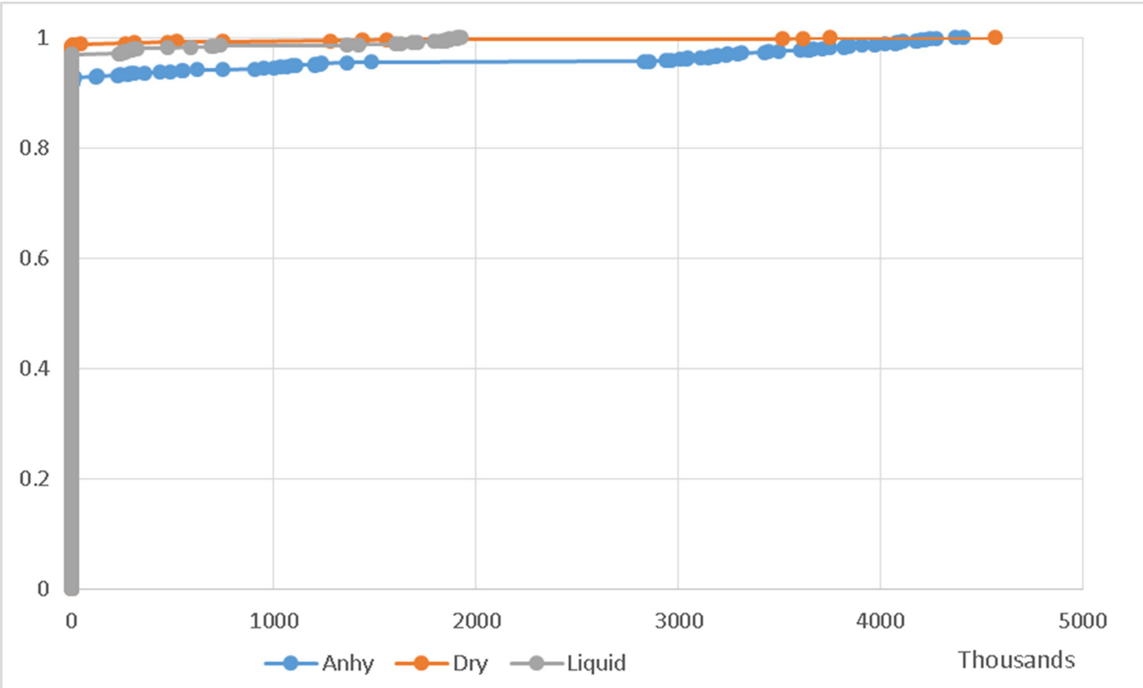

Figure D.13. Cumulative probability for 2200374 (New Orleans, LA) in stochastic mixed-integer case.

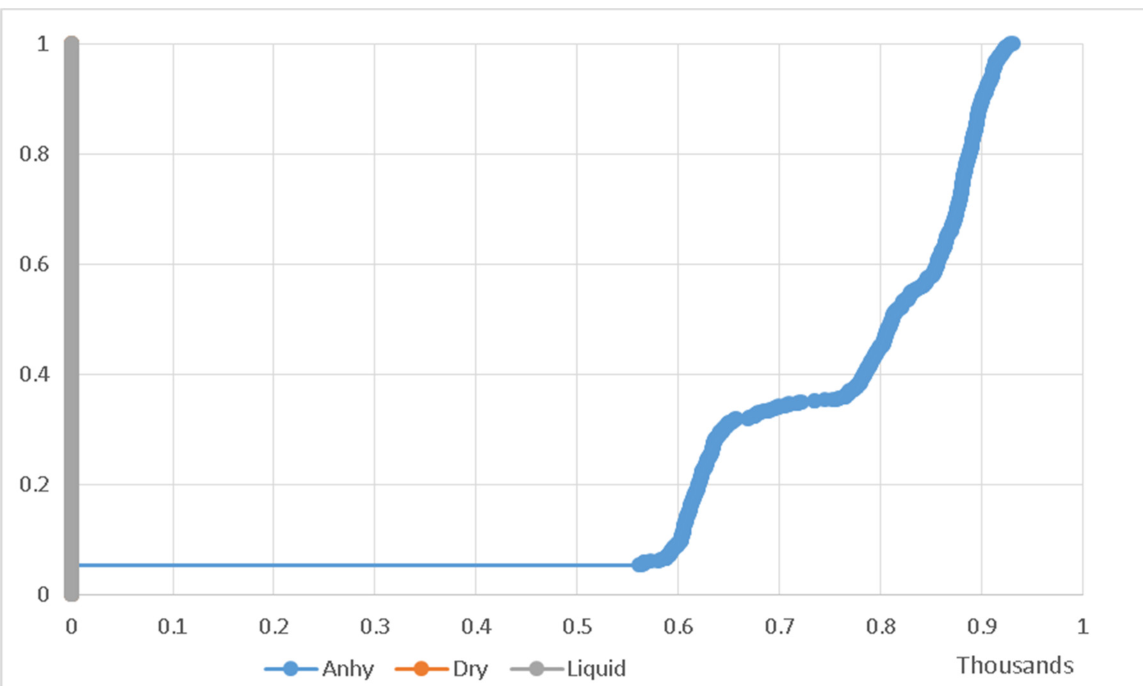

Figure D.14. Cumulative probability for 23860 (Hopewell, VA) in stochastic mixed-integer case.

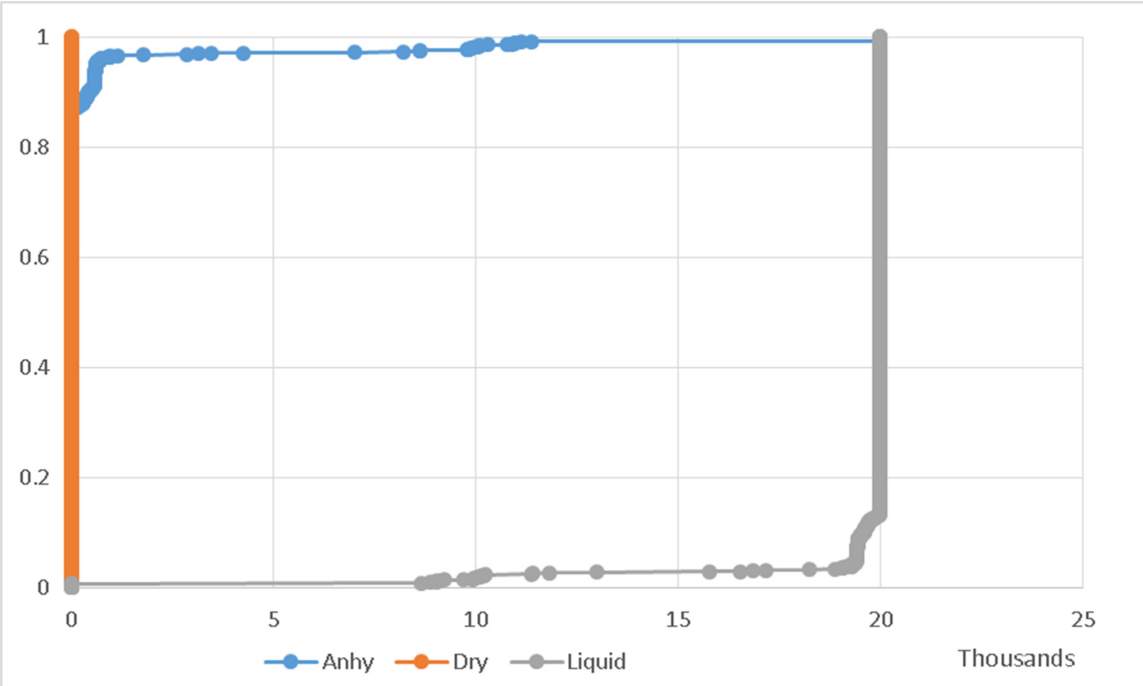

Figure D.15. Cumulative probability for 2700093 (Minneapolis, MN) in stochastic mixed-integer case.

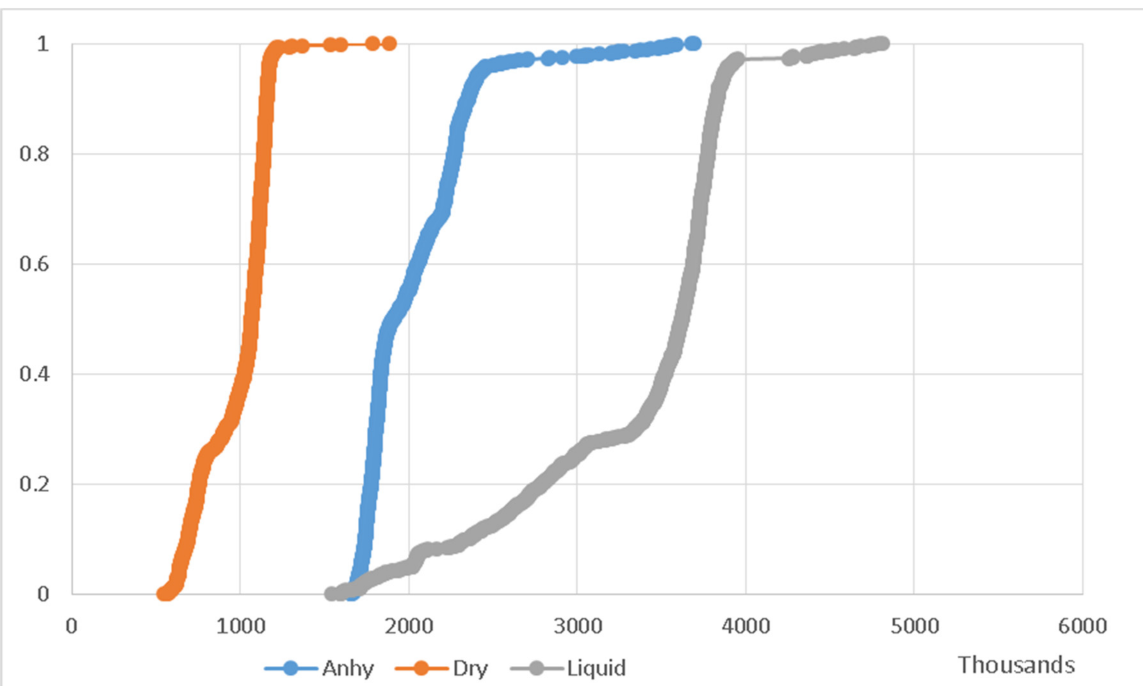

Figure D.16. Cumulative probability for 2900310 (St Louis, MO) in stochastic mixed-integer case.

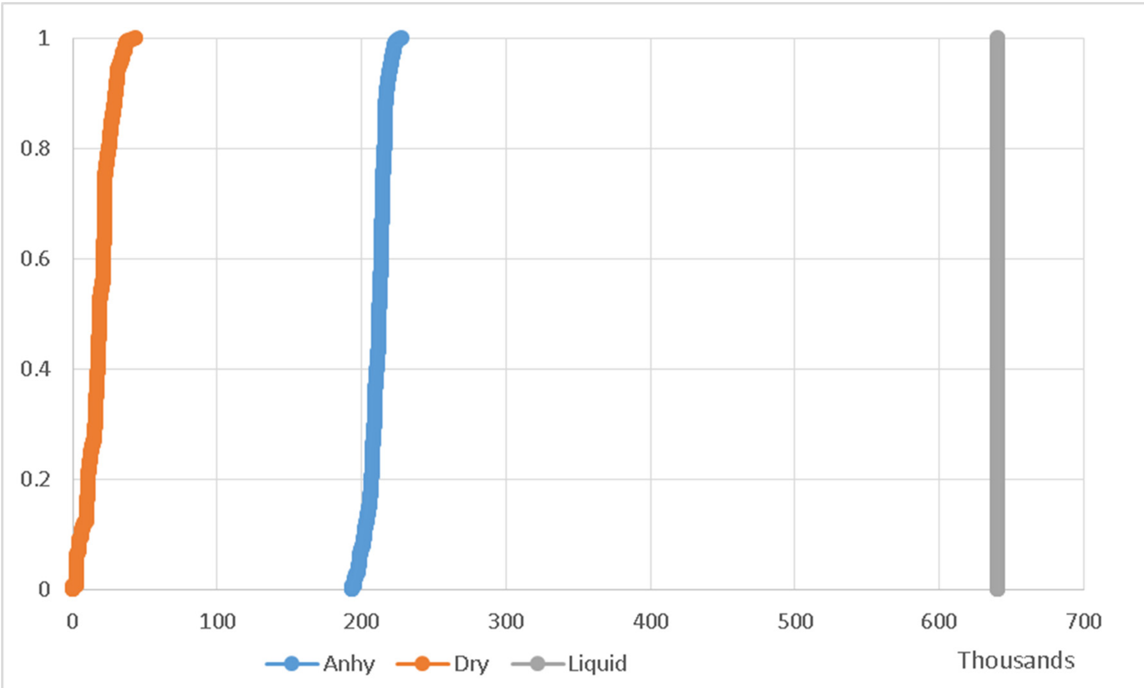

Figure D.17. Cumulative probability for 30901 (Augusta, GA) in stochastic mixed-integer case.

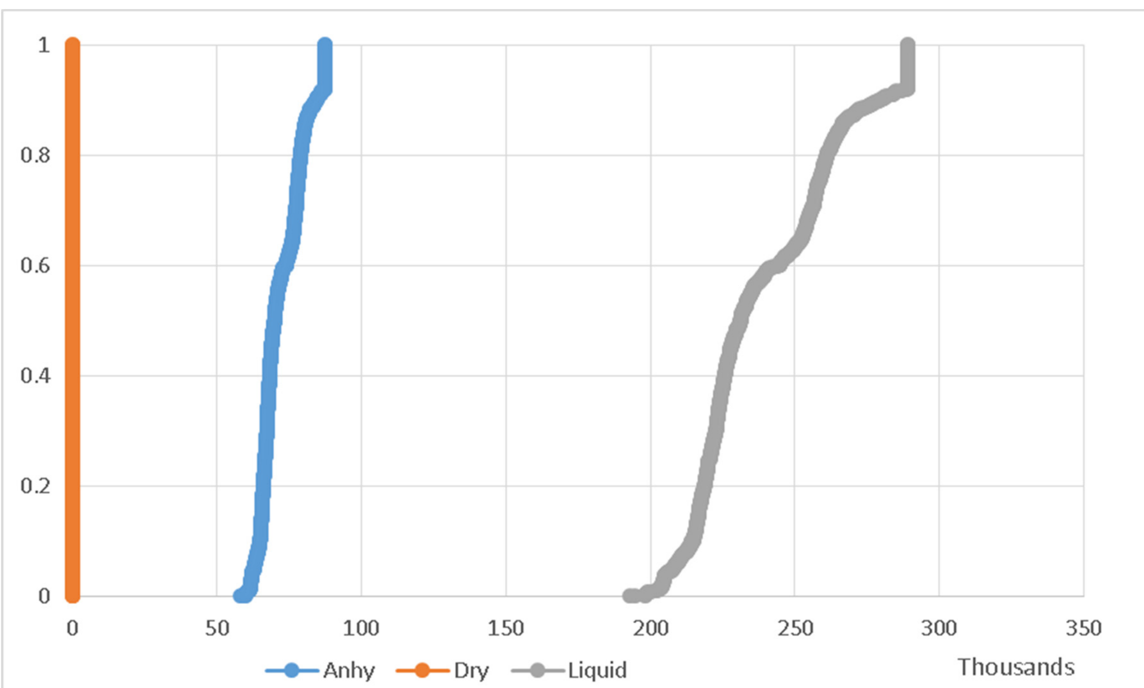

Figure D.18. Cumulative probability for 35616 (Cherokee, AL) in stochastic mixed-integer case.

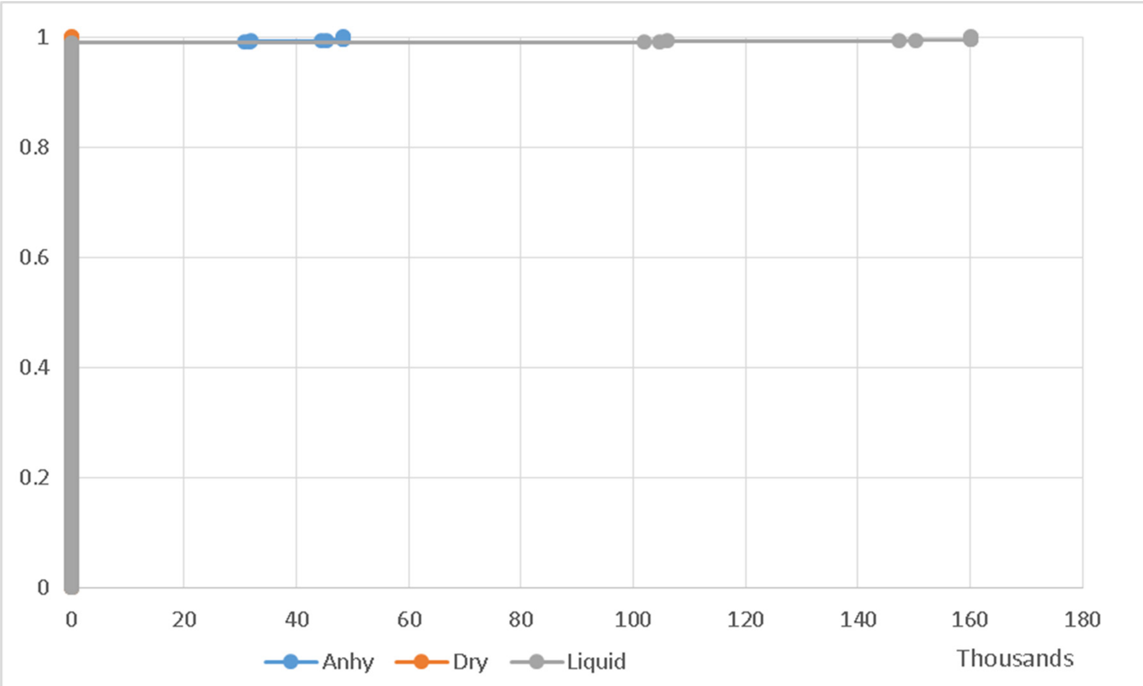

Figure D.19. Cumulative probability for 39194 (Yazoo City, MS) in stochastic mixed-integer case.

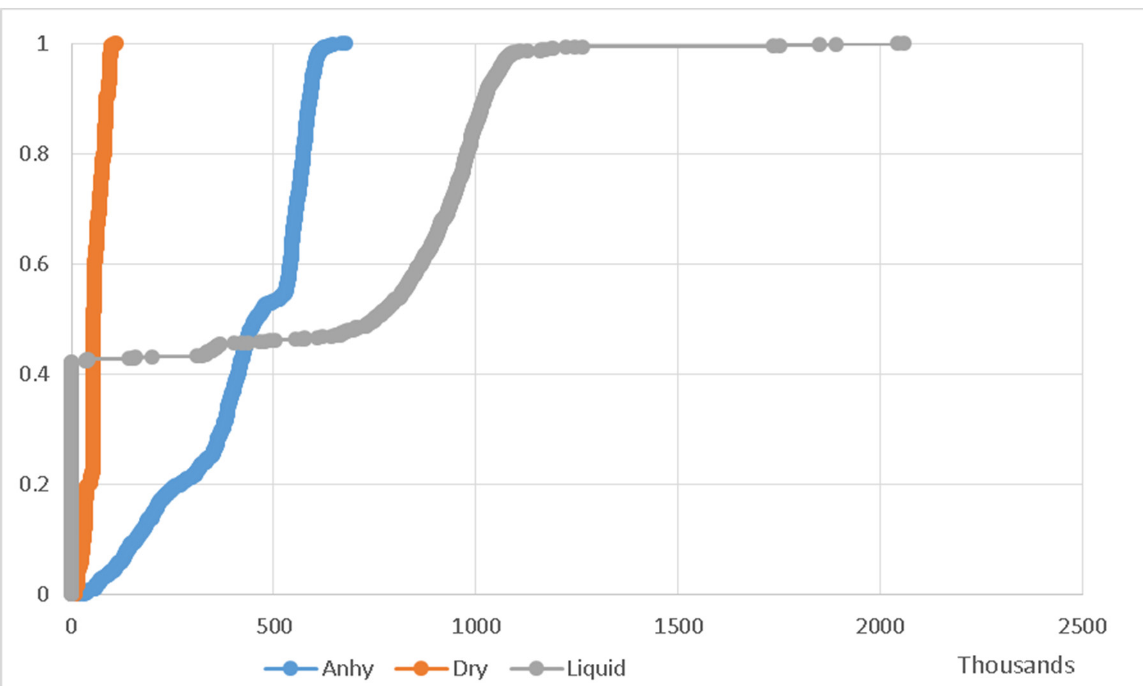

Figure D.20. Cumulative probability for 4000131 (Catoosa, OK) in stochastic mixed-integer case.

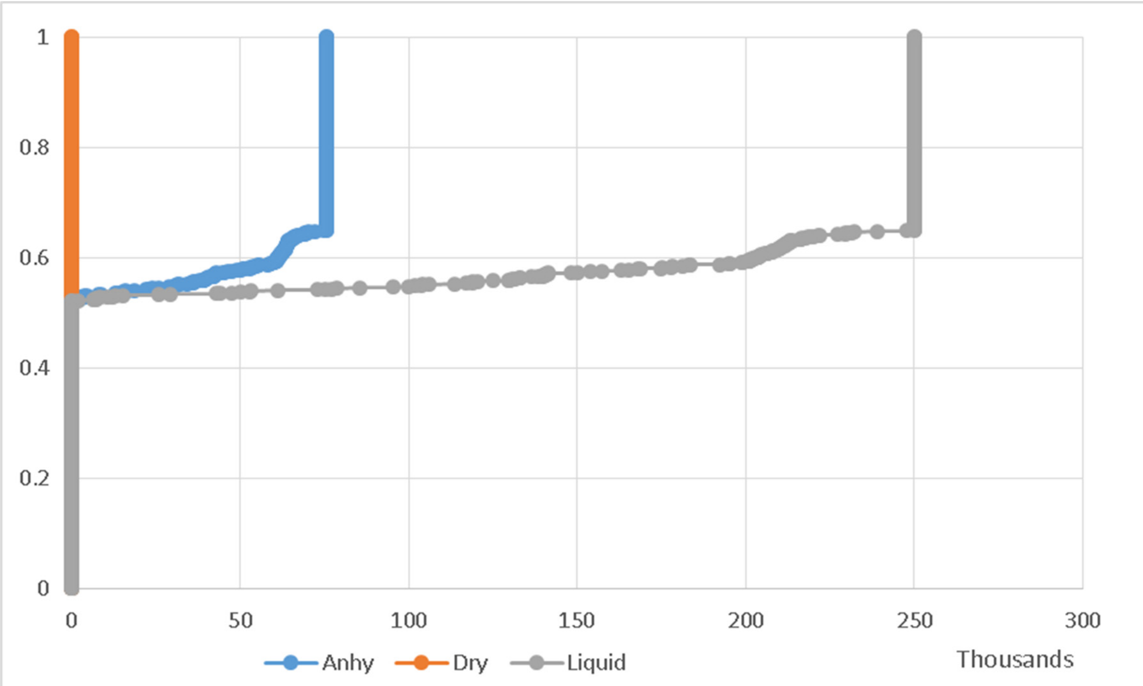

Figure D.21. Cumulative probability for 45804 (Lima, OH) in stochastic mixed-integer case.

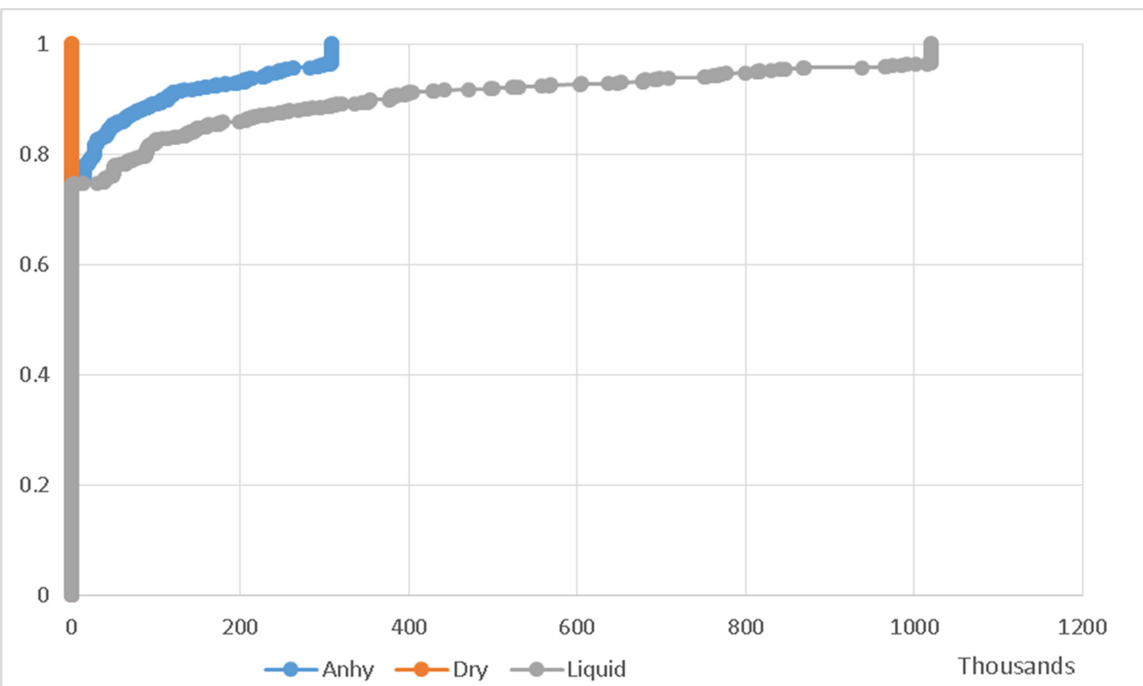

Figure D.22. Cumulative probability for 47635 (Rockport, IN) in stochastic mixed-integer case.

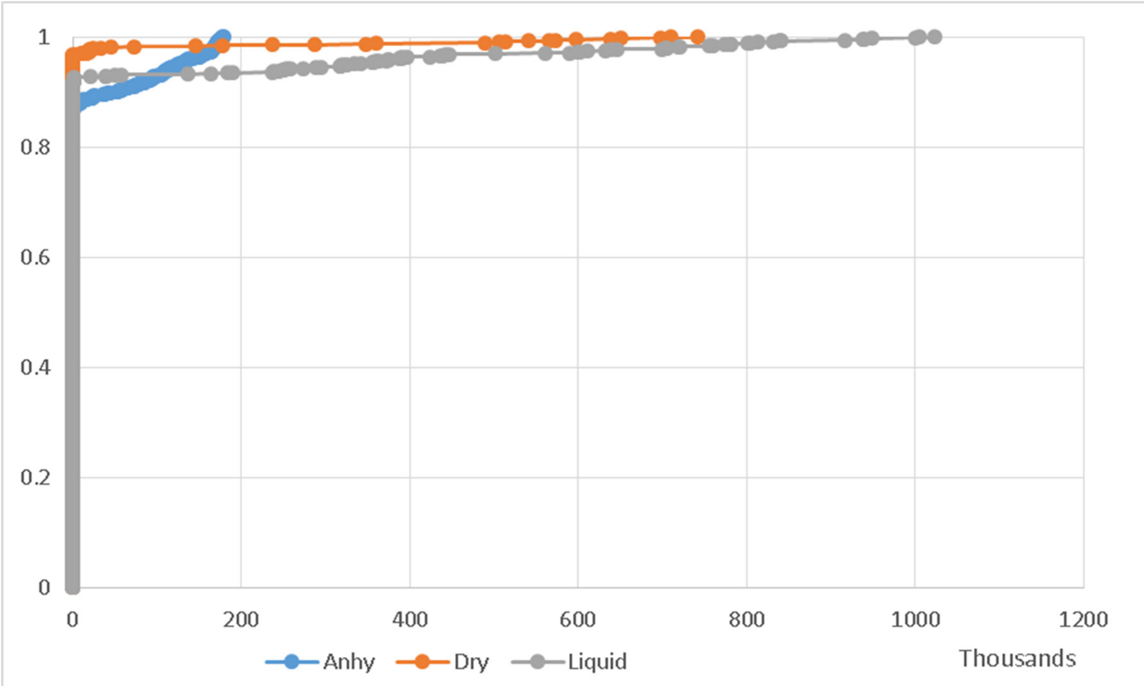

Figure D.23. Cumulative probability for 4800608 (Galveston, TX) in stochastic mixed-integer case.

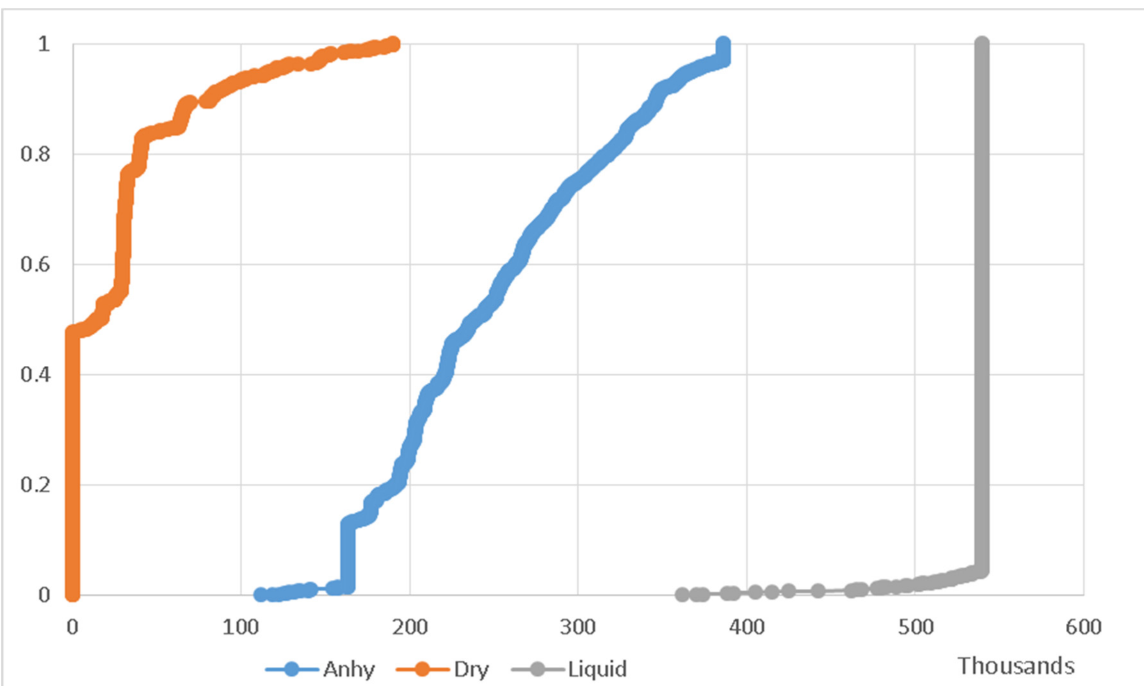

Figure D.24. Cumulative probability for 50501 (Fort Dodge, IA) in stochastic mixed-integer case.

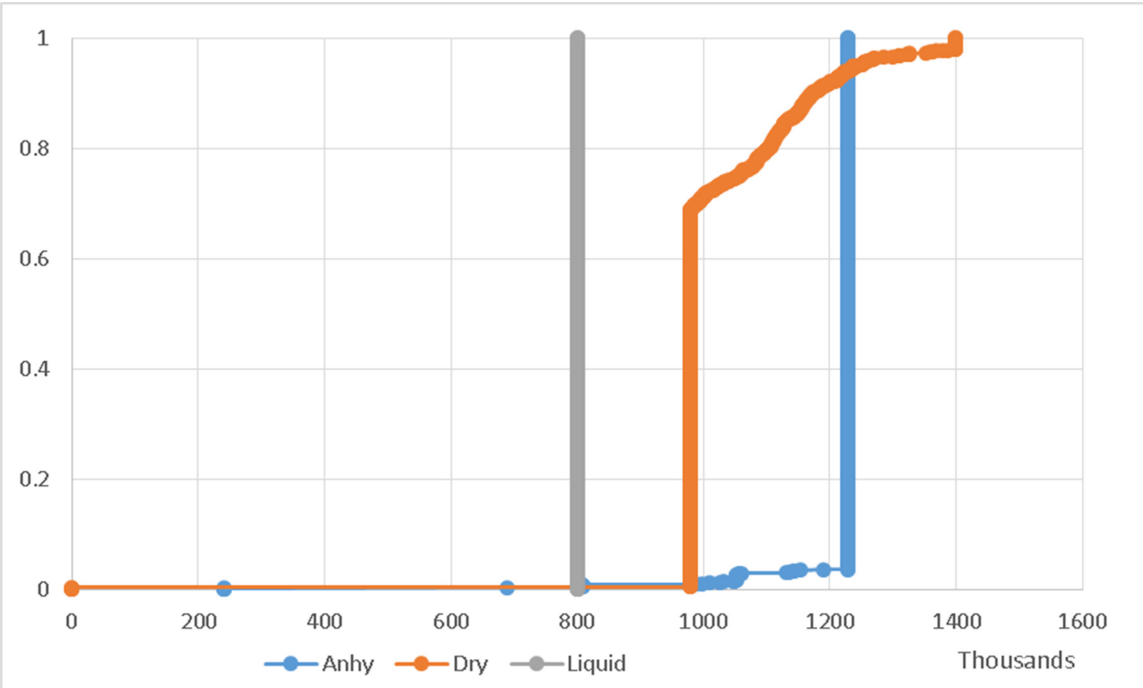

Figure D.25. Cumulative probability for 51054 (Port Neal, IA) in stochastic mixed-integer case.

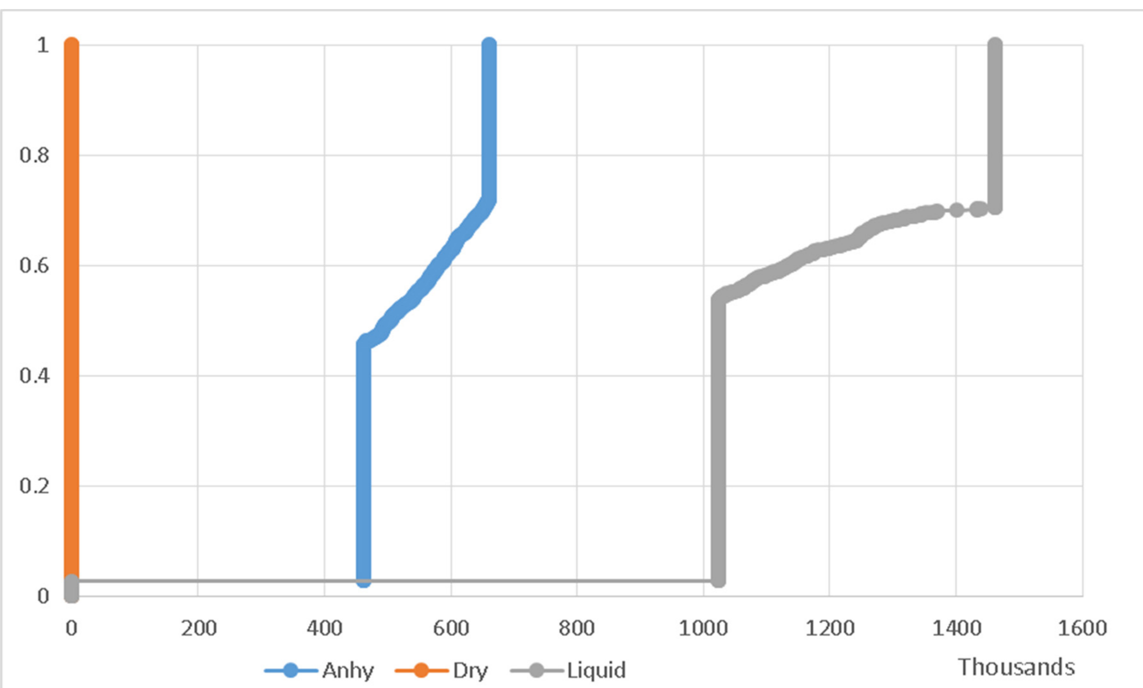

Figure D.26. Cumulative probability for 52658 (Wever, IA) in stochastic mixed-integer case.

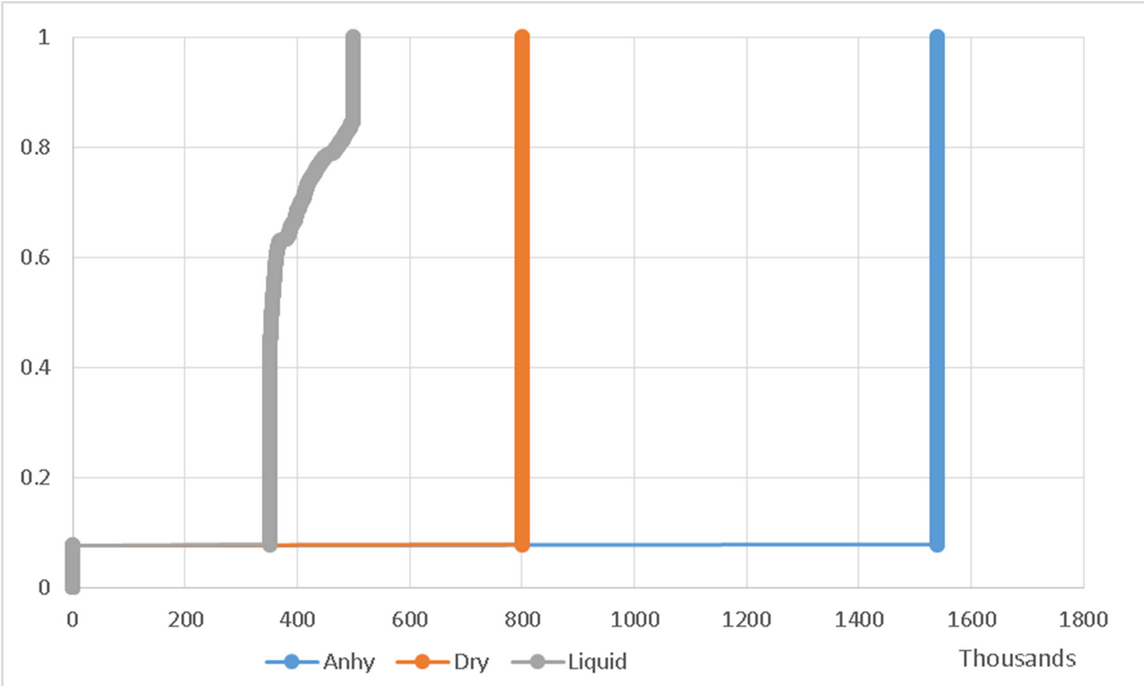

Figure D.27. Cumulative probability for 58203 (Grand Forks, ND) in stochastic mixed-integer case.

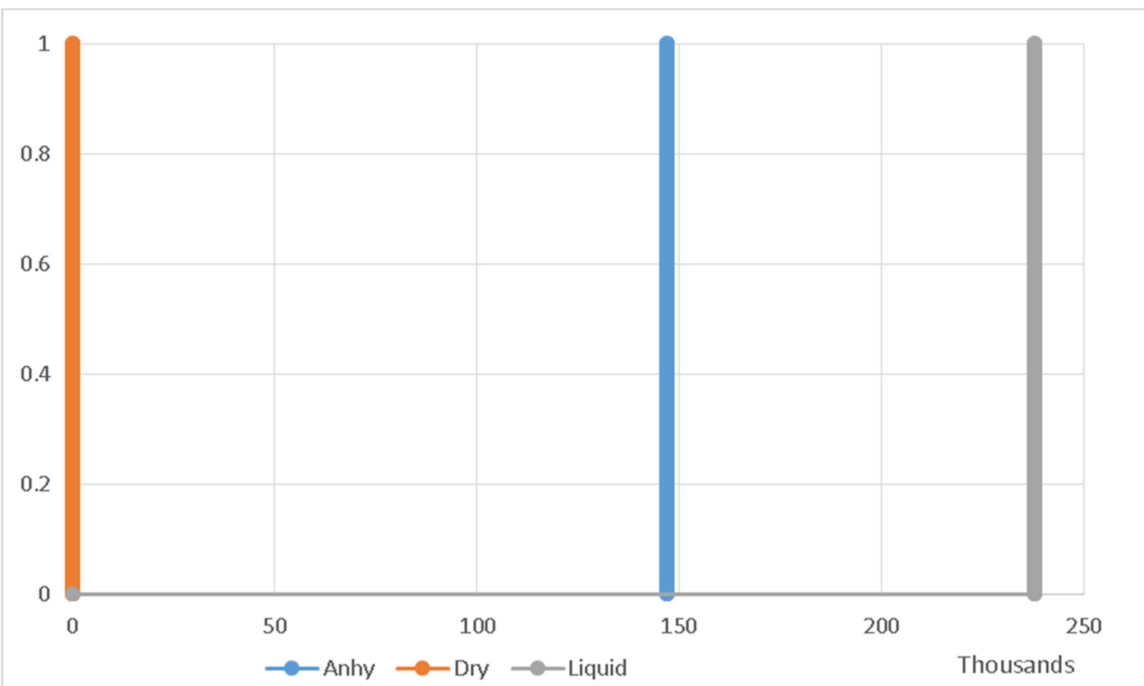

Figure D.28. Cumulative probability for 58481 (Jamestown, ND) in stochastic mixed-integer case.

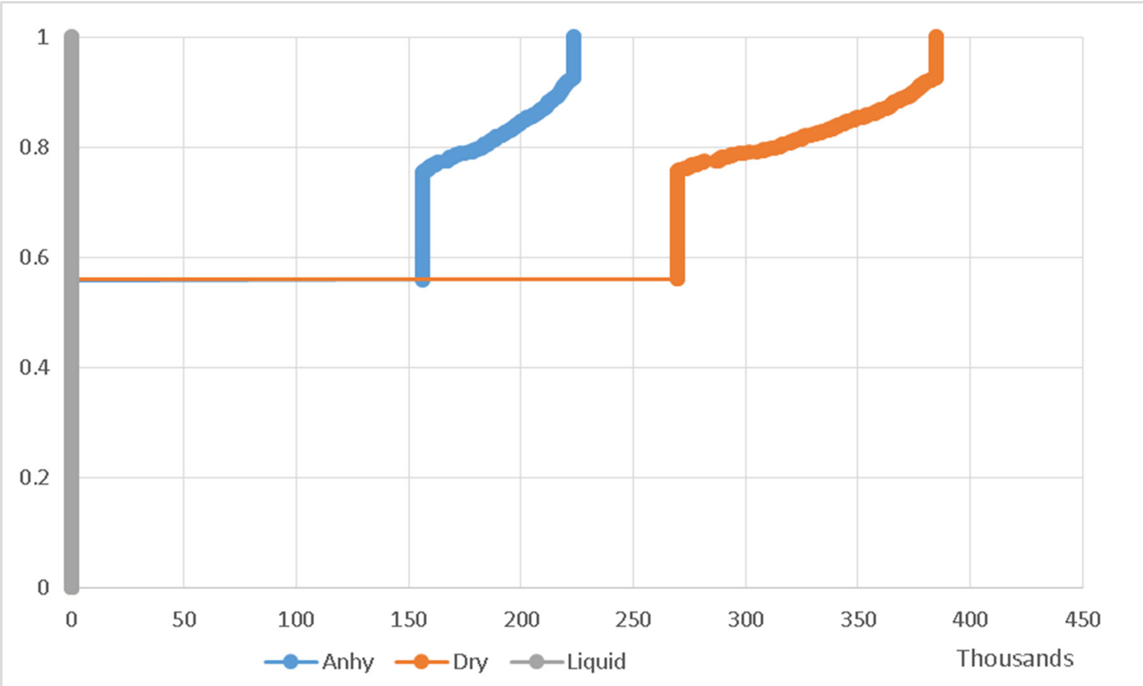

Figure D.29. Cumulative probability for 58523 (Beulah, ND) in stochastic mixed-integer case.

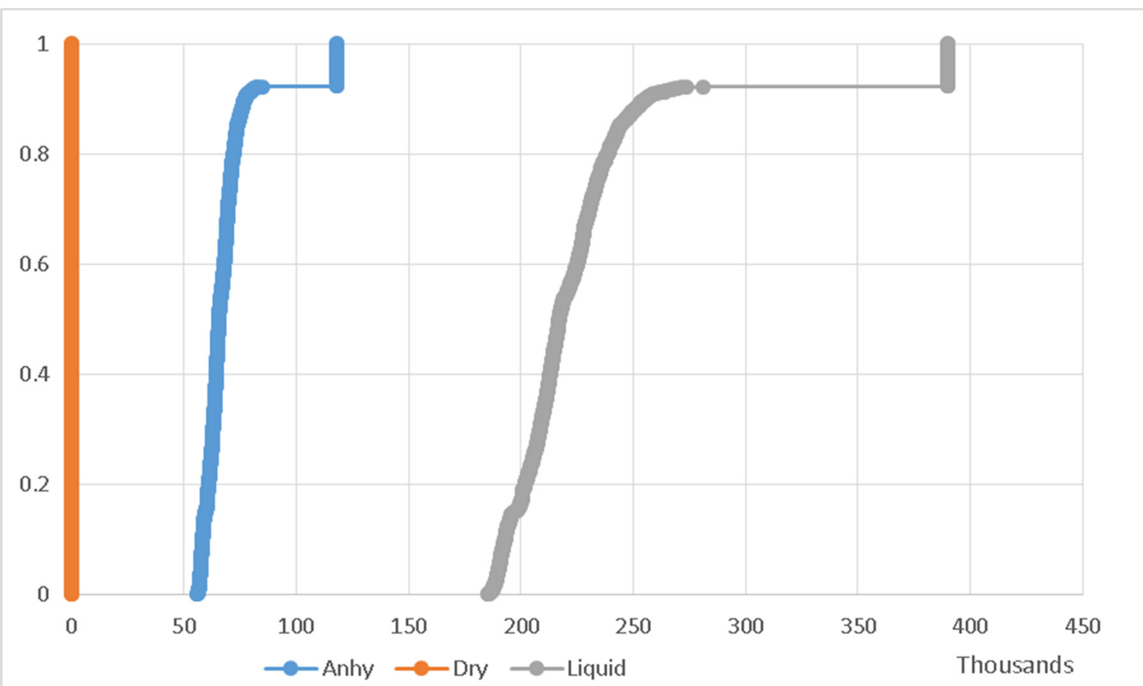

Figure D.30. Cumulative probability for 61025 (East Dubuque, IL) in stochastic mixed-integer case.

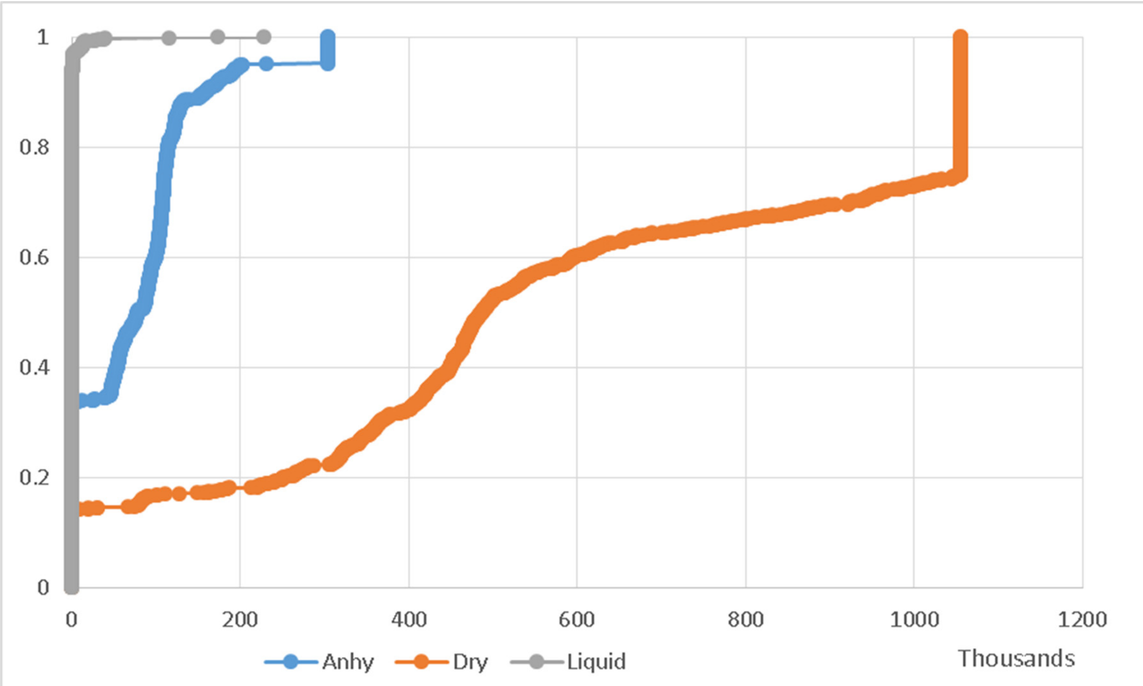

Figure D.31. Cumulative probability for 612 (Medicine Hat, AB) in stochastic mixed-integer case.

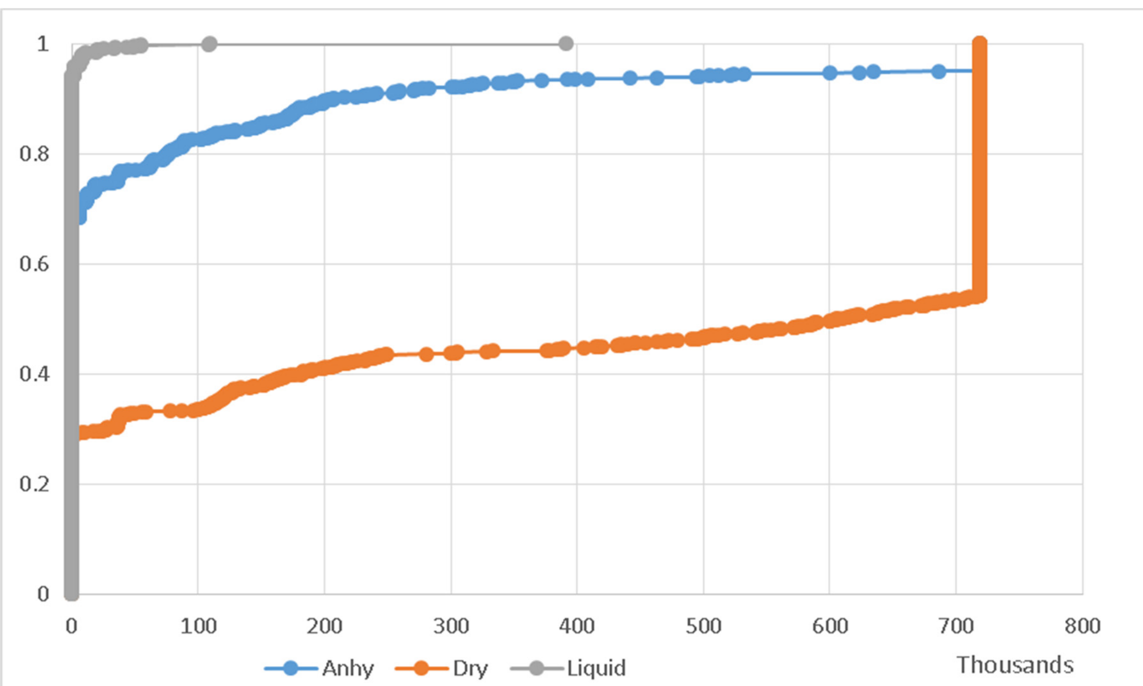

Figure D.32. Cumulative probability for 644 (Belle Plaine, SK) in stochastic mixed-integer case.

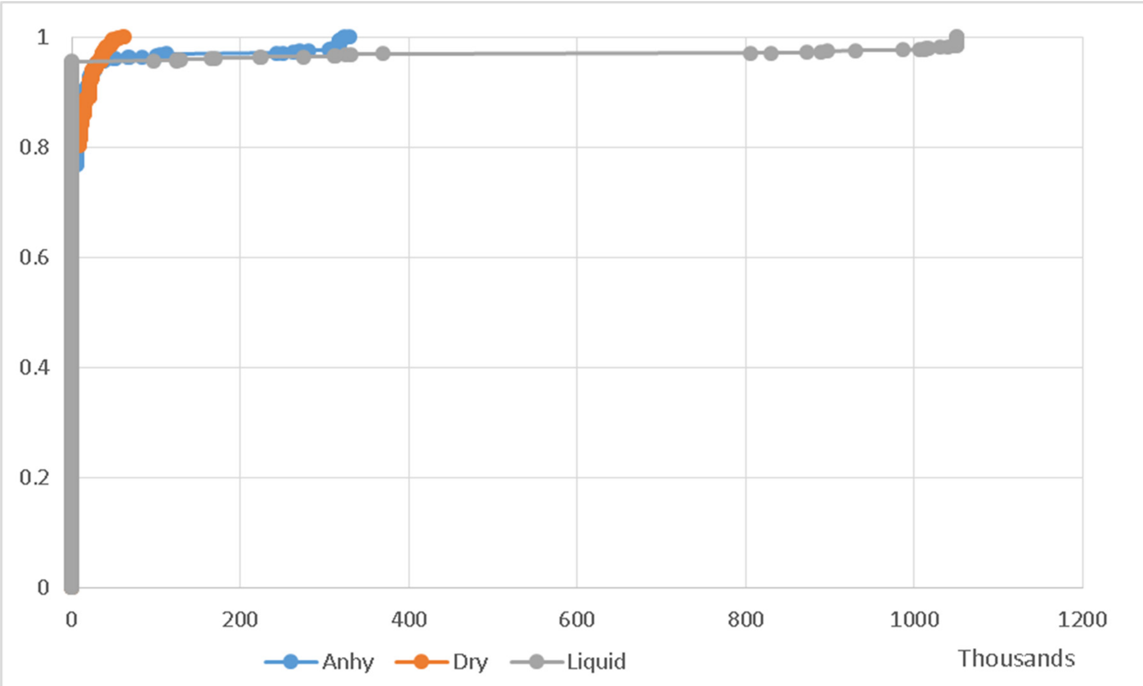

Figure D.33. Cumulative probability for 67337 (Coffeyville, KS) in stochastic mixed-integer case.

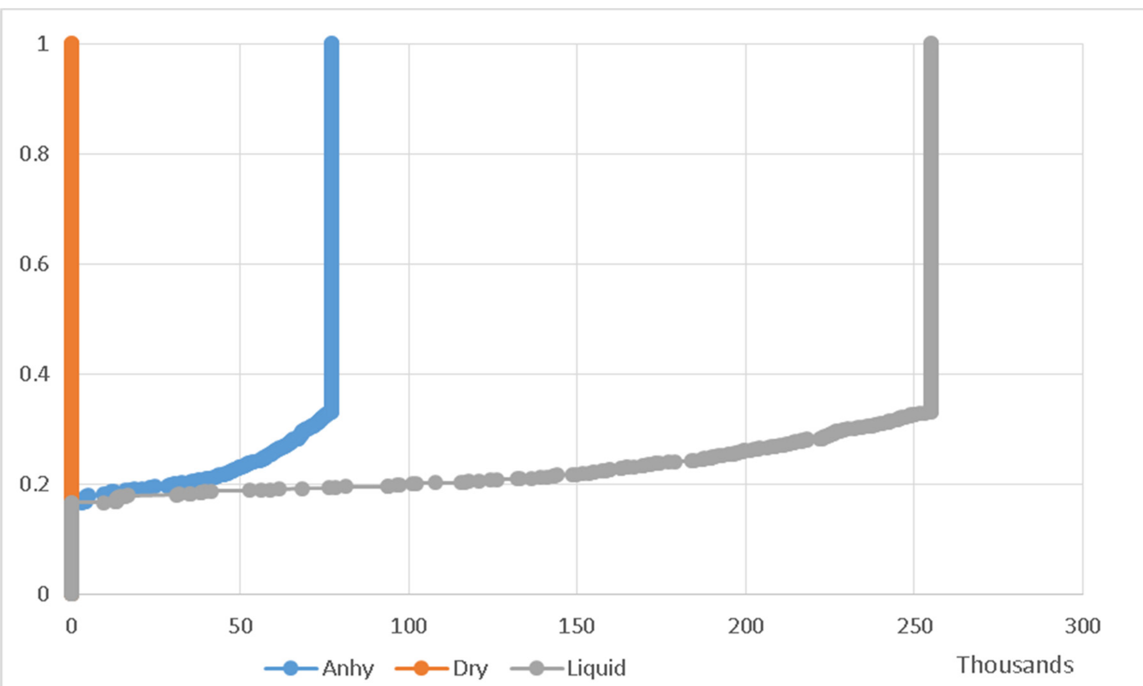

Figure D.34. Cumulative probability for 67801 (Dodge City, KS) in stochastic mixed-integer case.

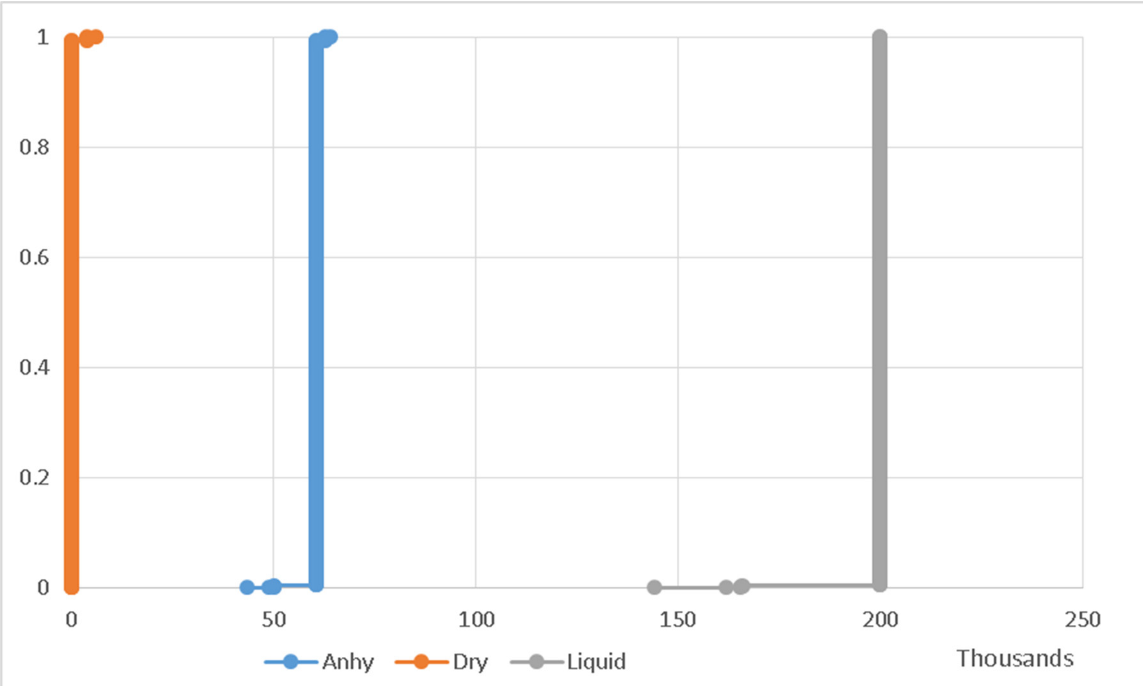

Figure D.35. Cumulative probability for 68310 (Beatrice, NE) in stochastic mixed-integer case.

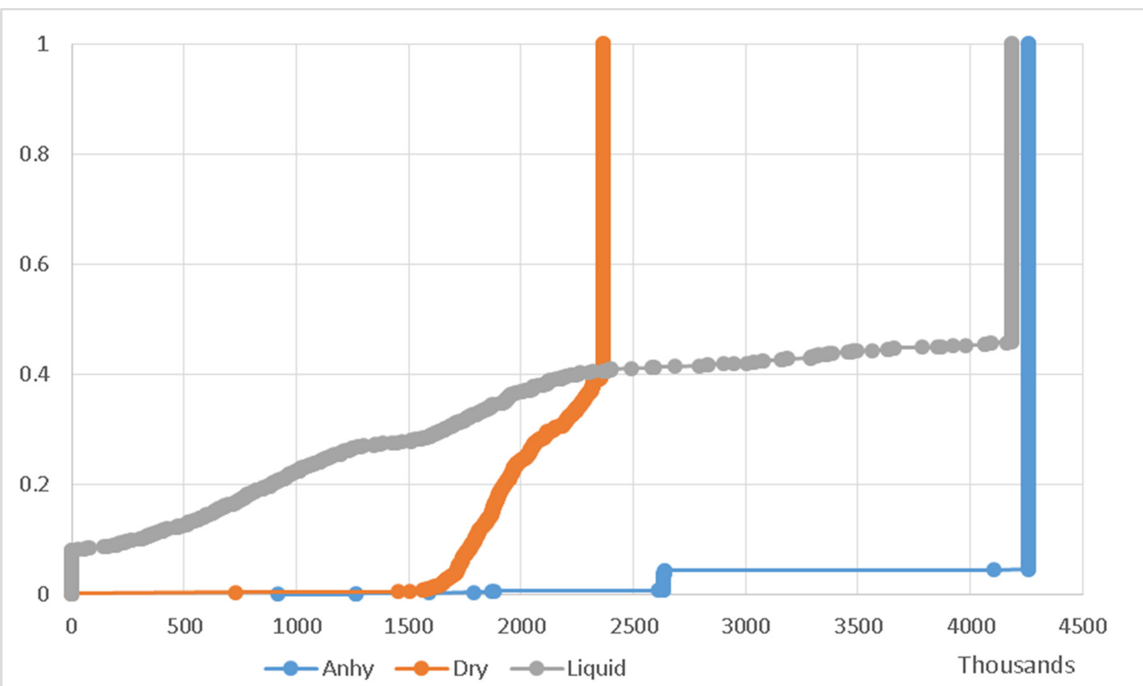

Figure D.36. Cumulative probability for 70346 (Donaldsonville, LA) in stochastic mixed-integer case.

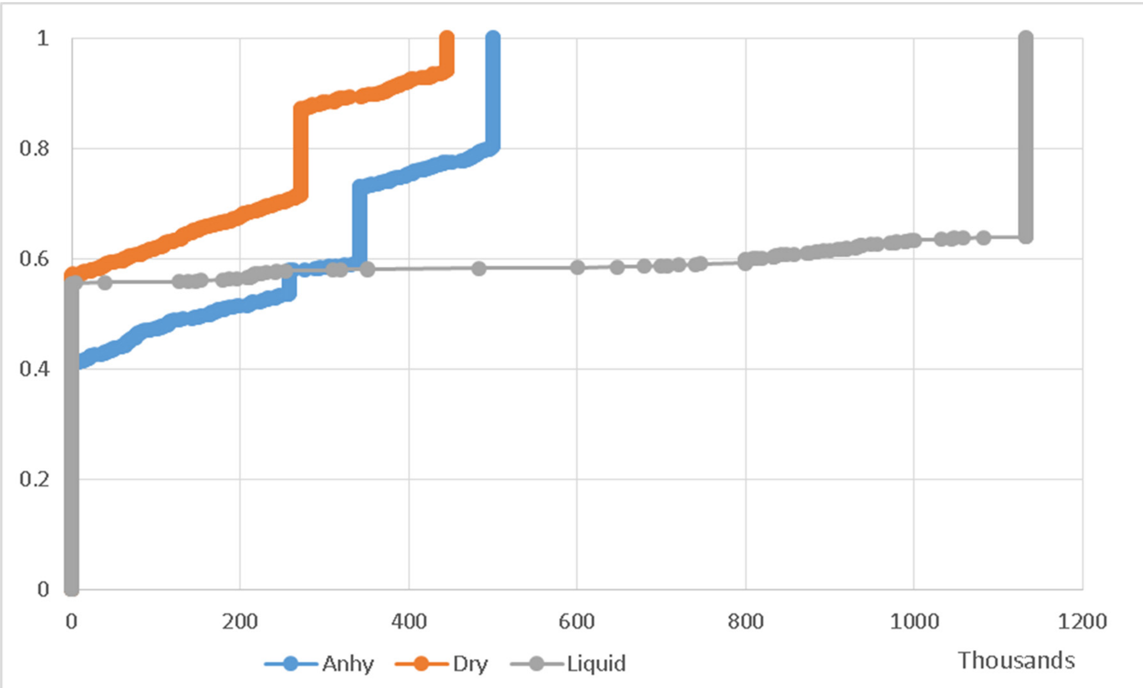

Figure D.37. Cumulative probability for 70734 (Geismar, LA) in stochastic mixed-integer case.

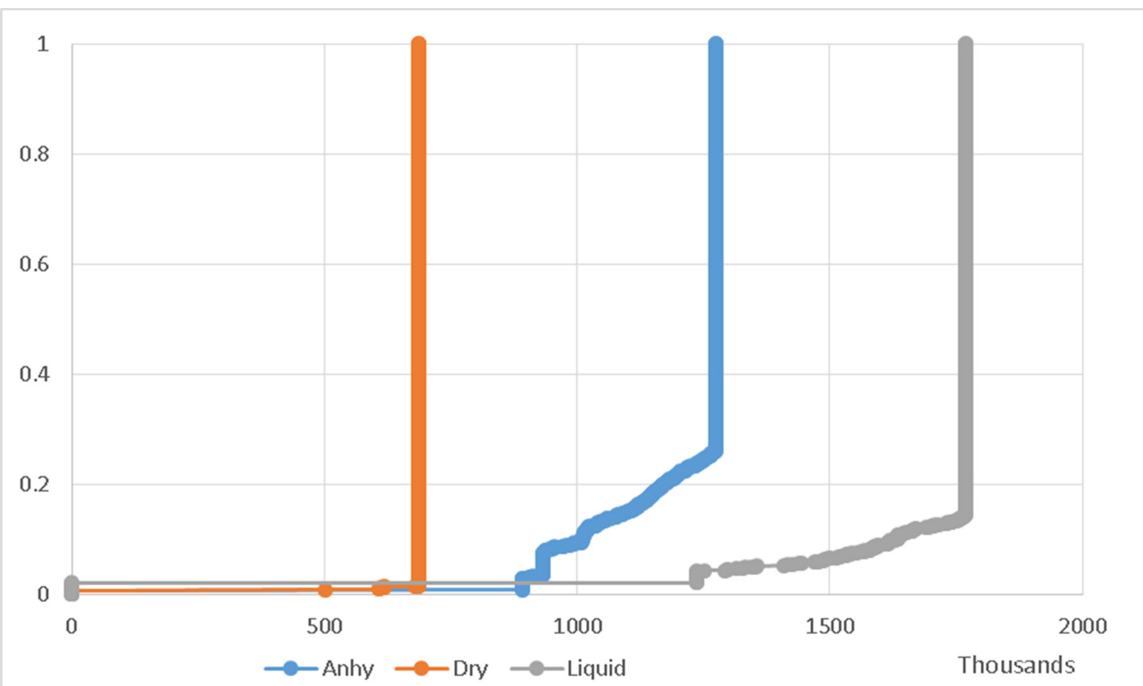

Figure D.38. Cumulative probability for 70765 (Iberville, LA) in stochastic mixed-integer case.

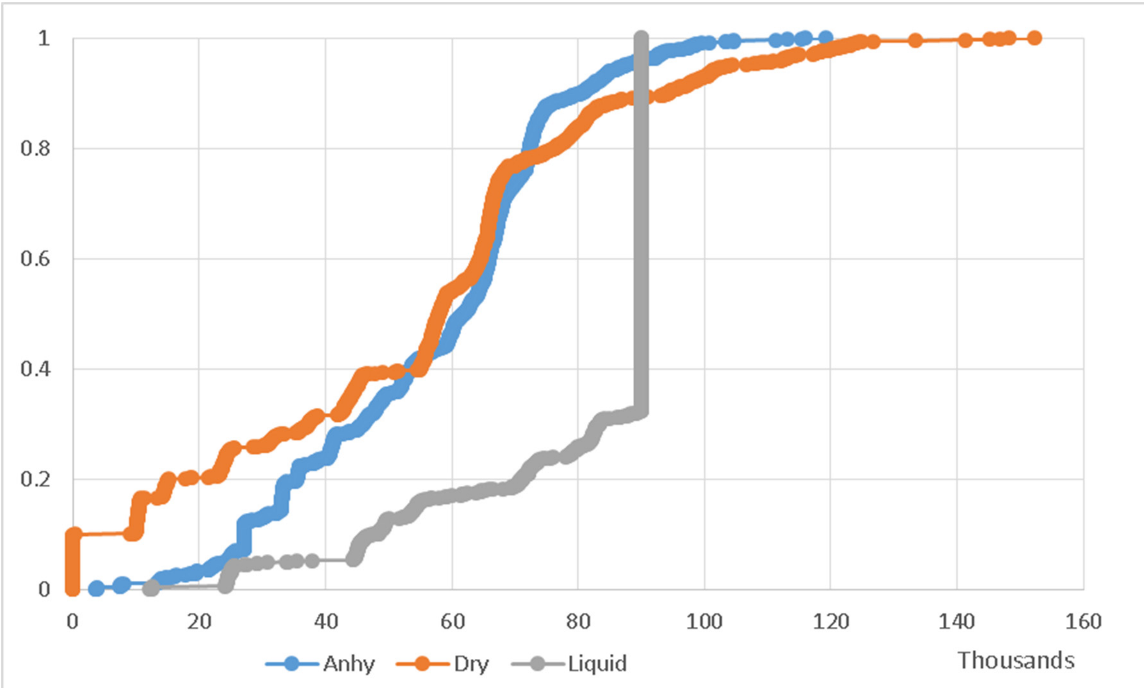

Figure D.39. Cumulative probability for 73701 (Enid, OK) in stochastic mixed-integer case.

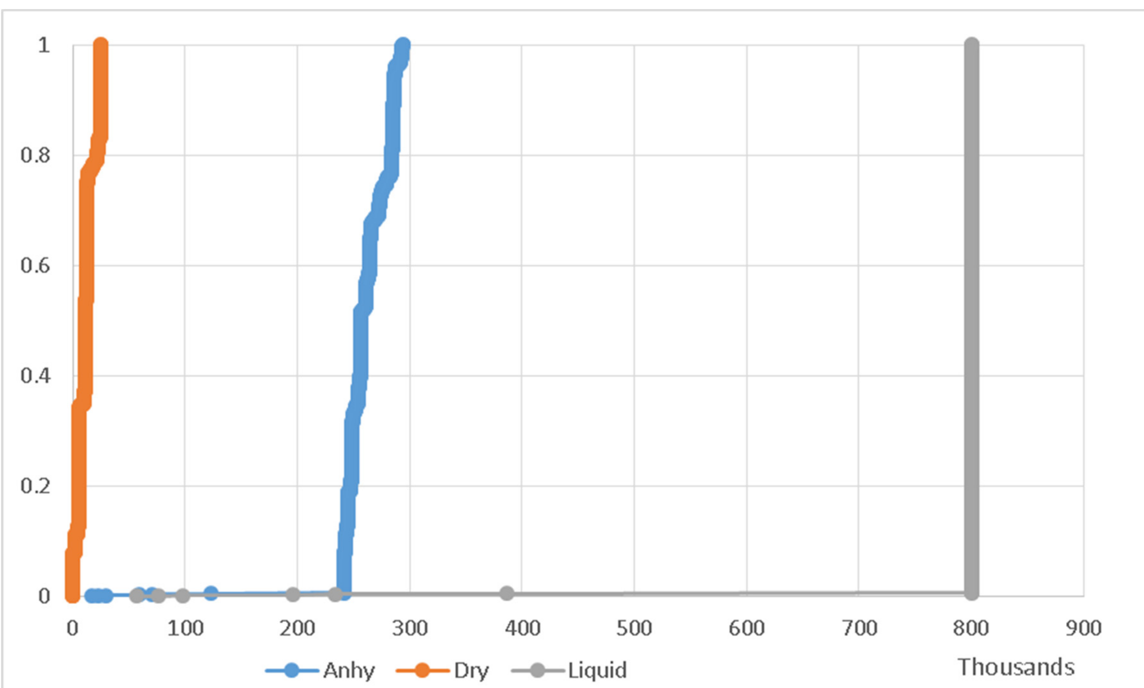

Figure D.40. Cumulative probability for 73801 (Woodward, OK) in stochastic mixed-integer case.

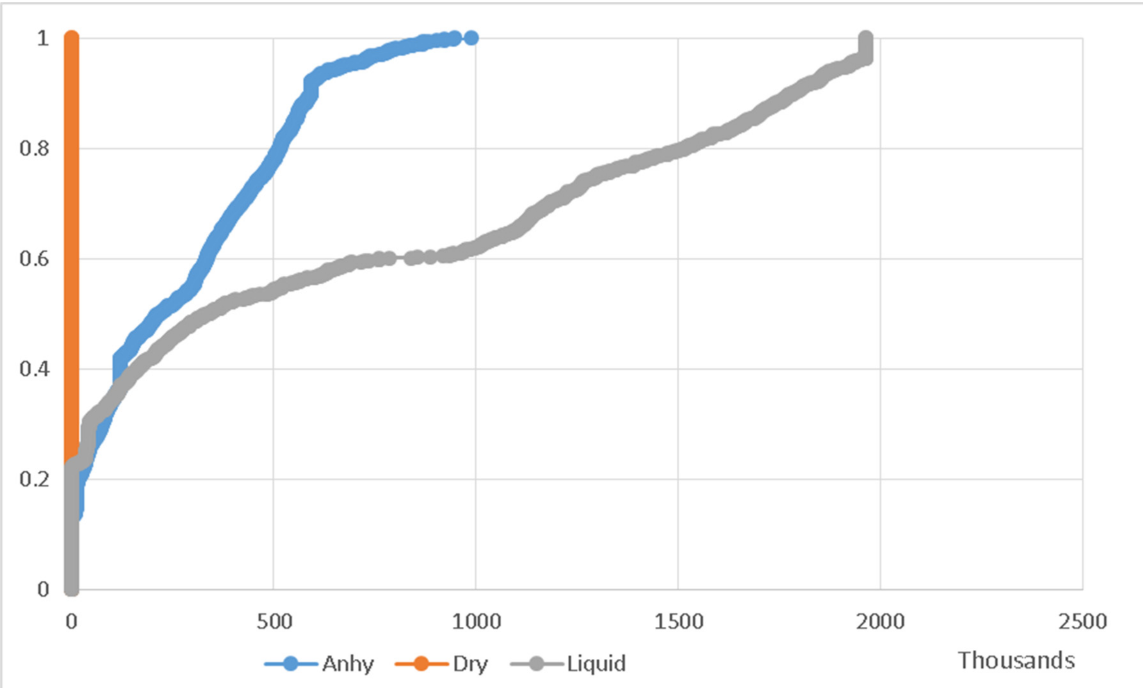

Figure D.41. Cumulative probability for 74019 (Verdigris, OK) in stochastic mixed-integer case.

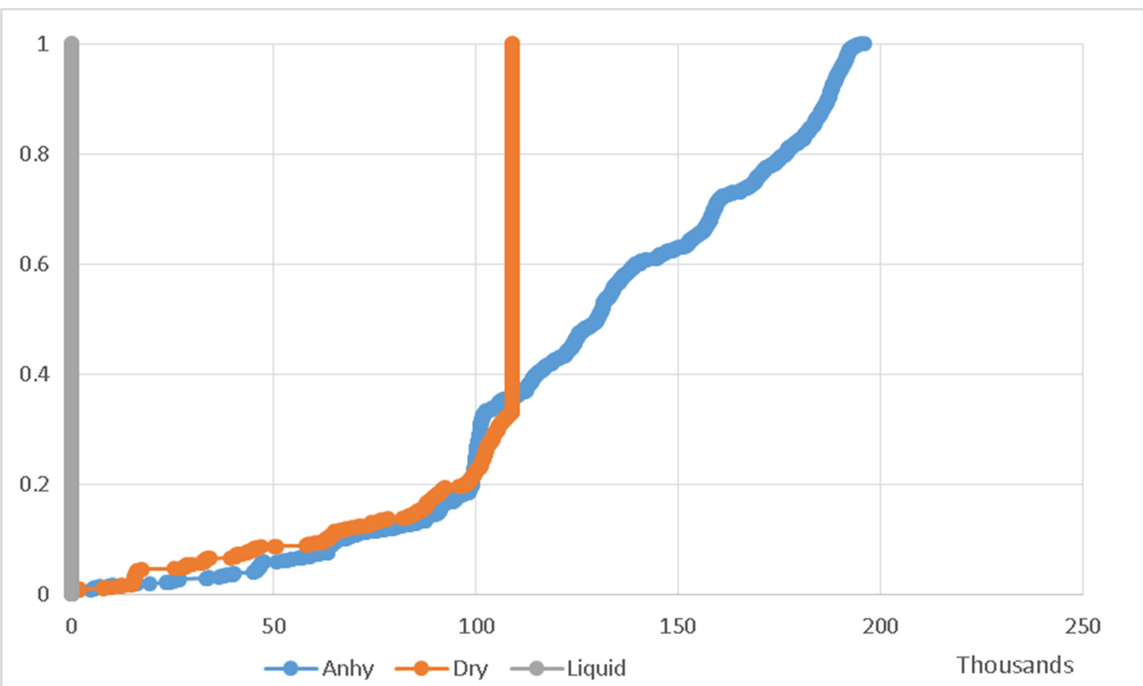

Figure D.42. Cumulative probability for 79007 (Borger, TX) in stochastic mixed-integer case.

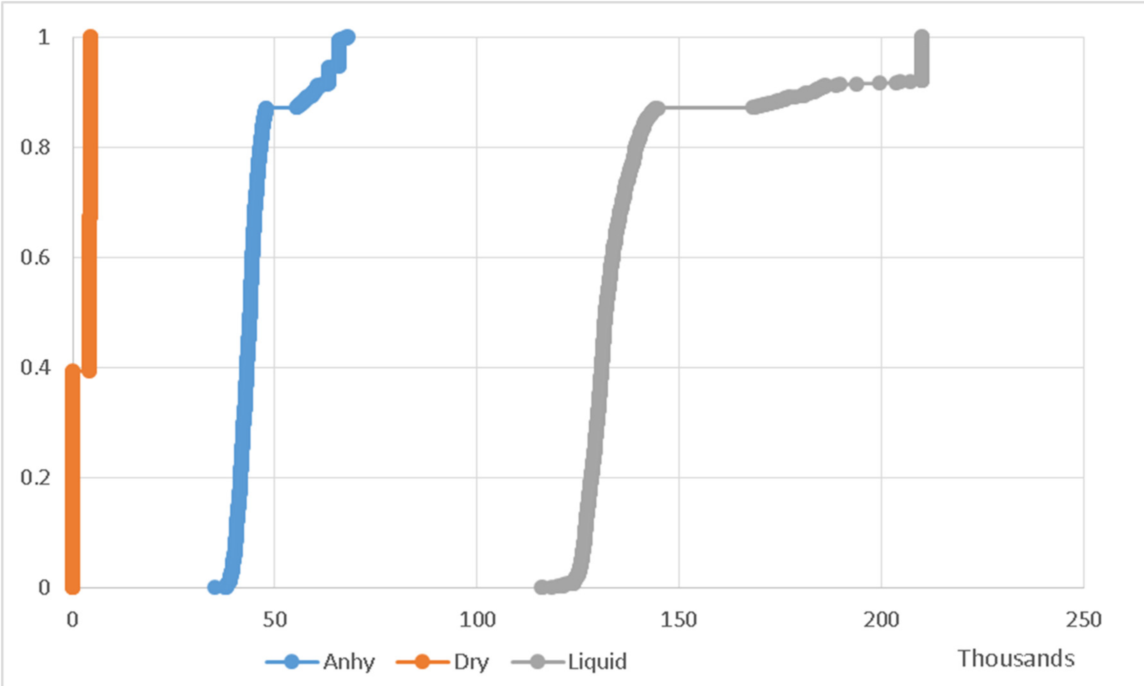

Figure D.43. Cumulative probability for 82001 (Cheyenne, WY) in stochastic mixed-integer case.

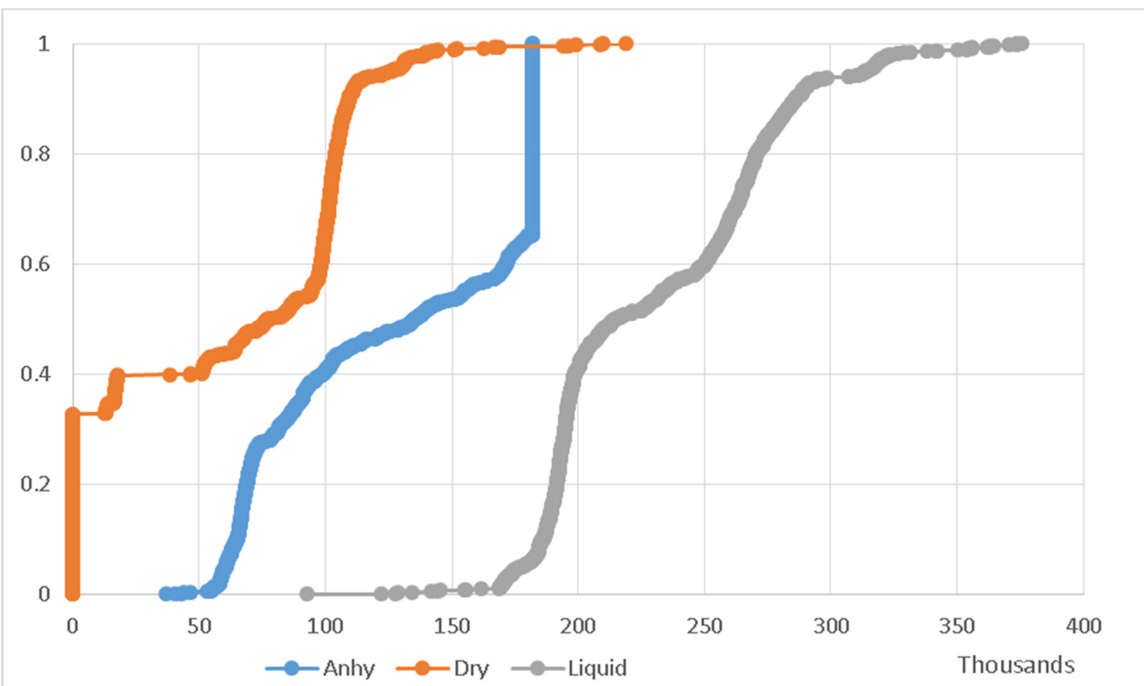

Figure D.44. Cumulative probability for 83211 (American Falls, ID) in stochastic mixed-integer case.

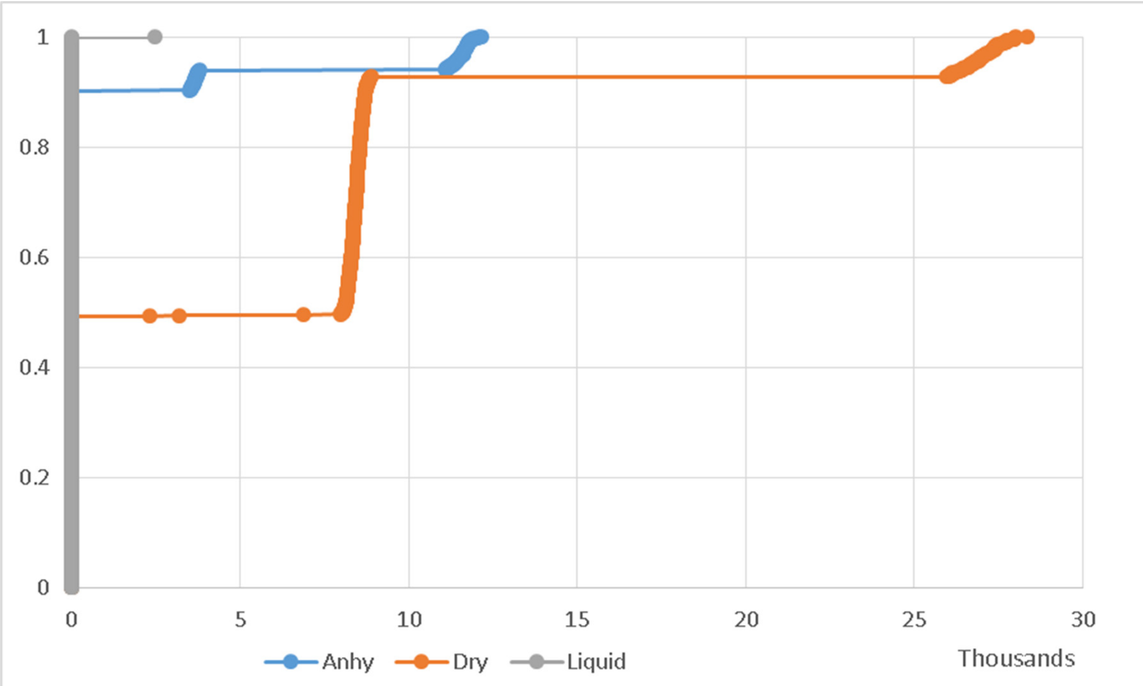

Figure D.45. Cumulative probability for 8800451 (POE: Emerson, ND) in stochastic mixed-integer case.

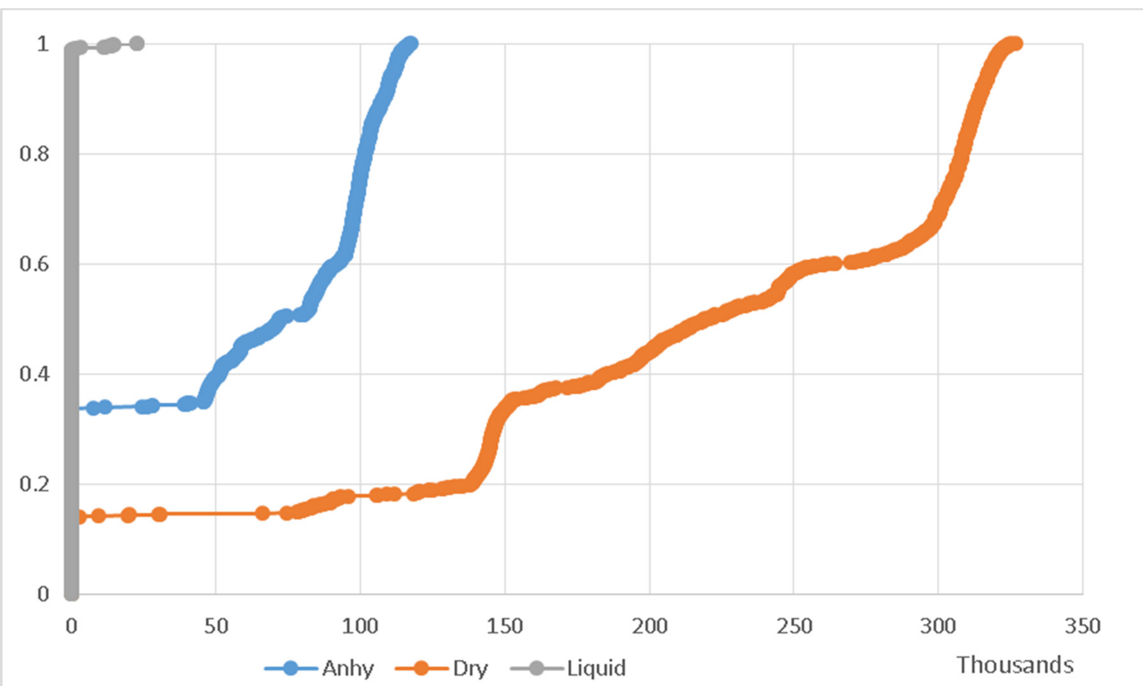

Figure D.46. Cumulative probability for 9163 (POE: Kingsgate, ID) in stochastic mixed-integer case.

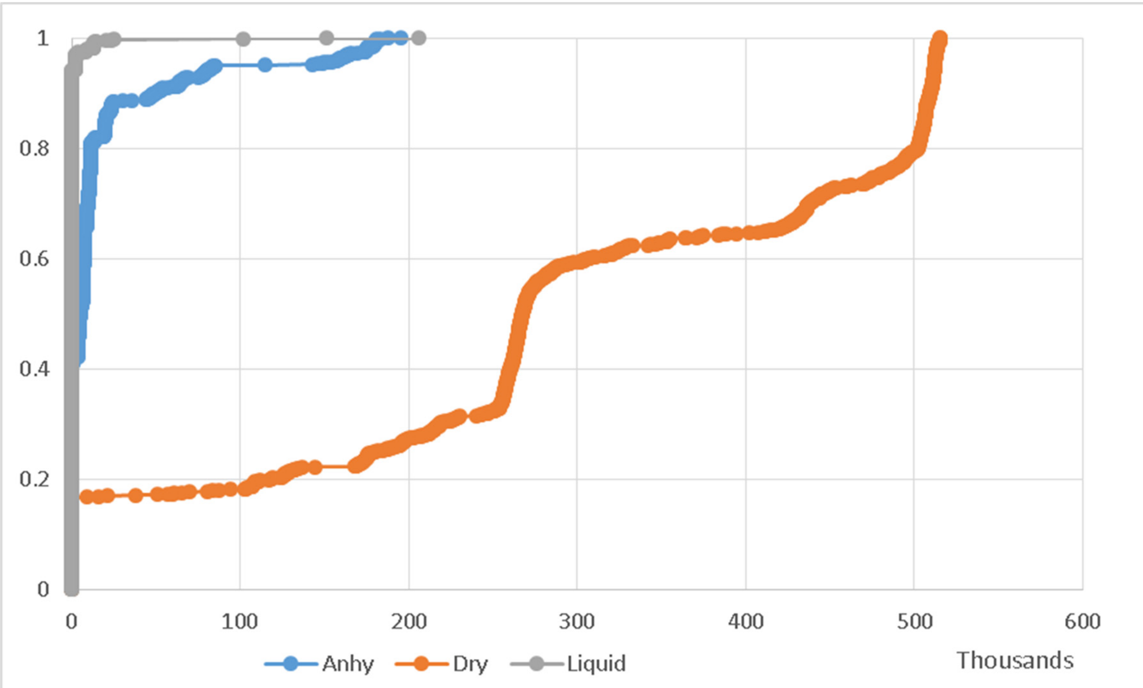

Figure D.47. Cumulative probability for 9303 (POE: Coutts, MT) in stochastic mixed-integer case.

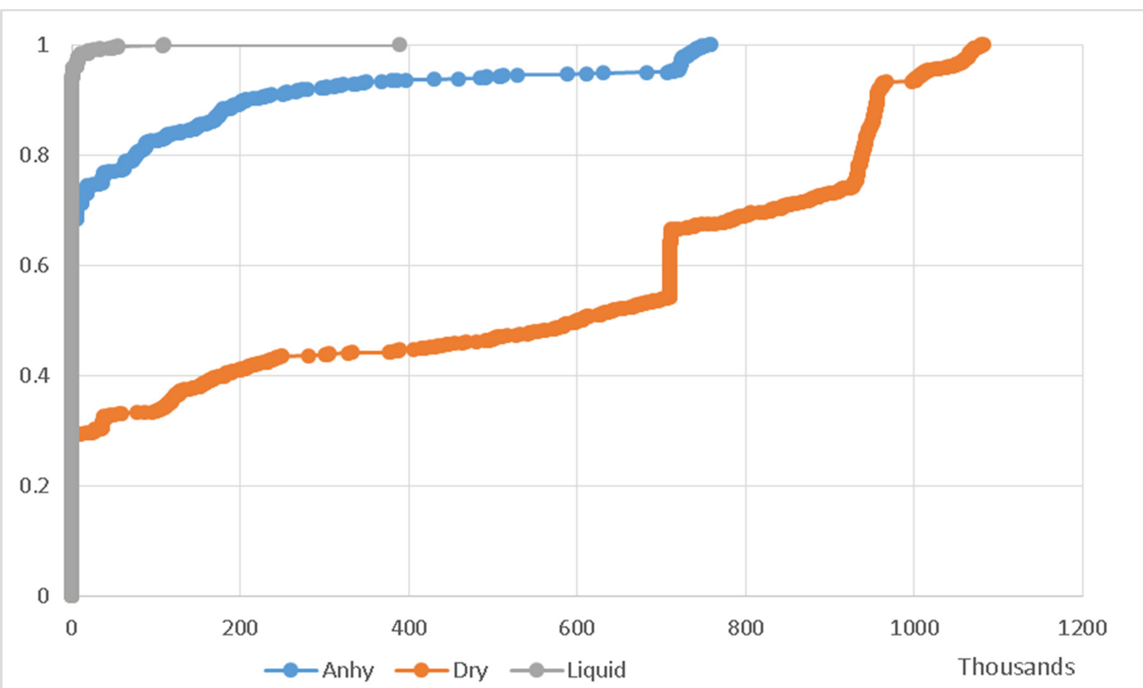

Figure D.48. Cumulative probability for 9384 (POE: Portal, ND) in stochastic mixed-integer case.

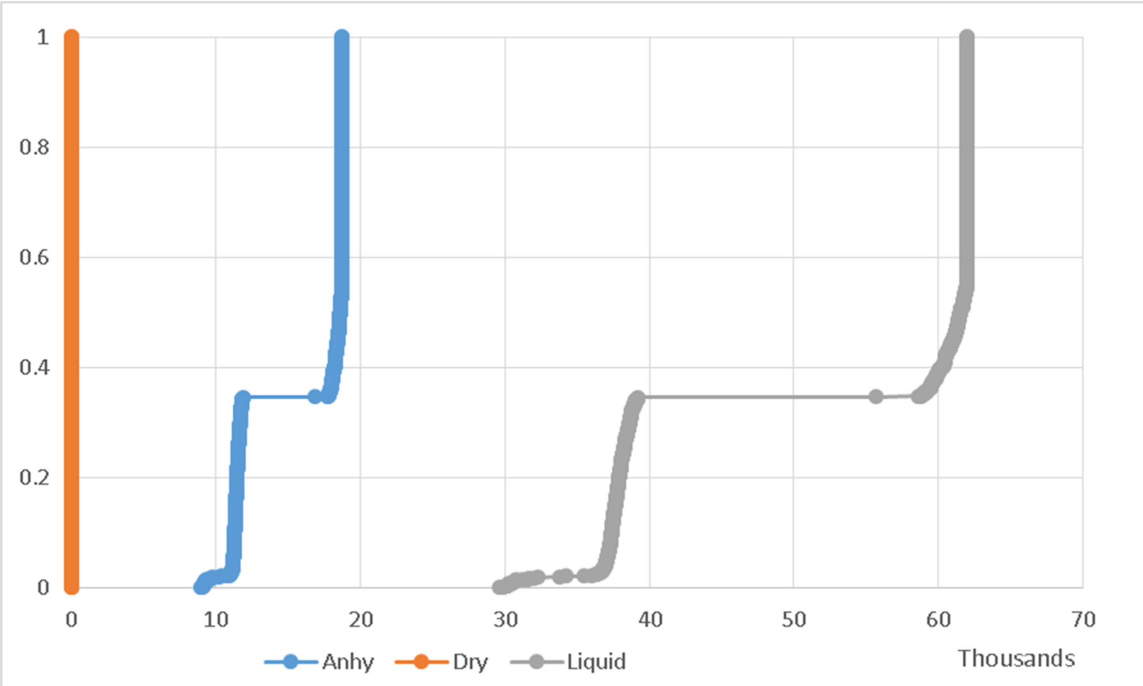

Figure D.49. Cumulative probability for 97051 (St. Helens, OR) in stochastic mixed-integer case.

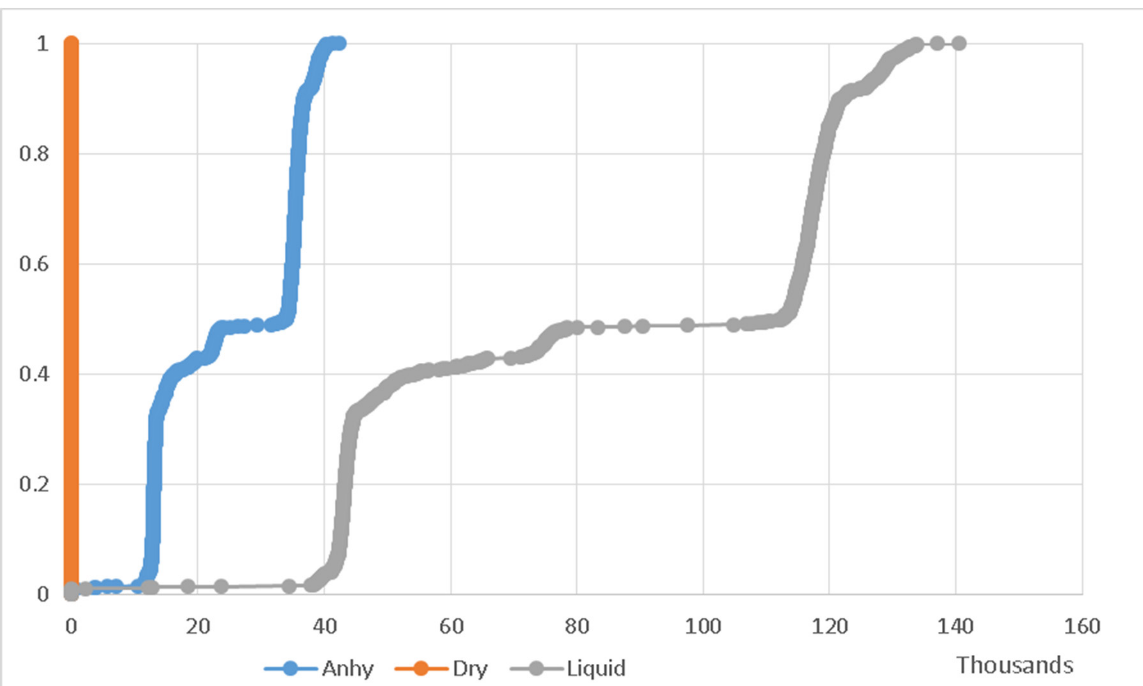

Figure D.50. Cumulative probability for 99337 (Kennewick, WA) in stochastic mixed-integer case.

APPENDIX E. STOCHASTIC LINEAR FUTURE CASE 2018 SENSITIVITY

E.1. Distribution of Origination Destination Matrix for Stochastic Linear Future Case 2018 Sensitivity

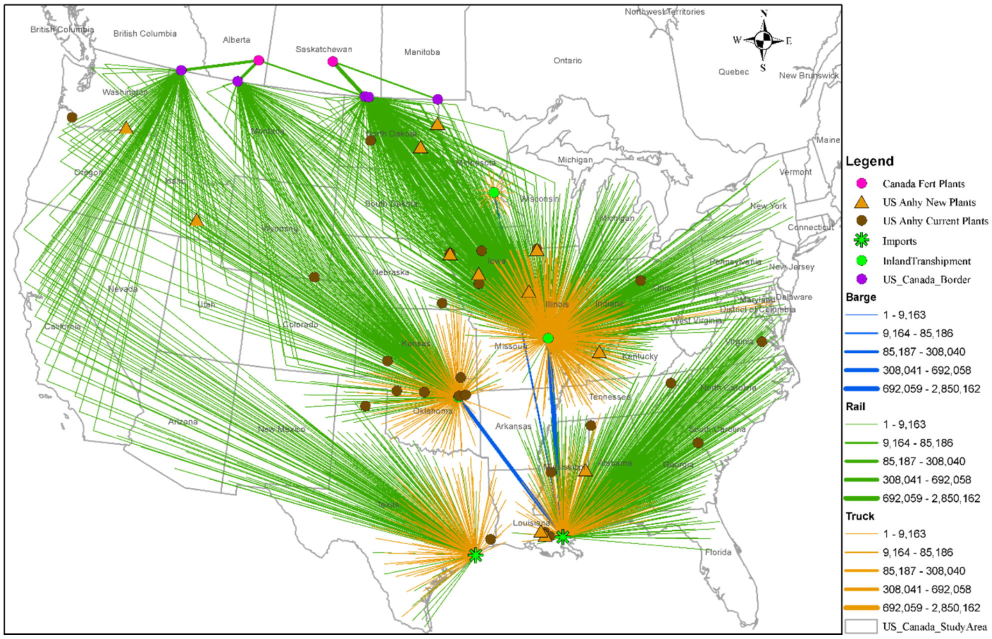

Figure E.1. Structure of supply chain for anhydrous ammonia for stochastic linear future case sensitivity by mode (Rail=Green, Truck=Orange, Barge=Blue).

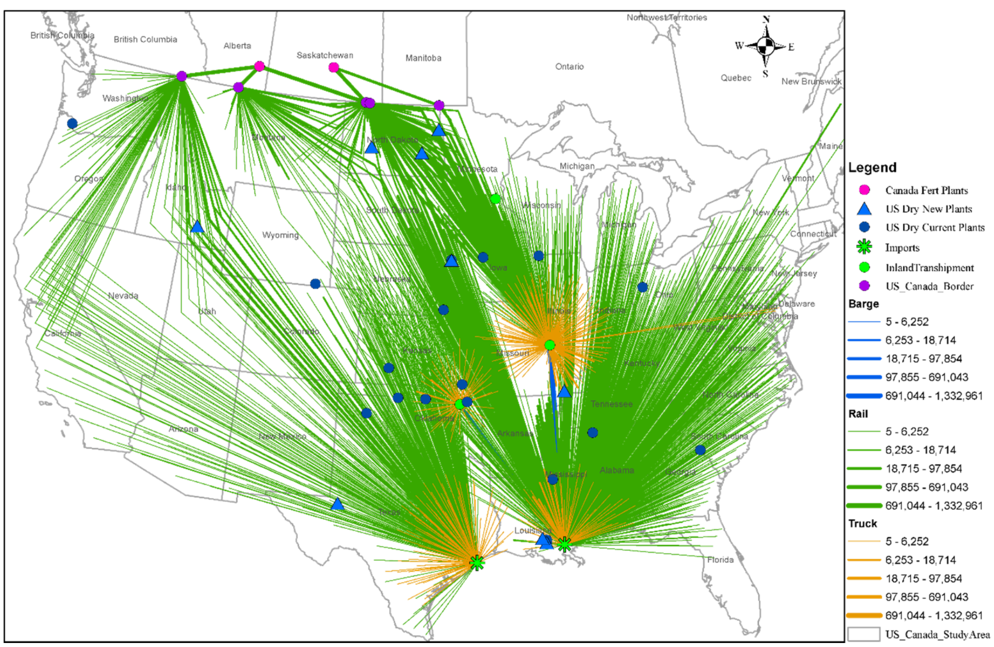

Figure E.2. Structure of supply chain for urea for stochastic linear future case sensitivity by mode (Rail=Green, Truck=Orange, Barge=Blue).

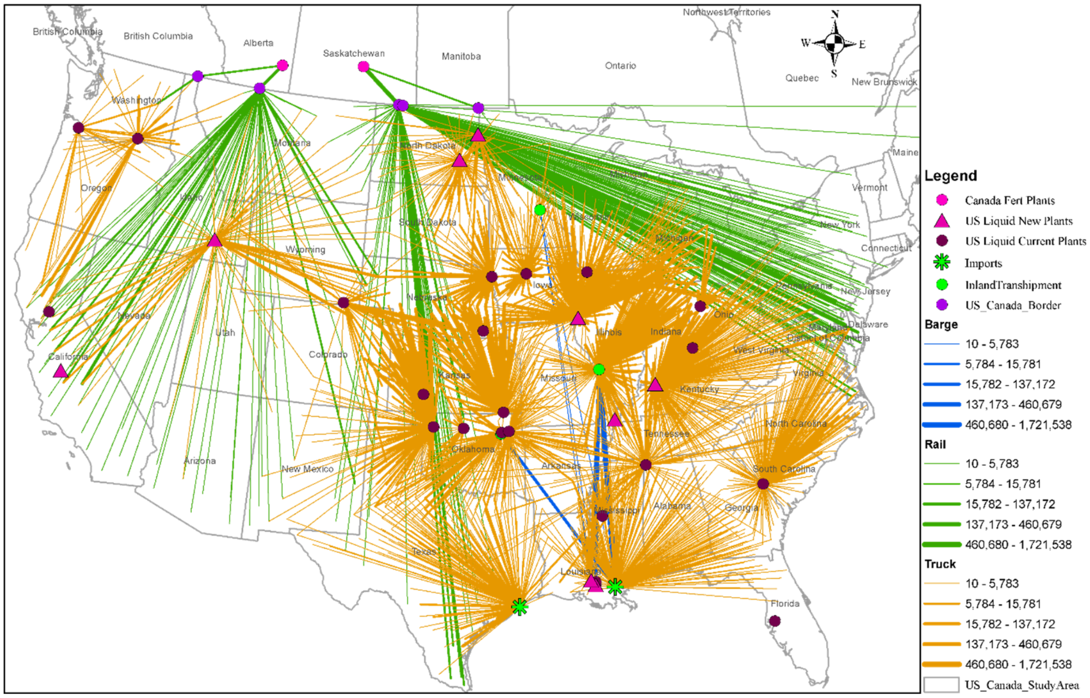

Figure E.3. Structure of supply chain for UAN for stochastic linear future case sensitivity by mode (Rail=Green, Truck=Orange, Barge=Blue).

E.2. Shadow Prices for Stochastic Linear Future Case 2018 Sensitivity

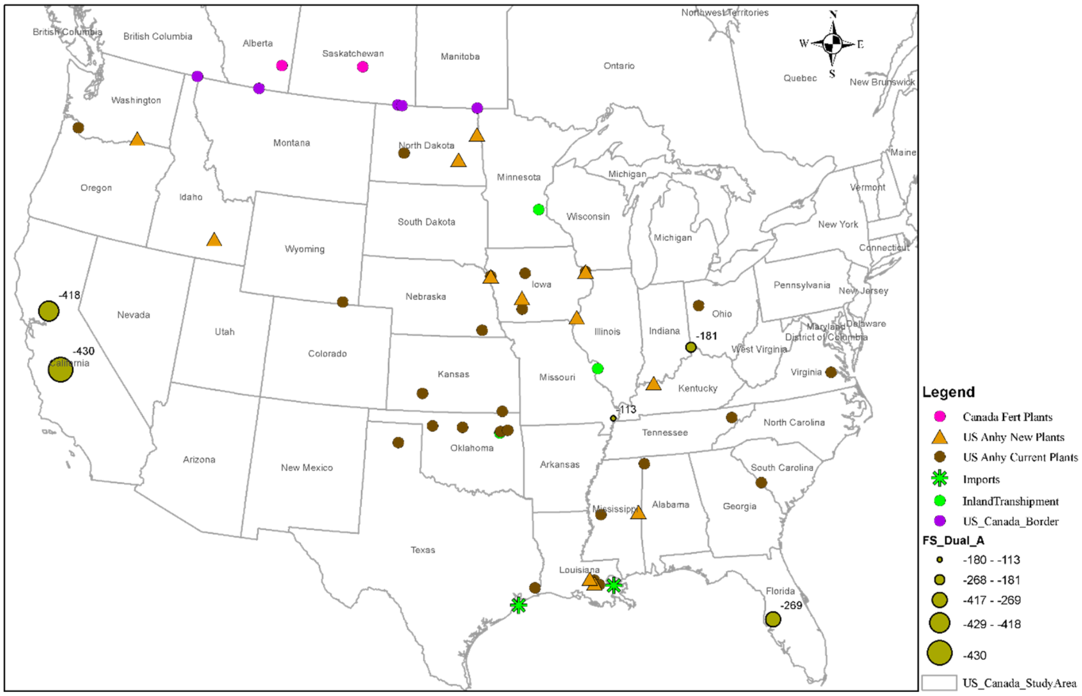

Figure E.4. Shadow Prices for anhydrous ammonia in stochastic linear future case sensitivity.

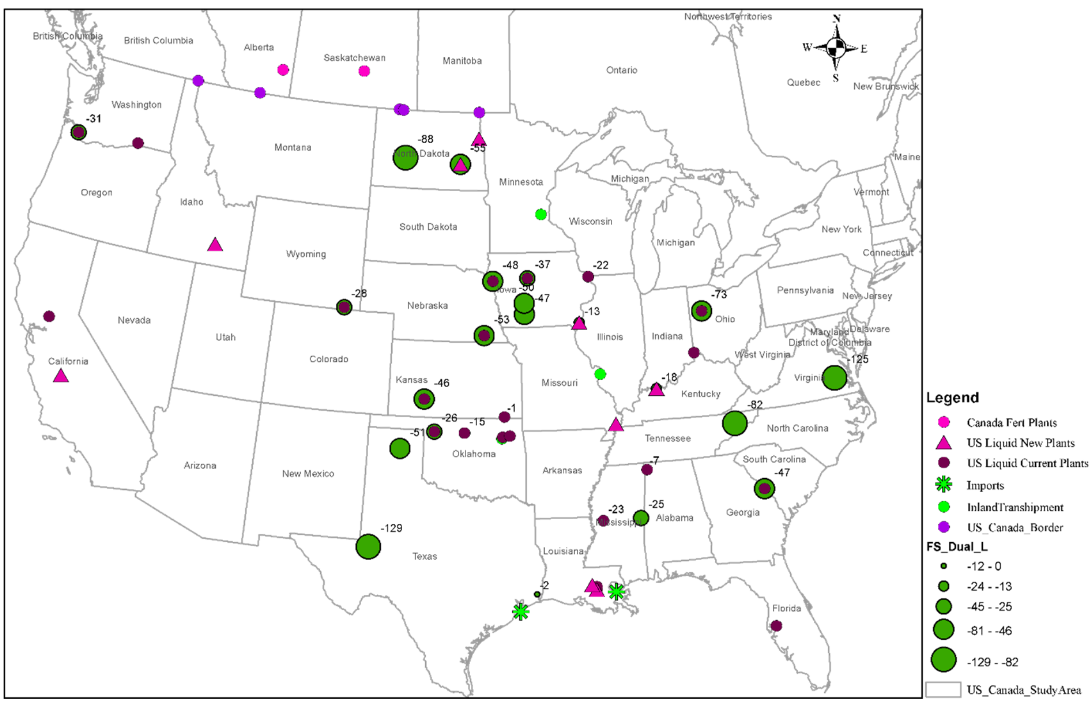

Figure E.5. Shadow Prices for UAN in stochastic linear future case sensitivity.

E.3. Market Boundaries for Selective Plants by Probability of Shipping for 1000 Iterations in Stochastic Linear Future Case 2018 Sensitivity

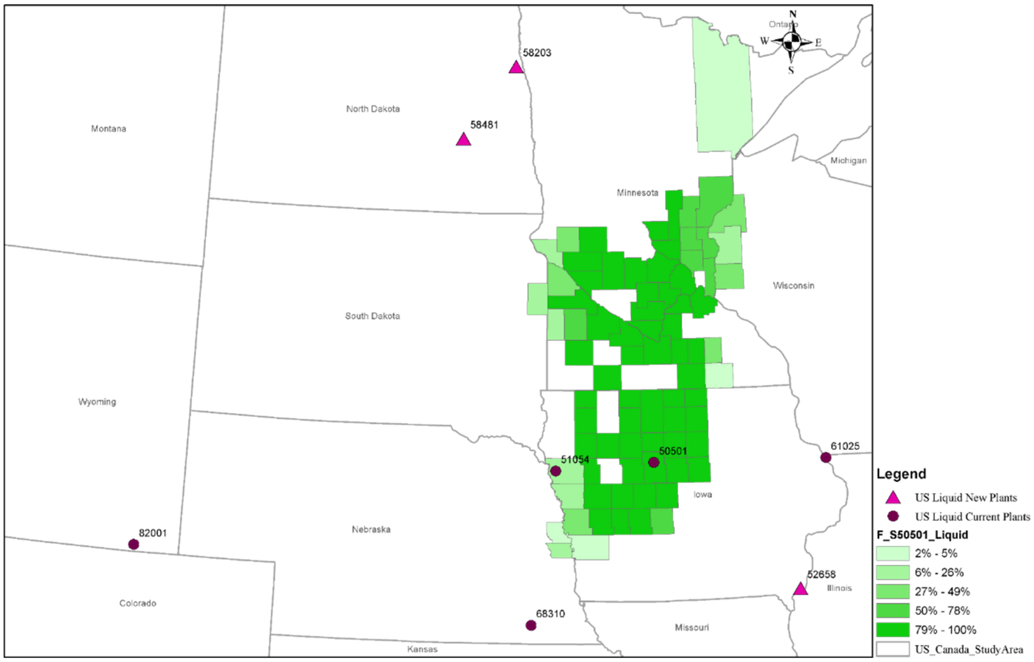

Figure E.6. Market boundaries for plant j=50501 for UAN (probability of shipping for 1000 iterations) in stochastic linear future case sensitivity.

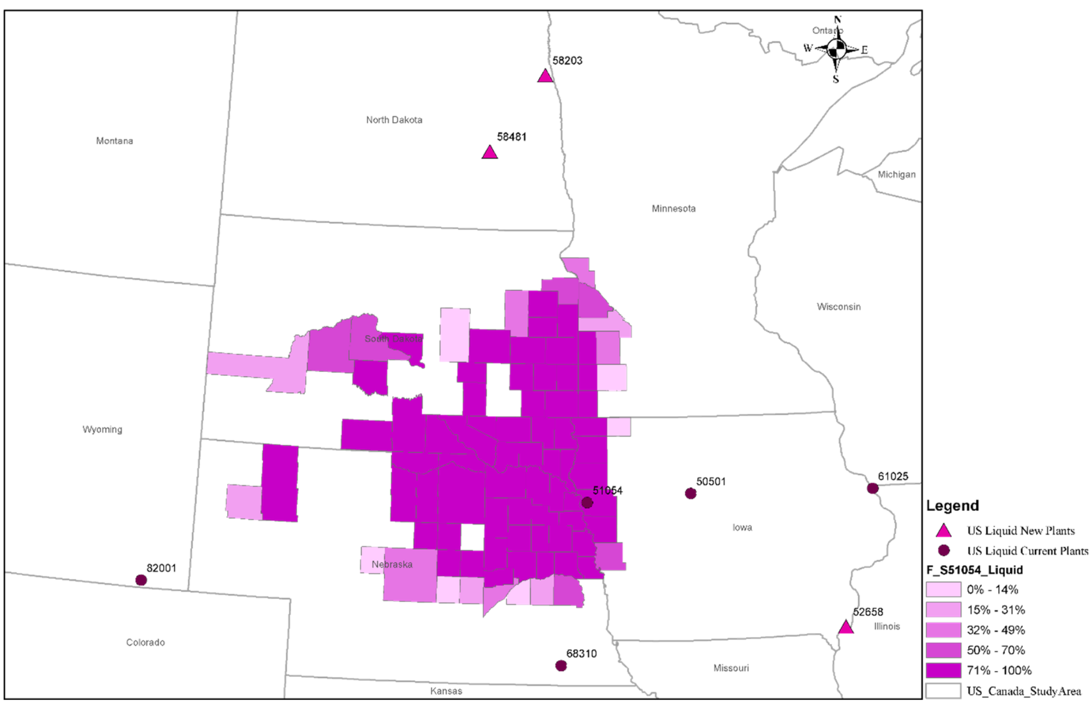

Figure E.7. Market boundaries for plant j=51054 for UAN (probability of shipping for 1000 iterations) in stochastic linear future case sensitivity.

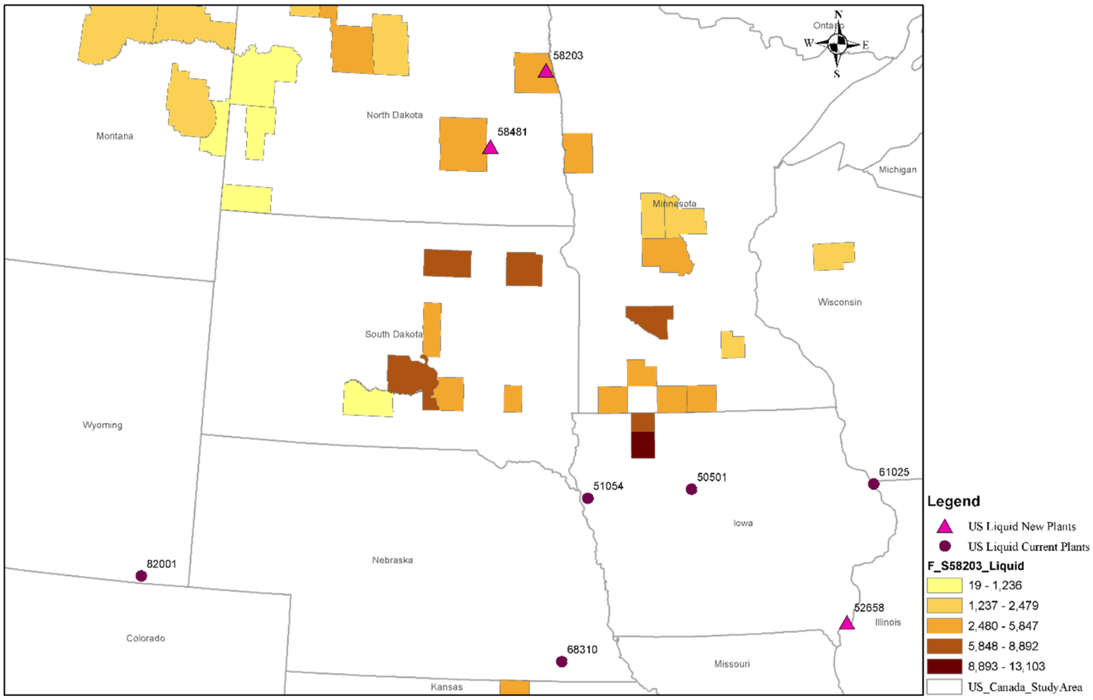

Figure E.8. Market boundaries for plant j=58203 for UAN (probability of shipping for 1000 iterations) in stochastic linear future case sensitivity.

E.4. Market Boundaries for Selective Plants by Mean Quantity of Shipping for 1000 Iterations in Stochastic Linear Future Case 2018 Sensitivity

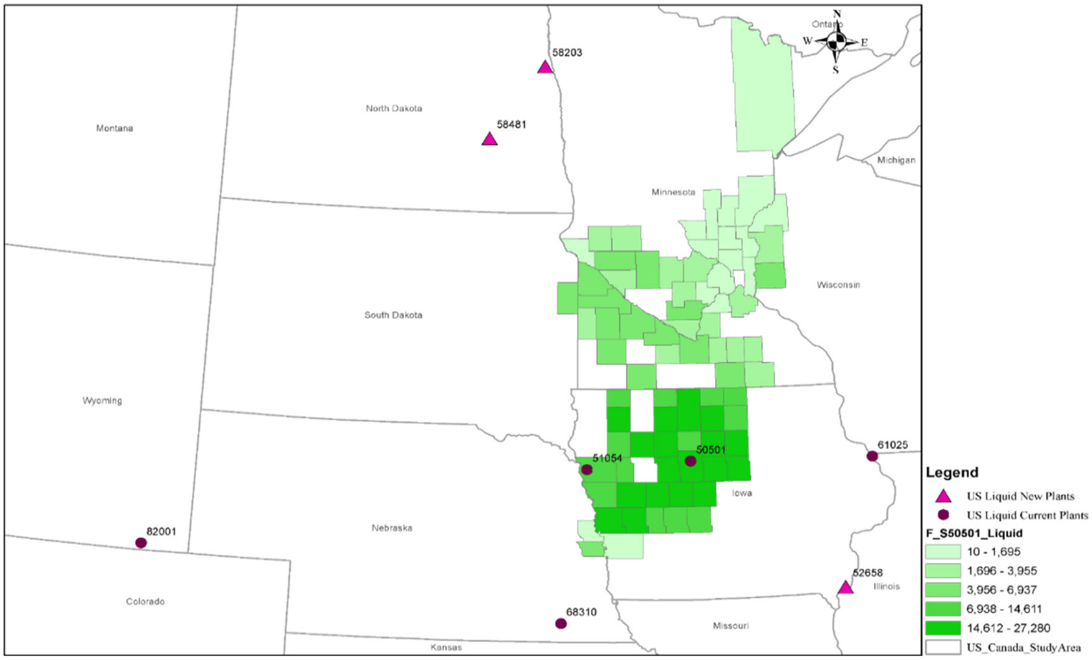

Figure E.9. Market boundaries for plant j=50501 for UAN (mean quantity of shipping for 1000 iterations) in stochastic linear future case sensitivity.

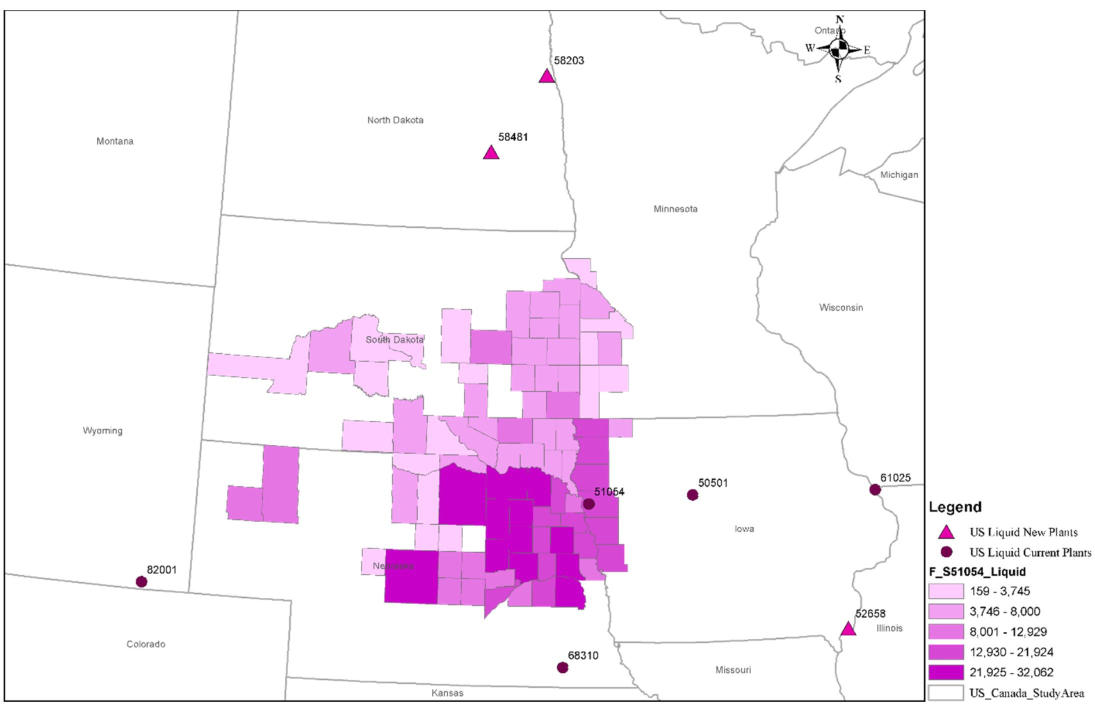

Figure E.10. Market boundaries for plant j=51054 for UAN (mean quantity of shipping for 1000 iterations) in stochastic linear future case sensitivity.

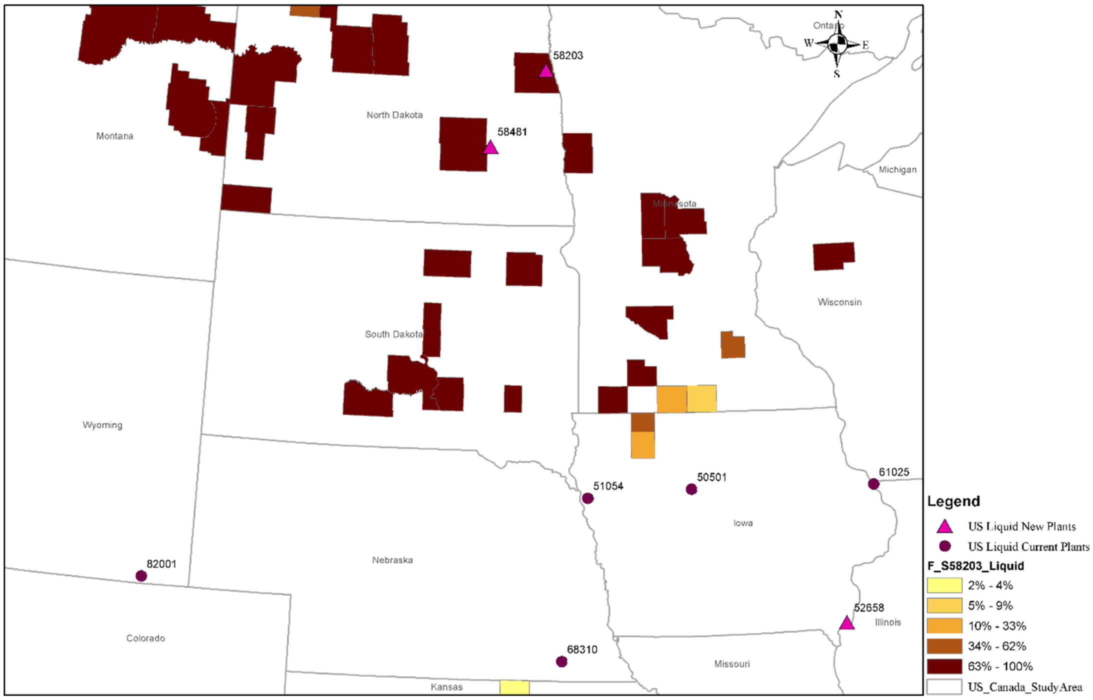

Figure E.11. Market boundaries for plant j=58203 for UAN (mean quantity of shipping for 1000 iterations) in stochastic linear future case sensitivity.

E.5. CDFs by Nodes in Stochastic Linear Future Case 2018 Sensitivity

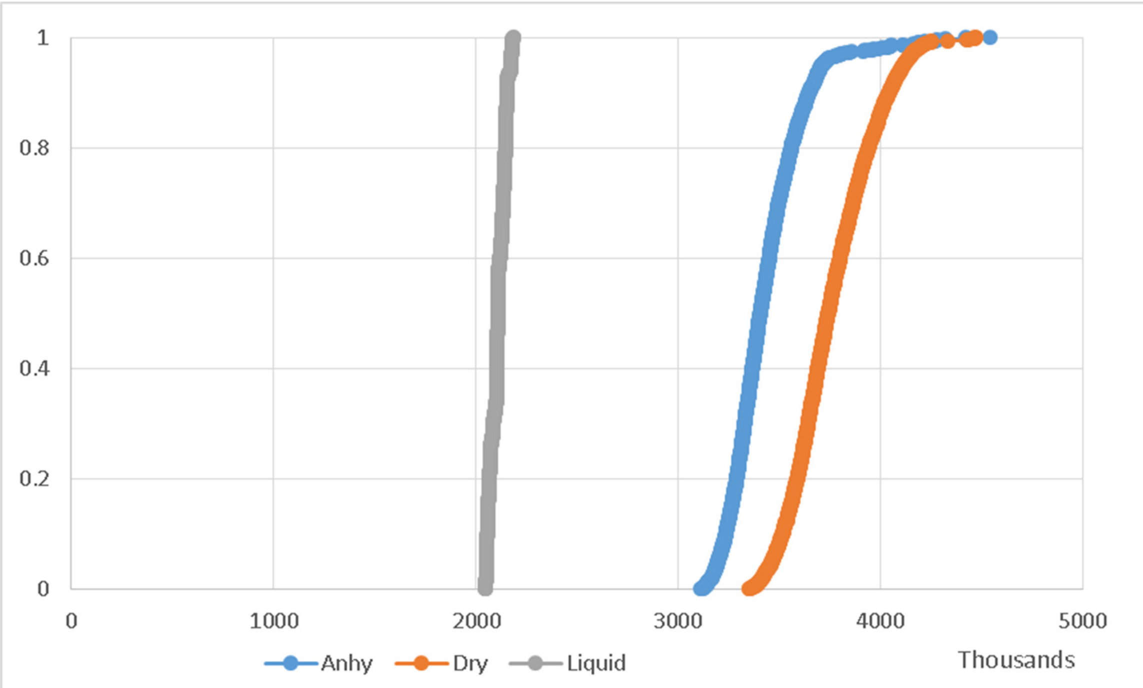

Figure E.12. Cumulative probability for 2200374 (New Orleans, LA) in stochastic linear future case sensitivity.

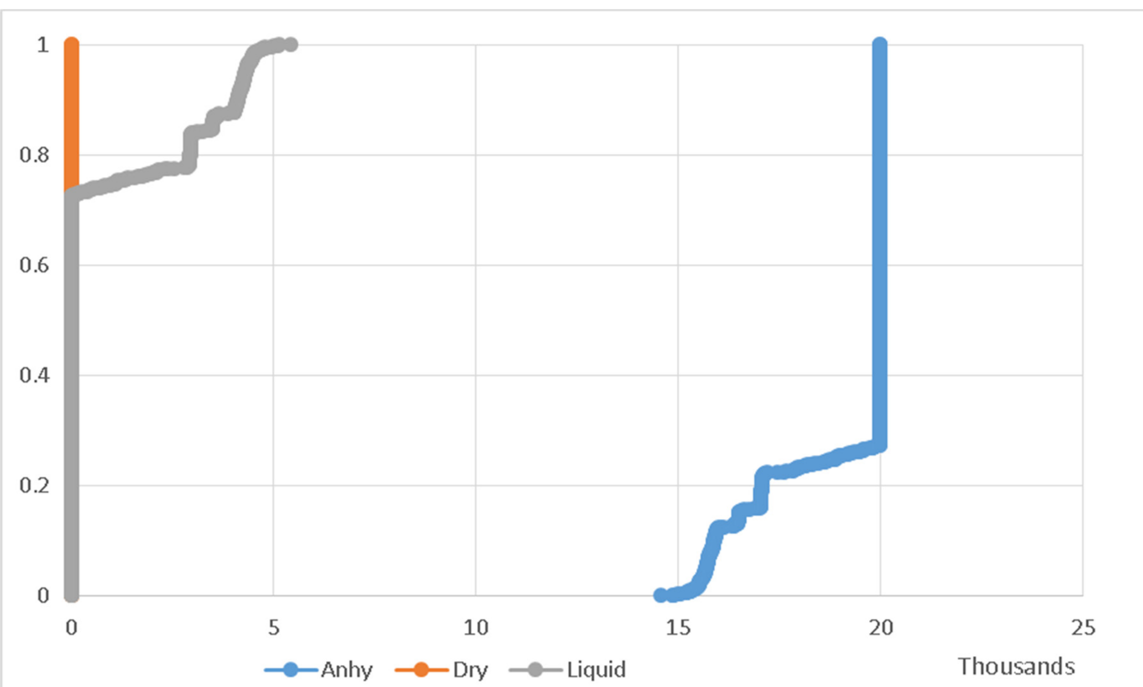

Figure E.13. Cumulative probability for 2700093 (Minneapolis, MN) in stochastic linear future case sensitivity.

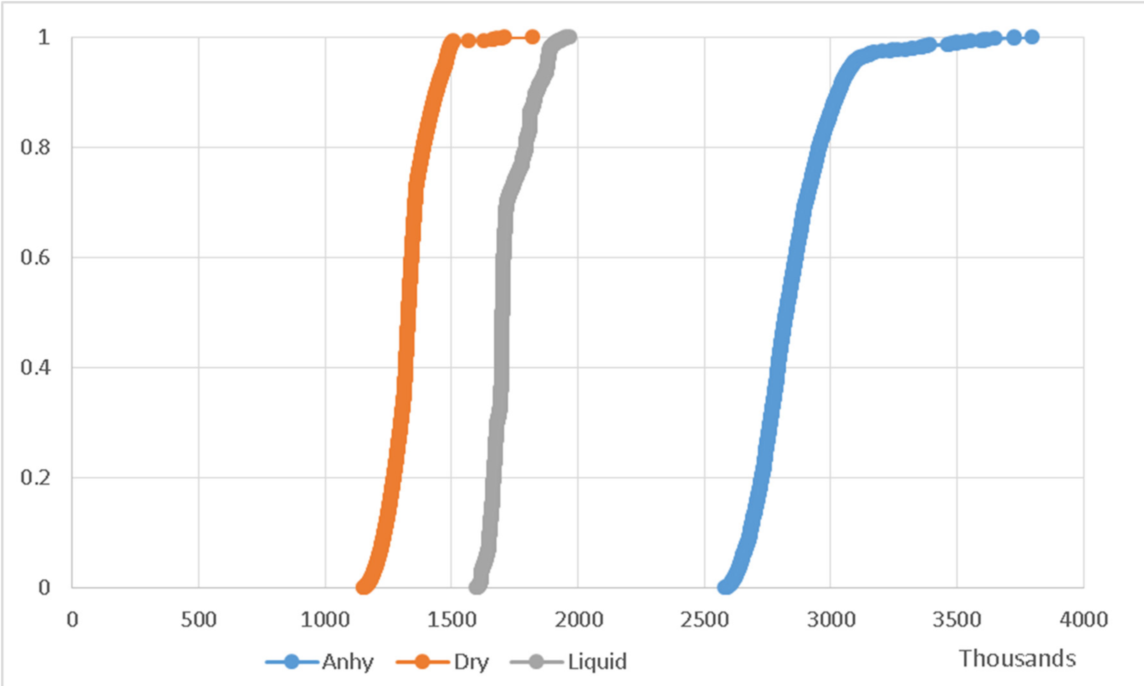

Figure E.14. Cumulative probability for 2900310 (St Louis, MO) in stochastic linear future case sensitivity.

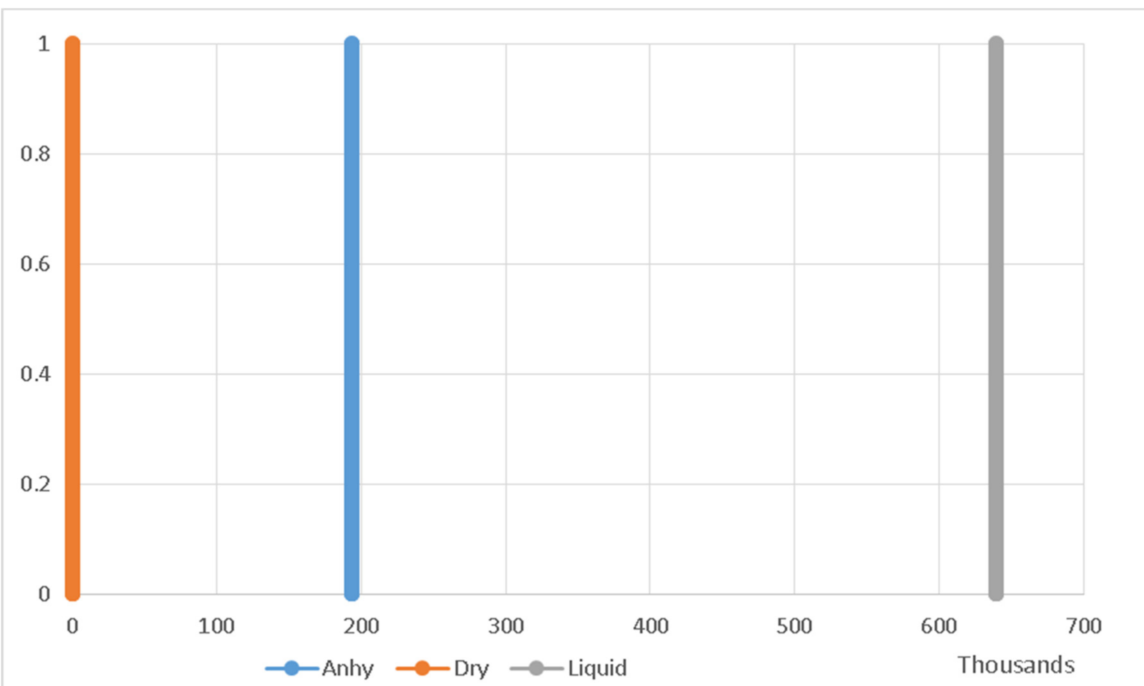

Figure E.15. Cumulative probability for 30901 (Augusta, GA) in stochastic linear future case sensitivity.

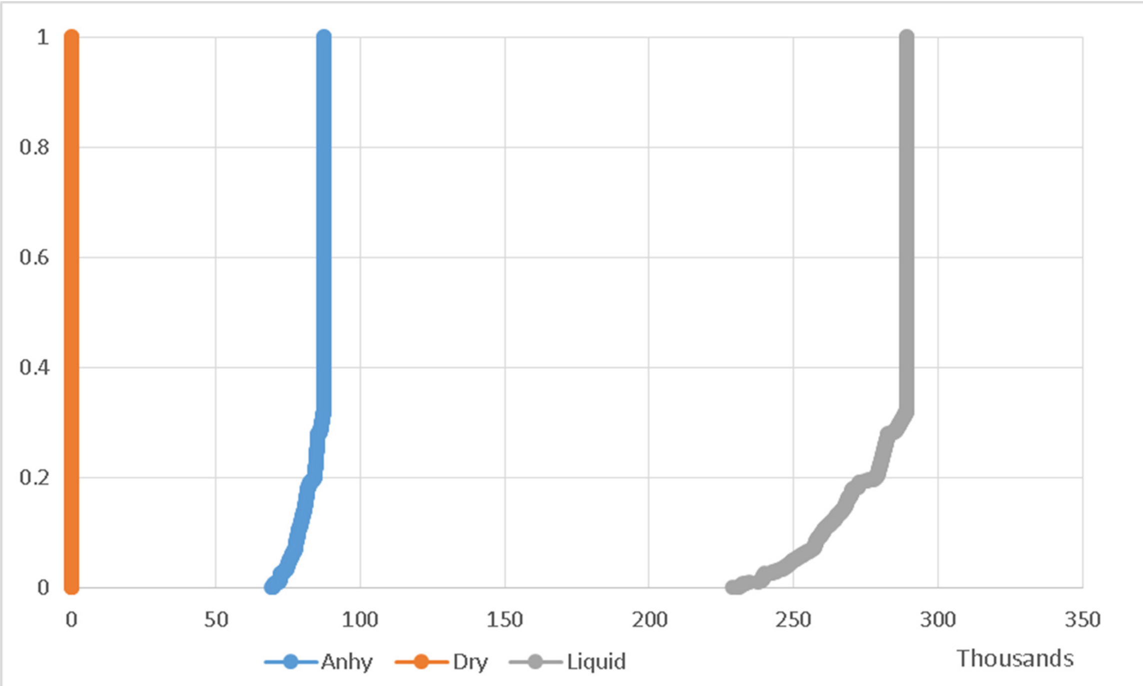

Figure E.16. Cumulative probability for 35616 (Cherokee, AL) in stochastic linear future case sensitivity.

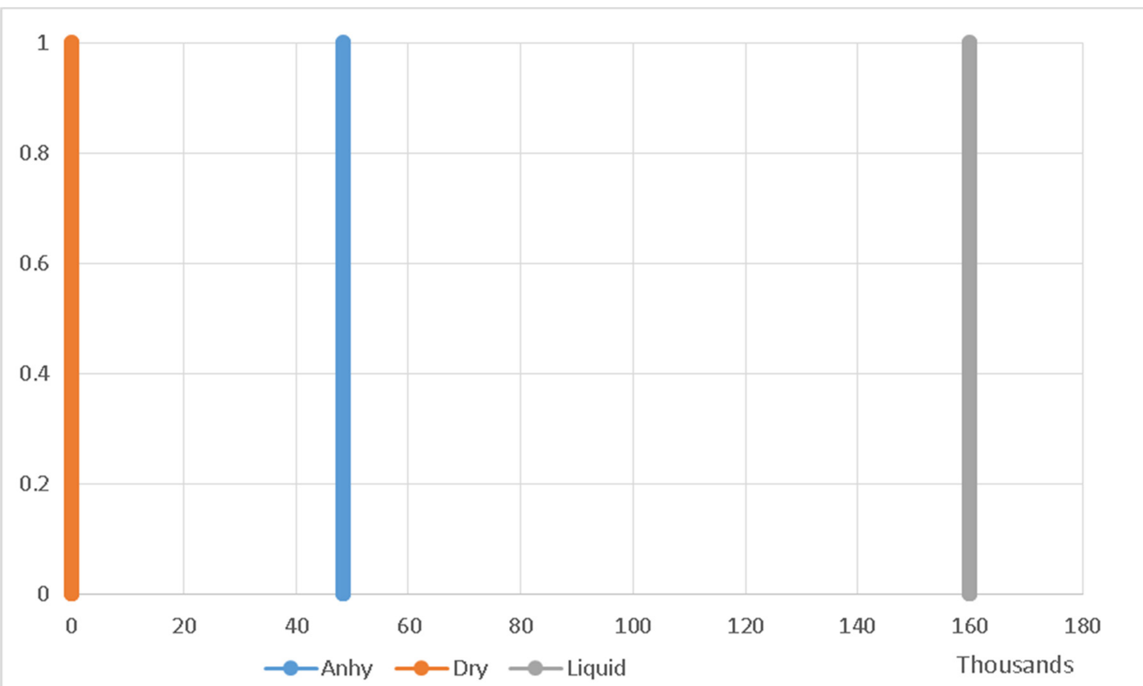

Figure E.17. Cumulative probability for 39194 (Yazoo City, MS) in stochastic linear future case sensitivity.

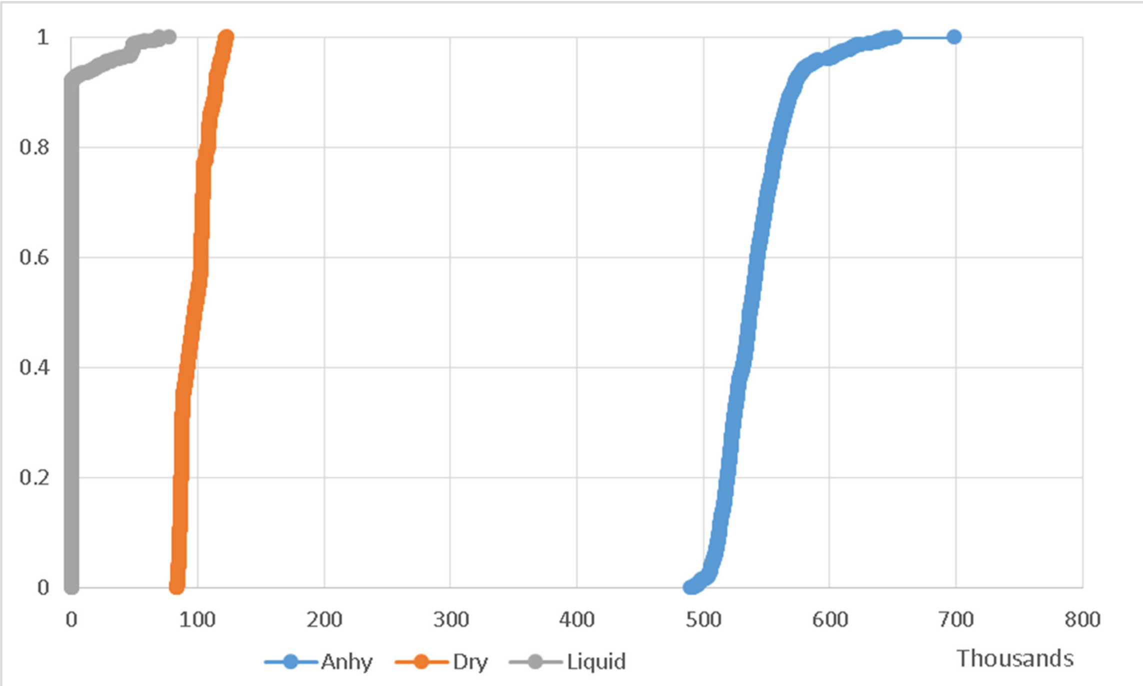

Figure E.18. Cumulative probability for 4000131 (Catoosa, OK) in stochastic linear future case sensitivity.

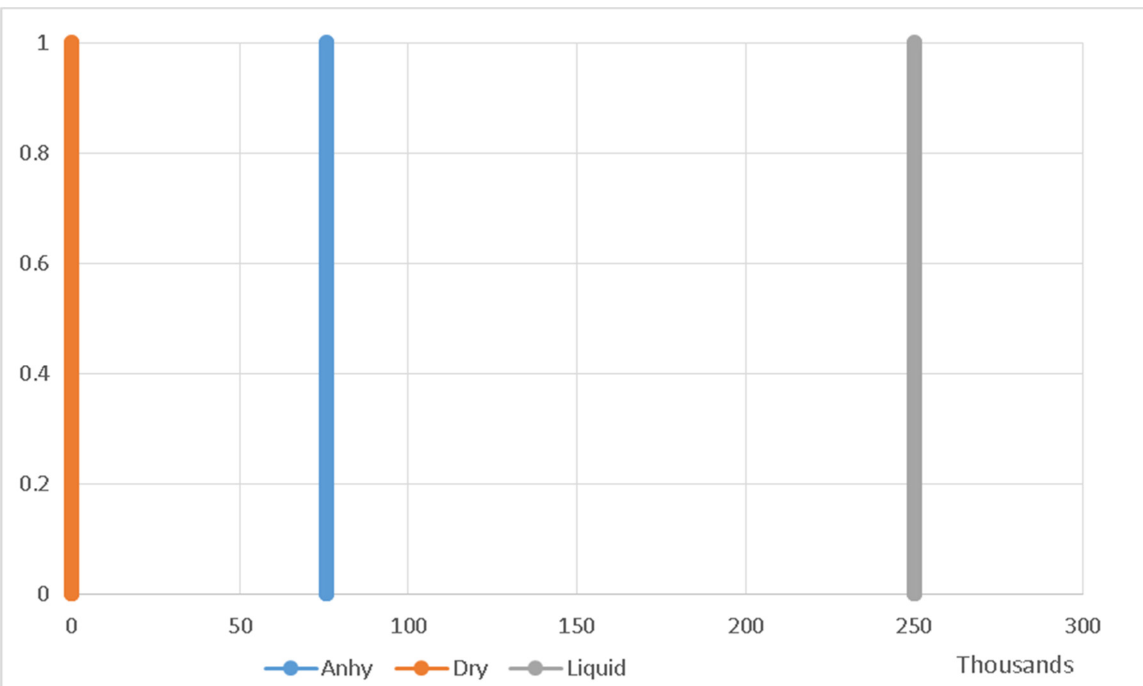

Figure E.19. Cumulative probability for 45804 (Lima, OH) in stochastic linear future case sensitivity.

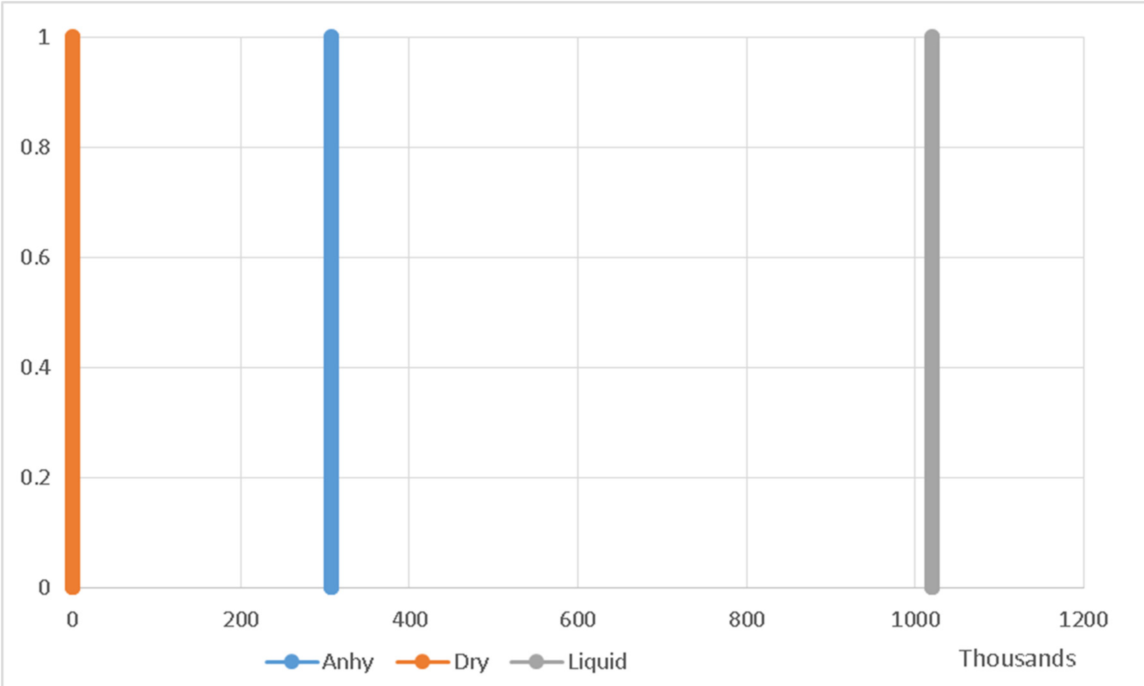

Figure E.20. Cumulative probability for 47635 (Rockport, IN) in stochastic linear future case sensitivity.

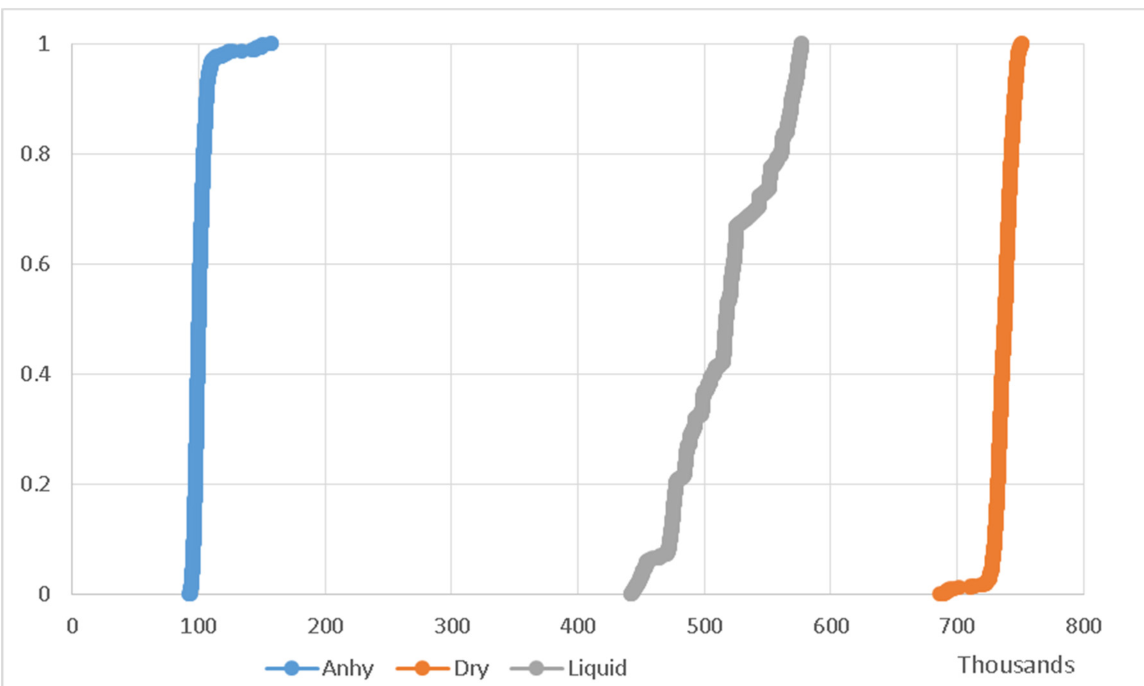

Figure E.21. Cumulative probability for 4800608 (Galveston, TX) in stochastic linear future case sensitivity.

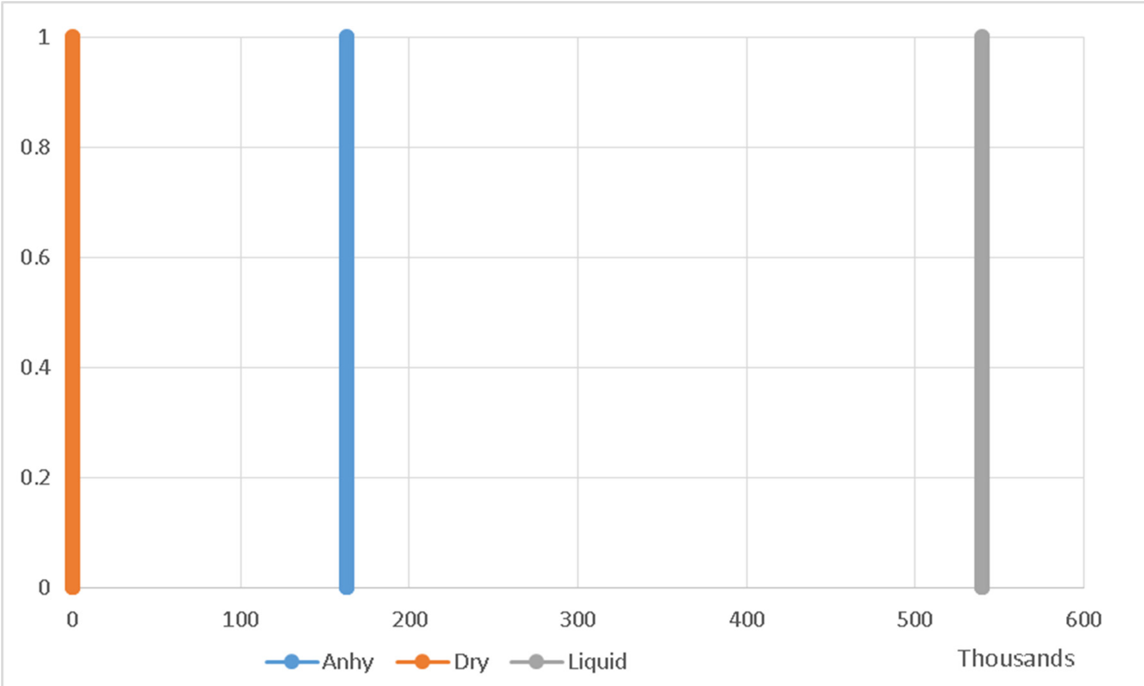

Figure E.22. Cumulative probability for 50501 (Fort Dodge, IA) in stochastic linear future case sensitivity.

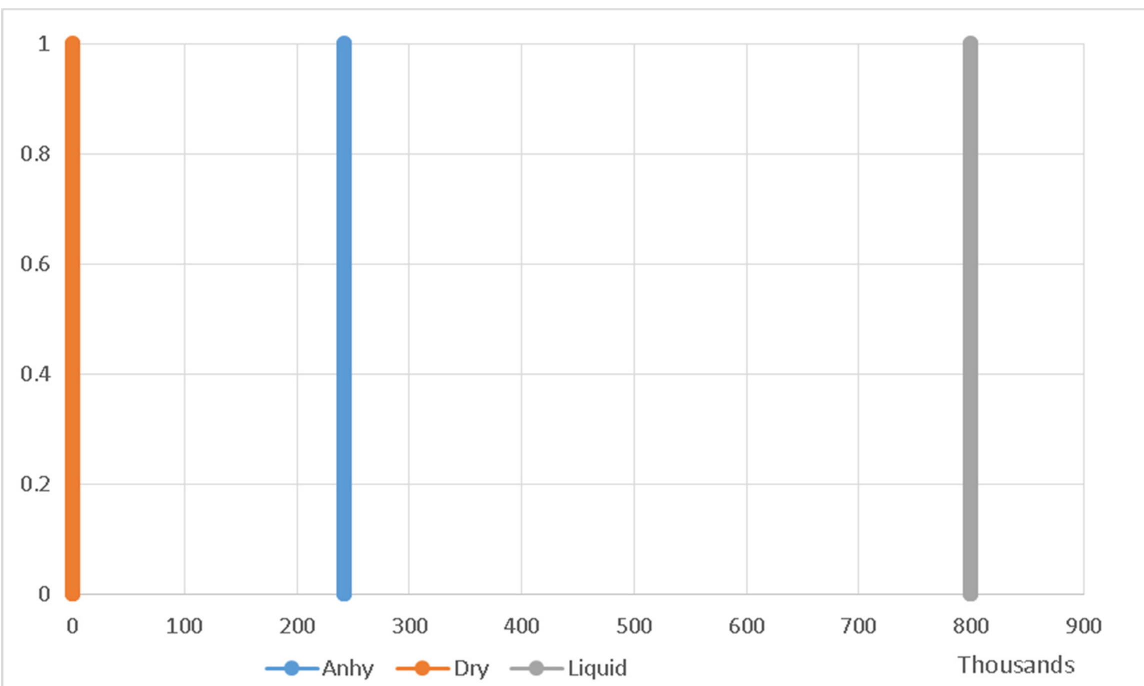

Figure E.23. Cumulative probability for 51054 (Port Neal, IA) in stochastic linear future case sensitivity.

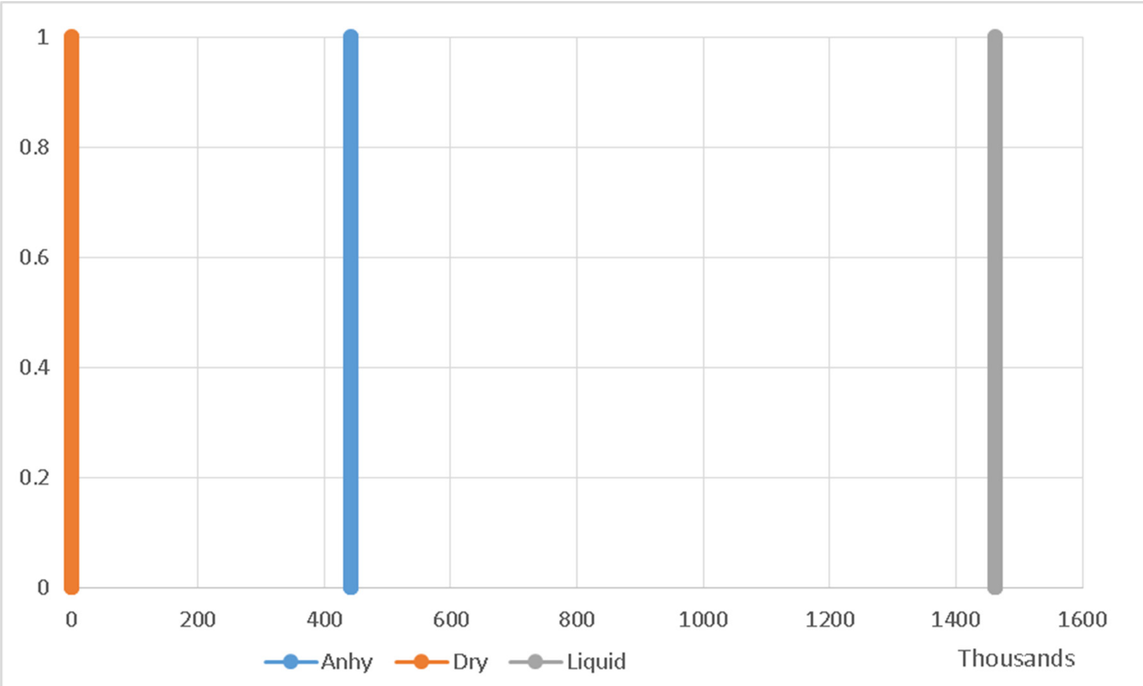

Figure E.24. Cumulative probability for 52658 (Wever, IA) in stochastic linear future case sensitivity.

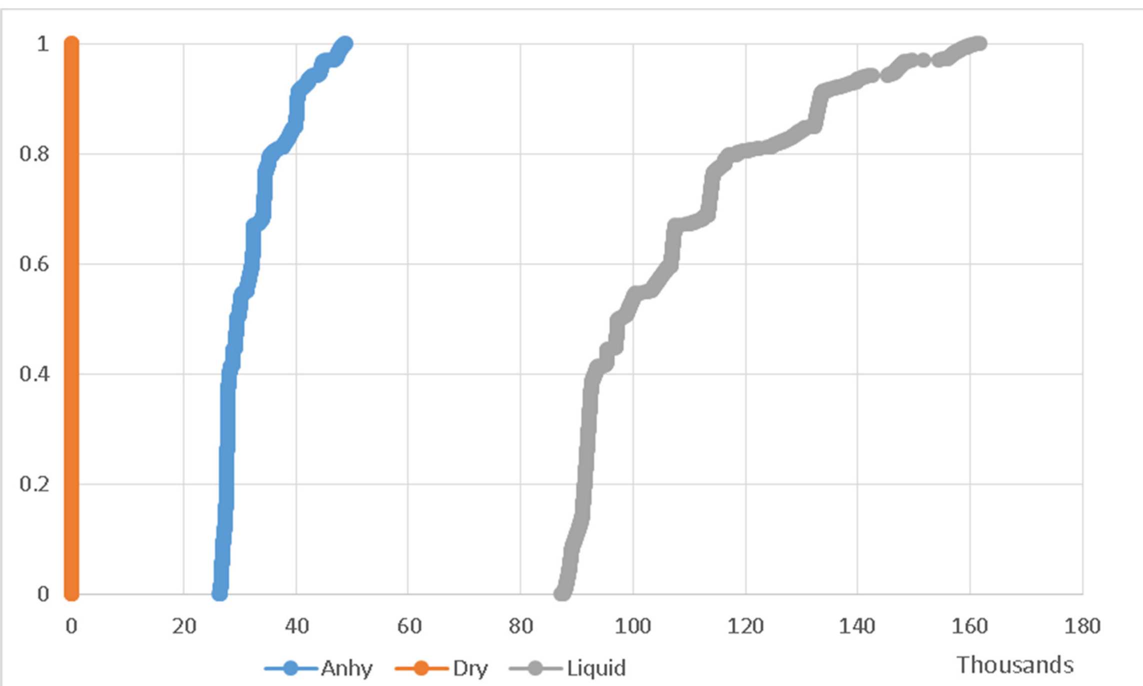

Figure E.25. Cumulative probability for 58203 (Grand Forks, ND) in stochastic linear future case sensitivity.

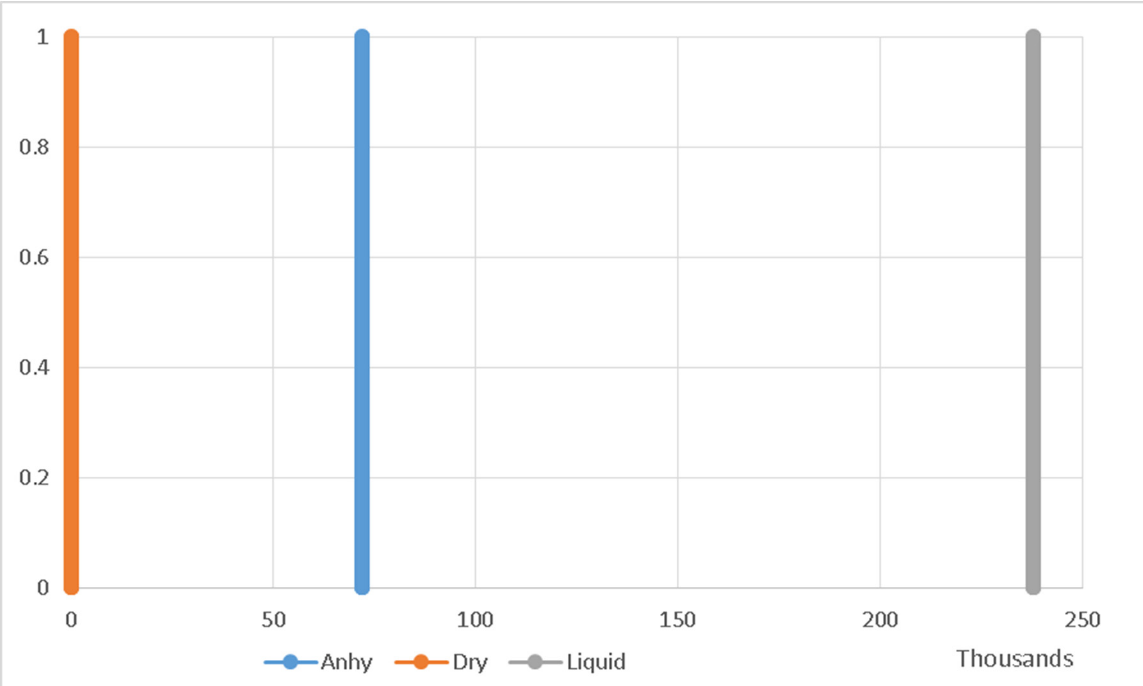

Figure E.26. Cumulative probability for 58481 (Jamestown, ND) in stochastic linear future case sensitivity.

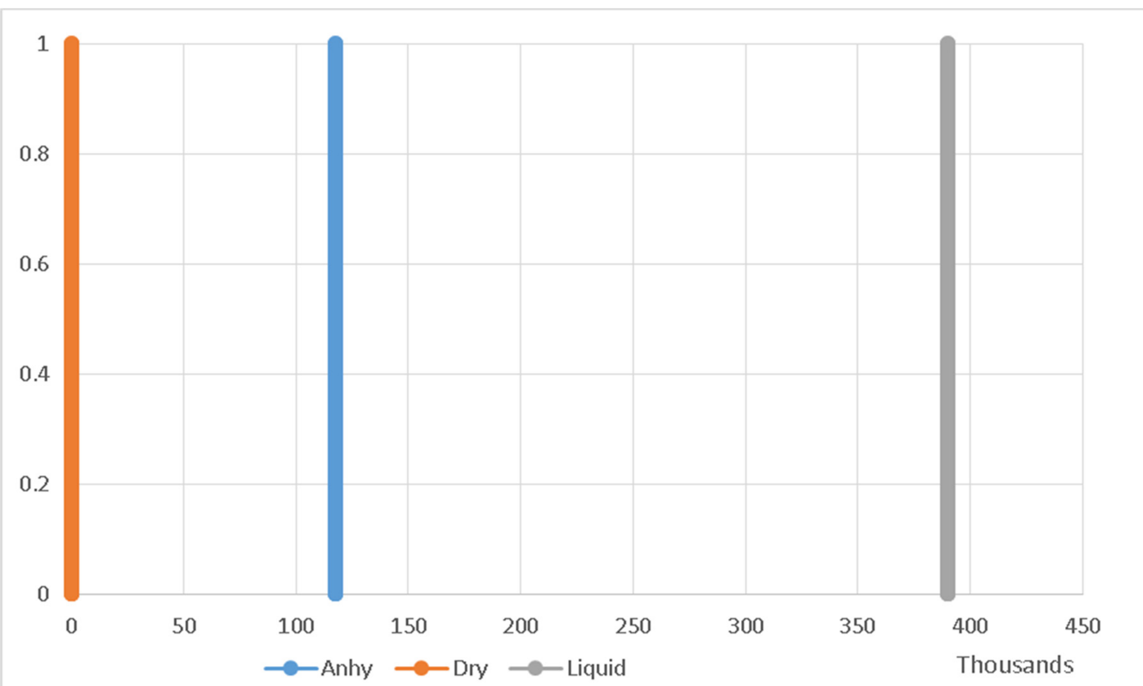

Figure E.27. Cumulative probability for 61025 (East Dubuque, IL) in stochastic linear future case sensitivity.

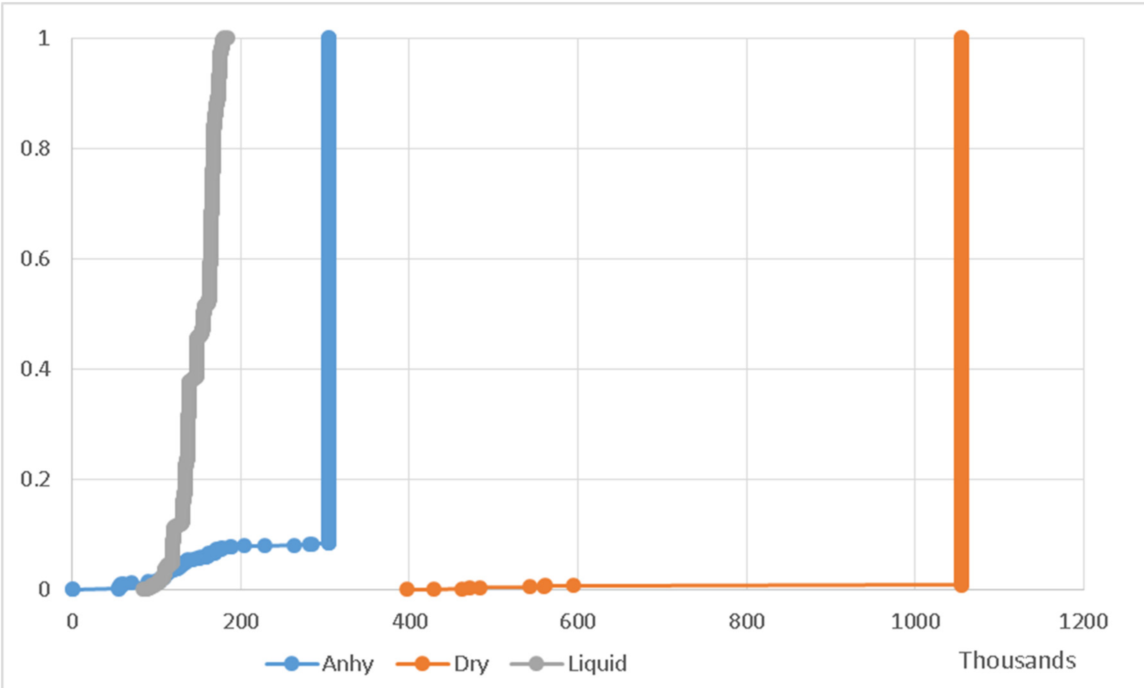

Figure E.28. Cumulative probability for 612 (Medicine Hat, AB) in stochastic linear future case sensitivity.

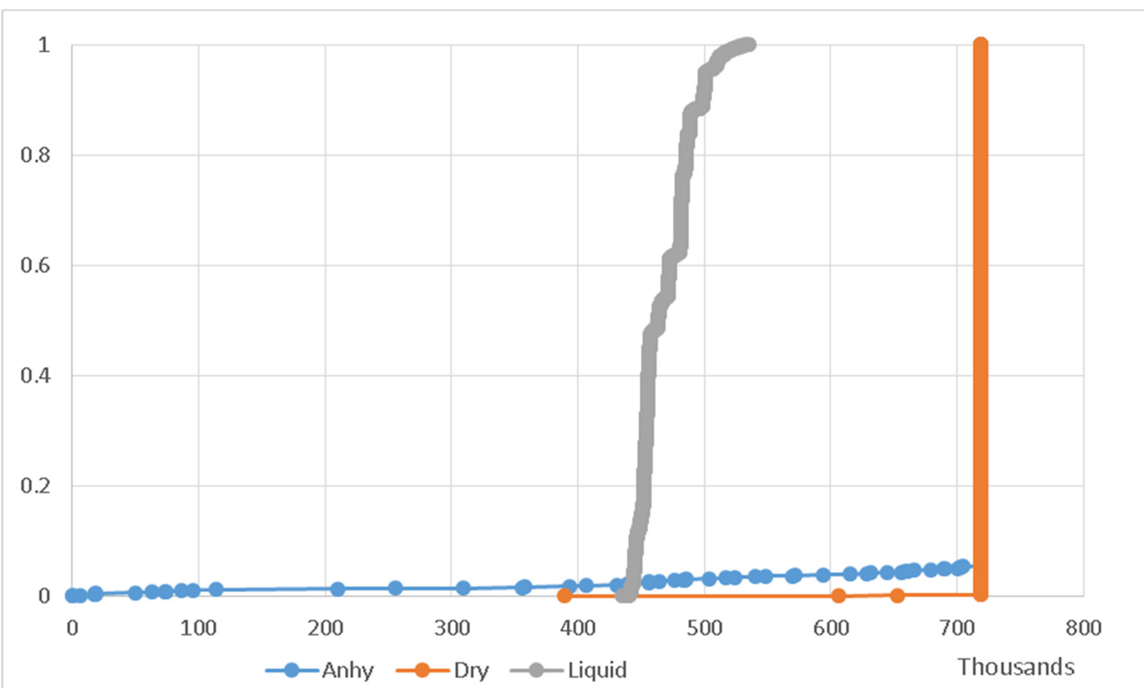

Figure E.29. Cumulative probability for 644 (Belle Plaine, SK) in stochastic linear future case sensitivity.

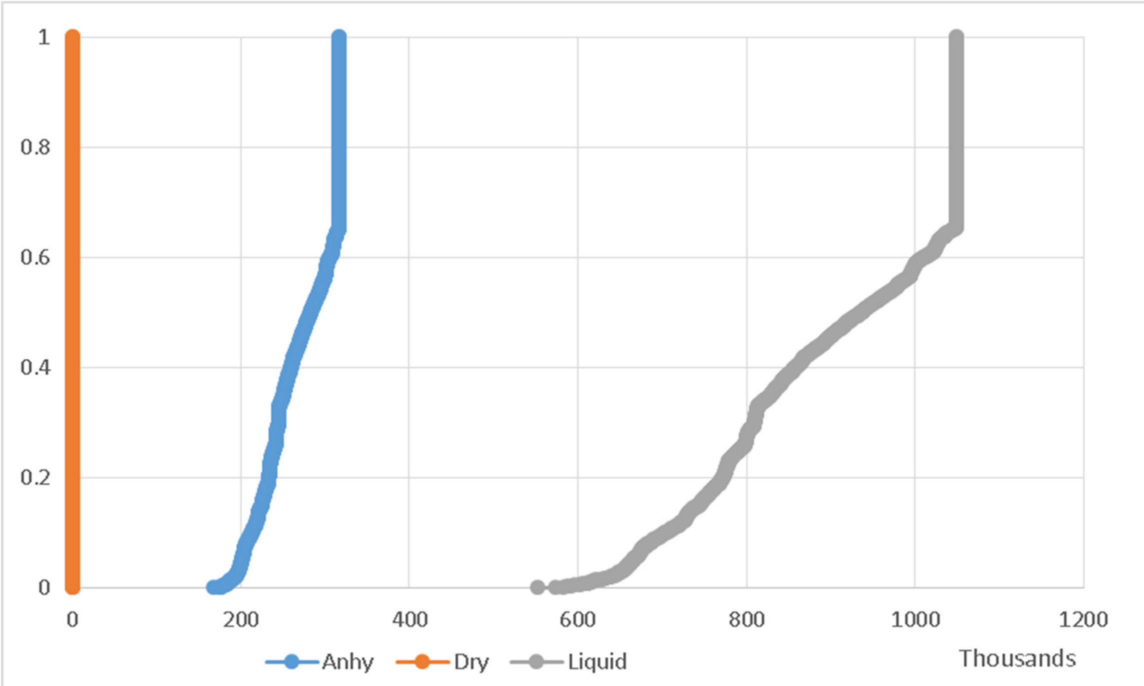

Figure E.30. Cumulative probability for 67337 (Coffeyville, KS) in stochastic linear future case sensitivity.

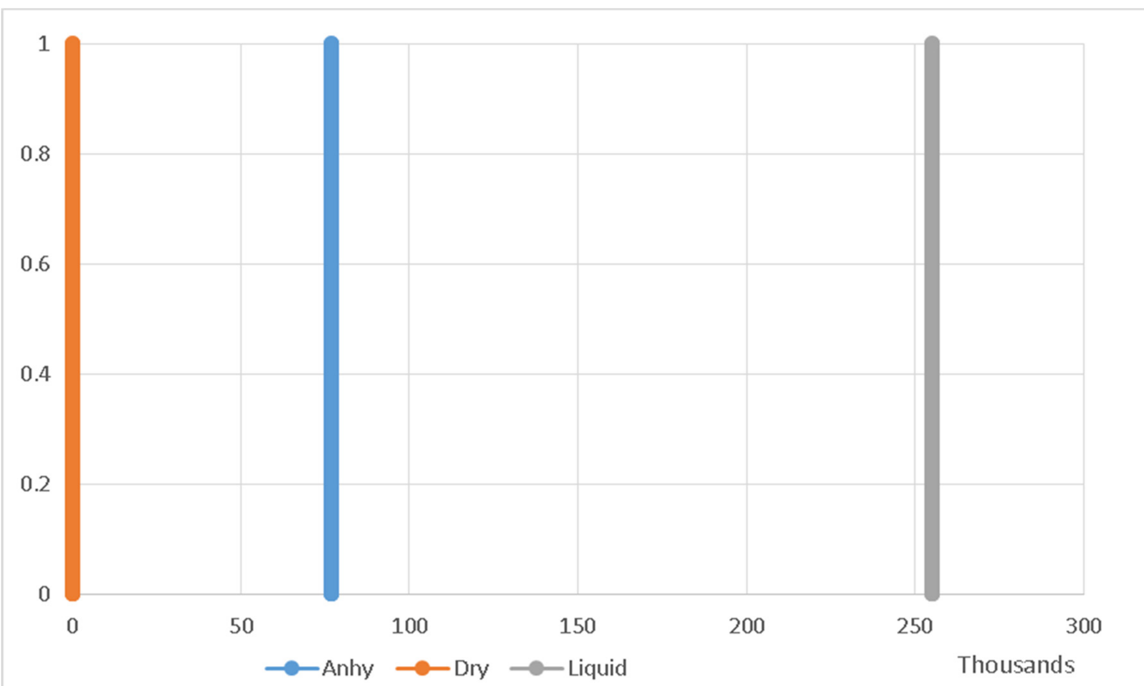

Figure E.31. Cumulative probability for 67801 (Dodge City, KS) in stochastic linear future case sensitivity.

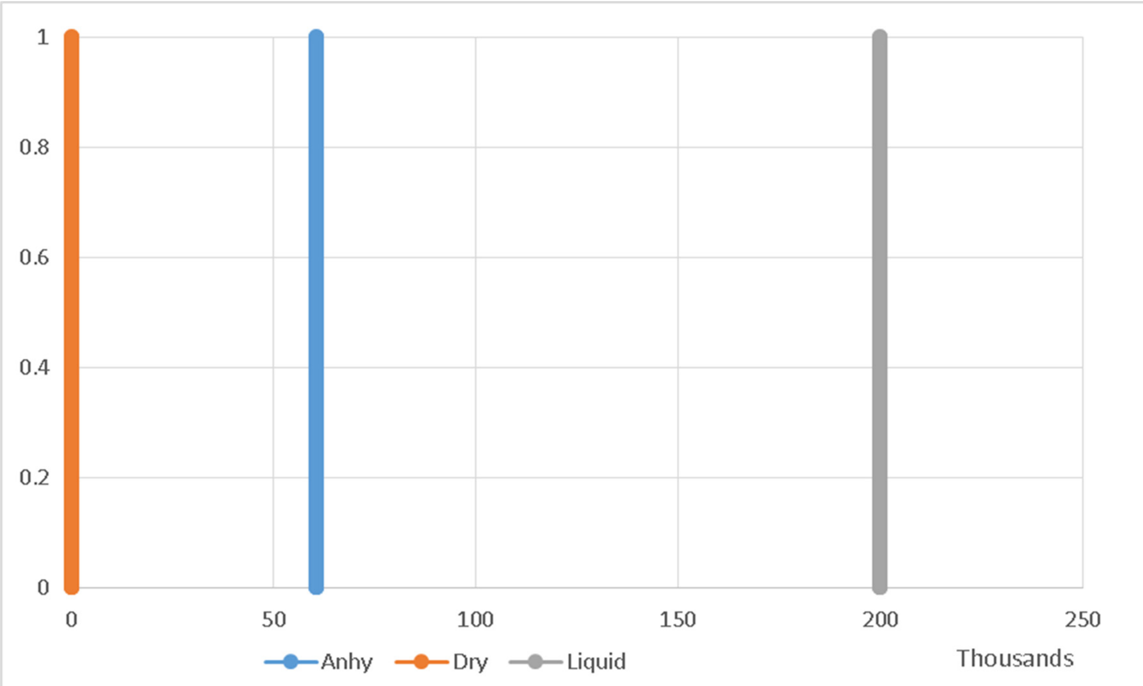

Figure E.32. Cumulative probability for 68310 (Beatrice, NE) in stochastic linear future case sensitivity.

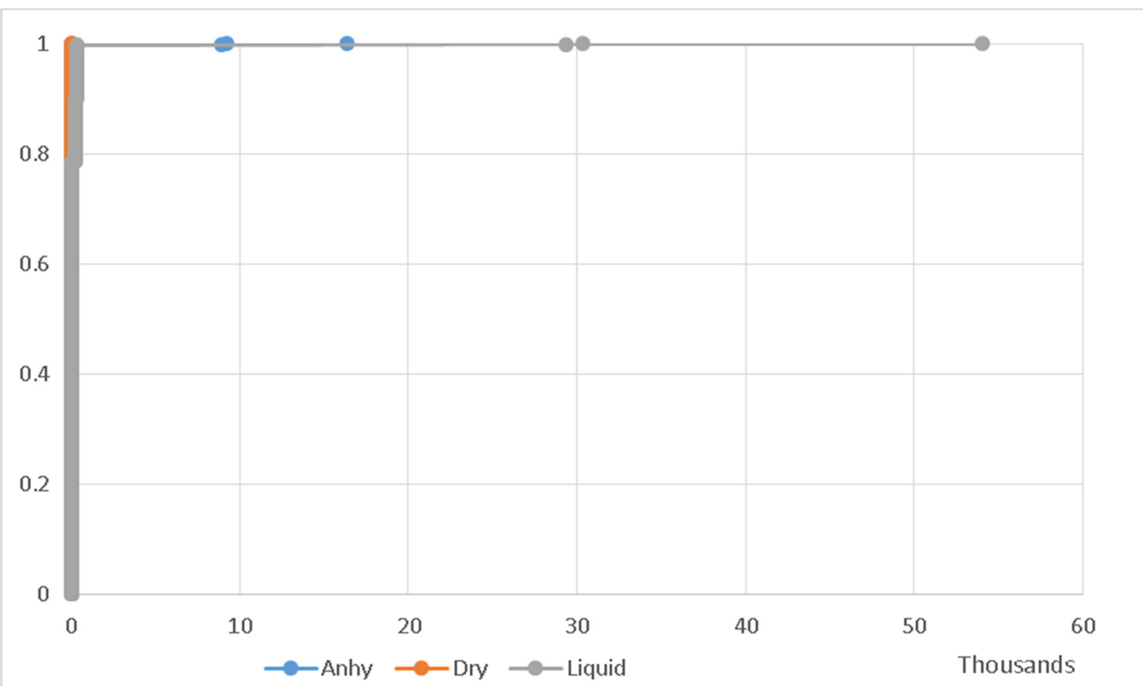

Figure E.33. Cumulative probability for 70346 (Donaldsonville, LA) in stochastic linear future case sensitivity.

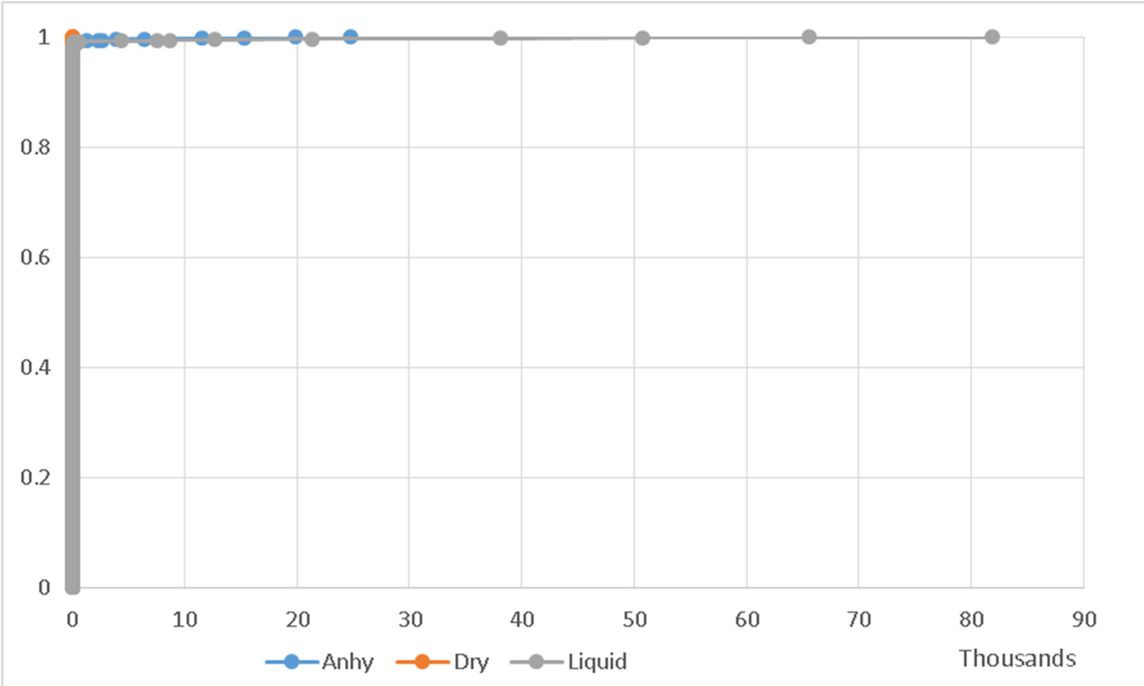

Figure E.34. Cumulative probability for 70734 (Geismar, LA) in stochastic linear future case sensitivity.

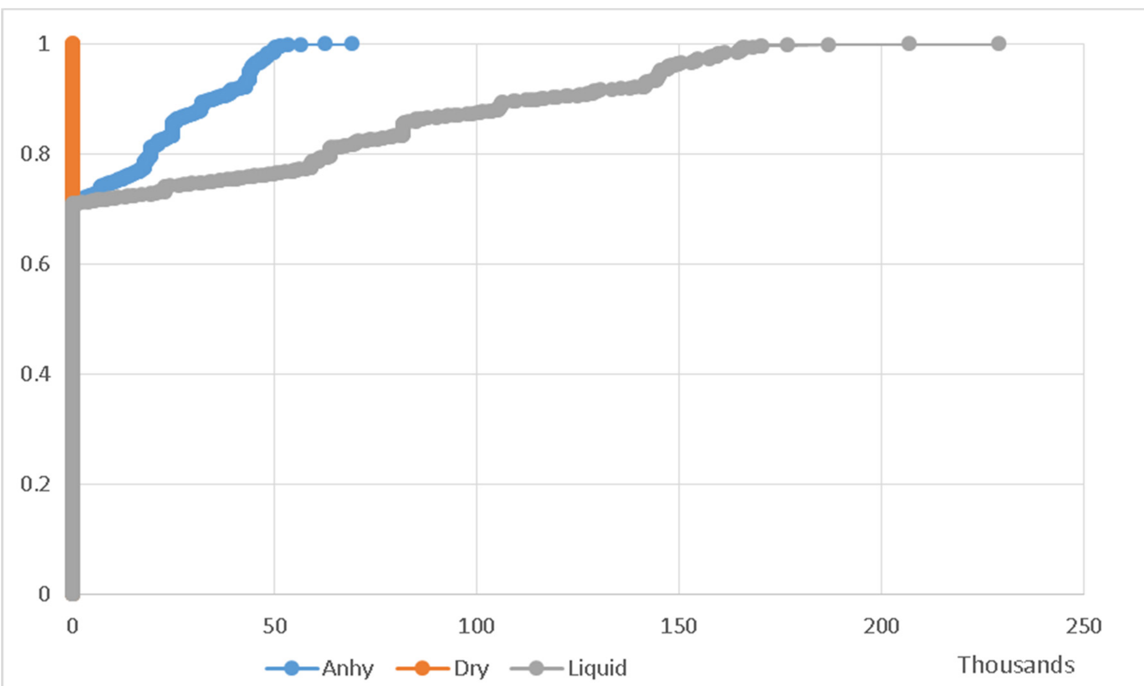

Figure E.35. Cumulative probability for 70765 (Iberville, LA) in stochastic linear future case sensitivity.

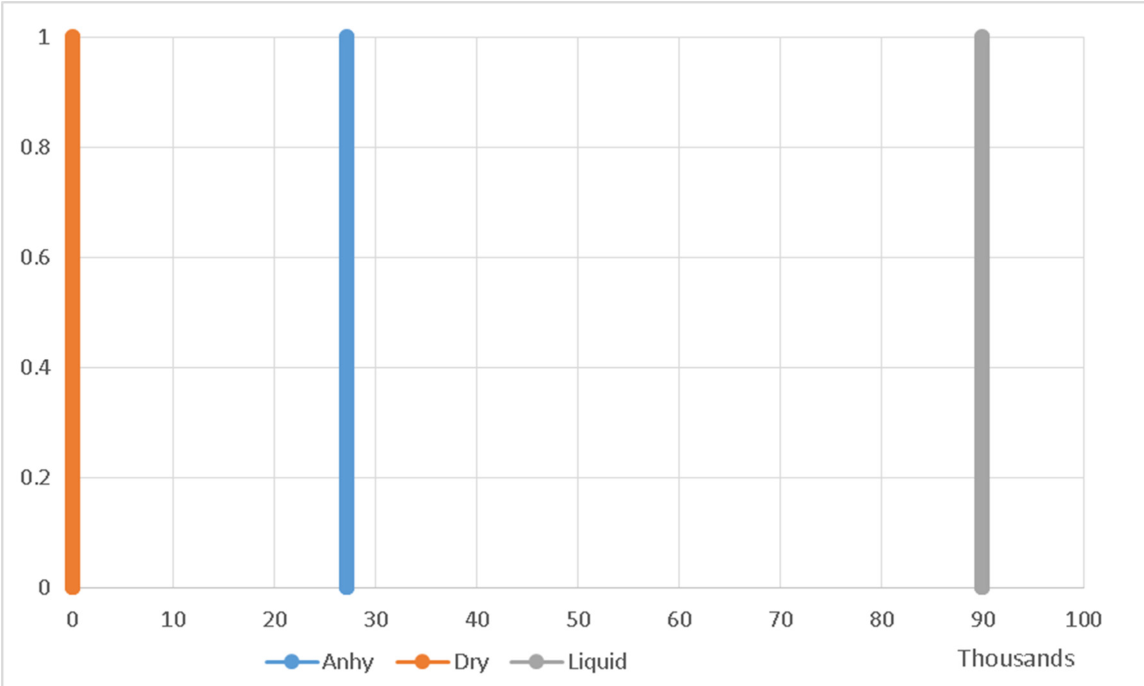

Figure E.36. Cumulative probability for 73701 (Enid, OK) in stochastic linear future case sensitivity.

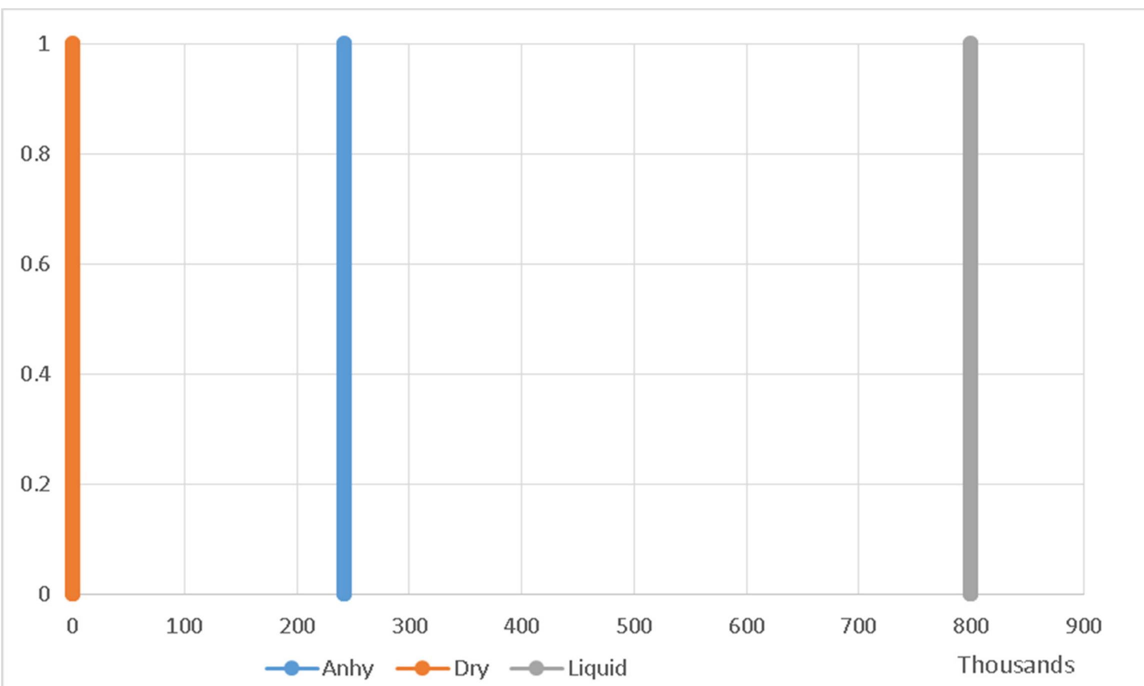

Figure E.37. Cumulative probability for 73801 (Woodward, OK) in stochastic linear future case sensitivity.

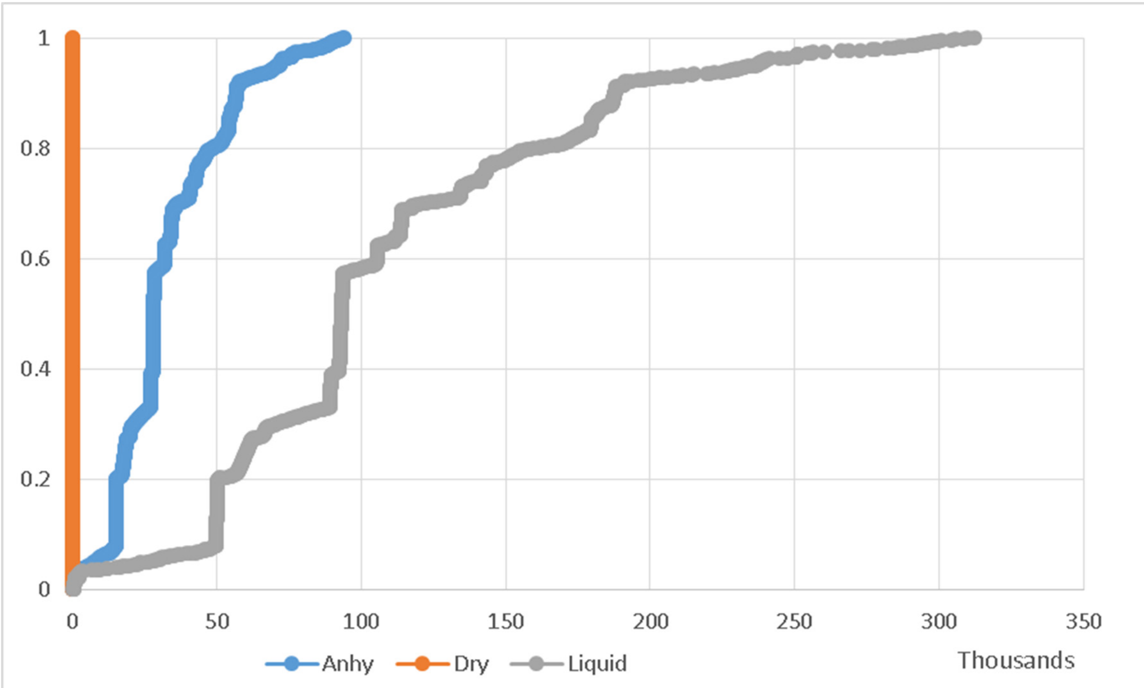

Figure E.38. Cumulative probability for 74019 (Verdigris, OK) in stochastic linear future case sensitivity.

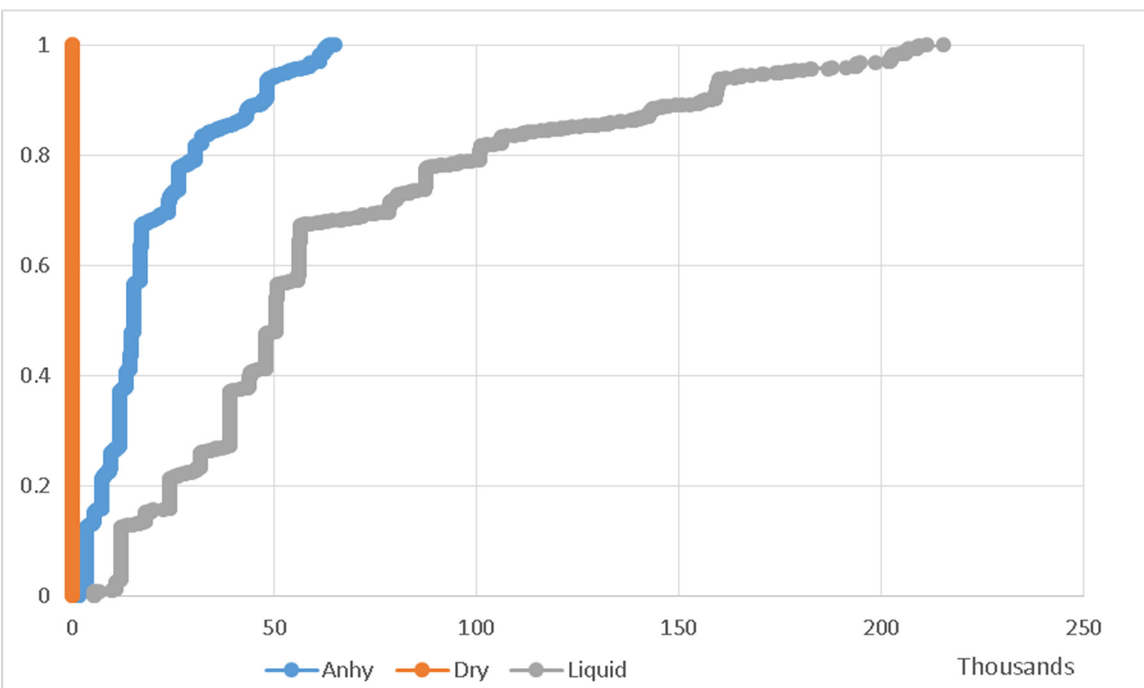

Figure E.39. Cumulative probability for 74362 (Pryor OK) in stochastic linear future case sensitivity.

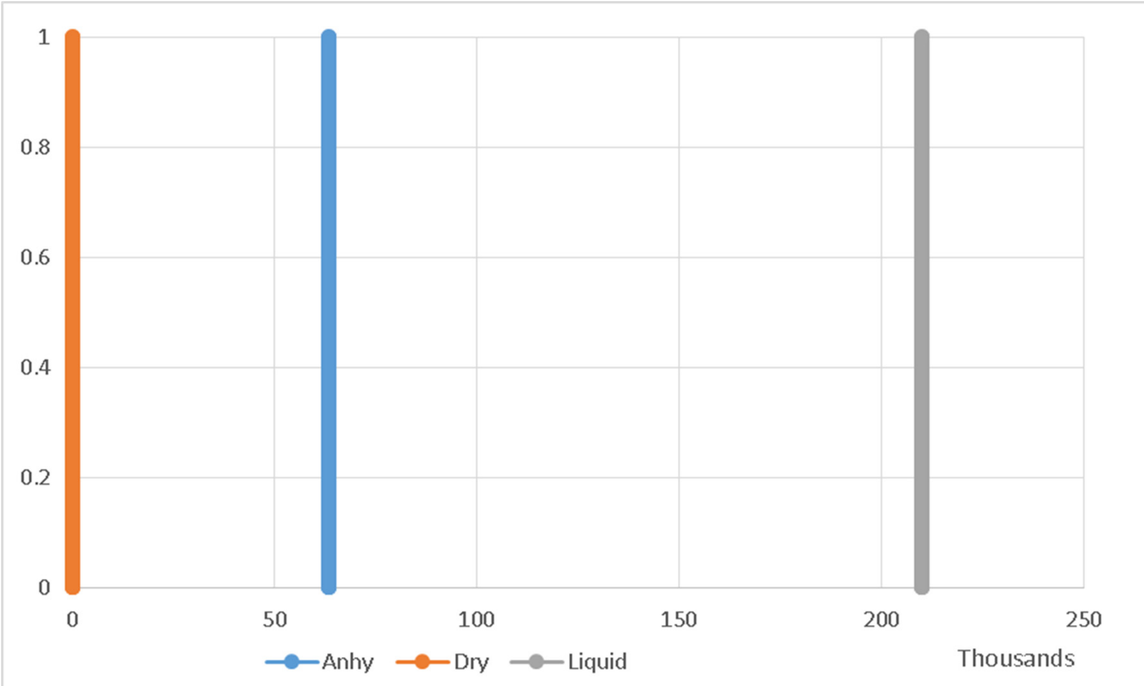

Figure E.40. Cumulative probability for 82001 (Cheyenne, WY) in stochastic linear future case sensitivity.

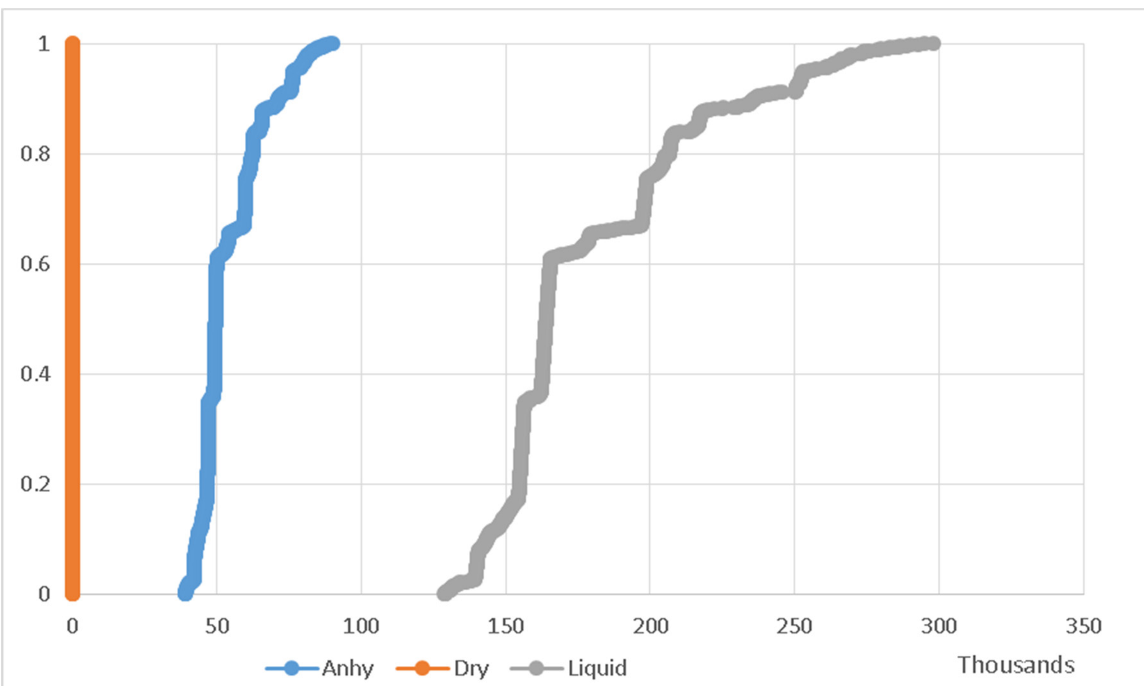

Figure E.41. Cumulative probability for 83211 (American Falls, ID) in stochastic linear future case sensitivity.

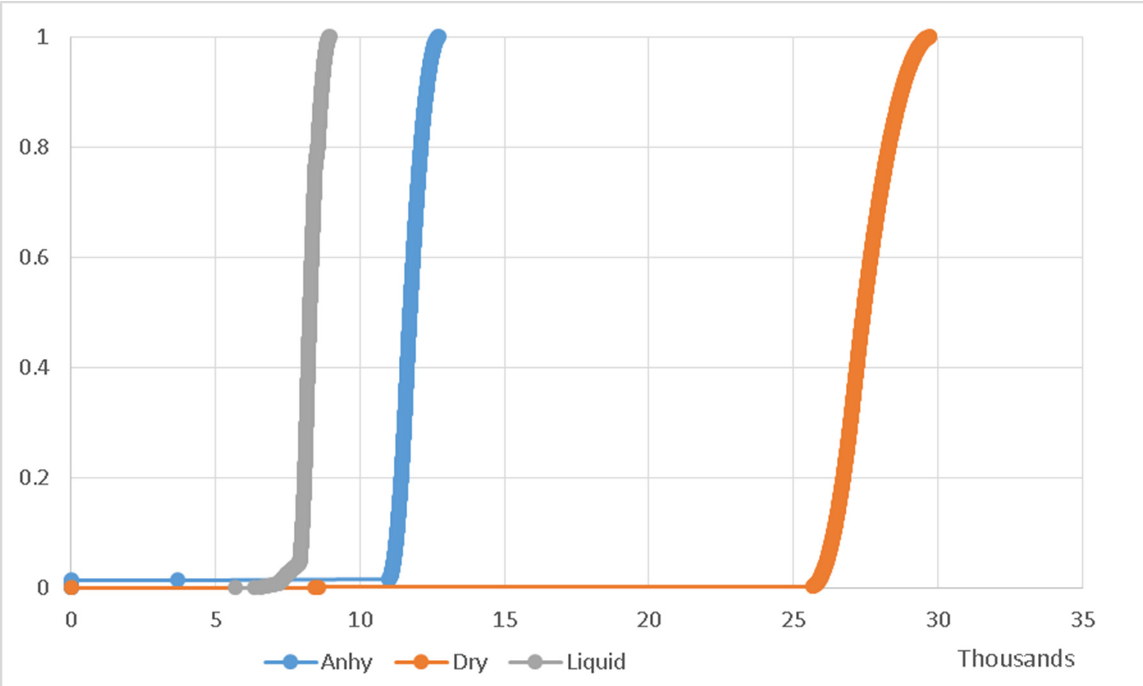

Figure E.42. Cumulative probability for 8800451 (POE: Emerson, ND) in stochastic linear future case sensitivity.

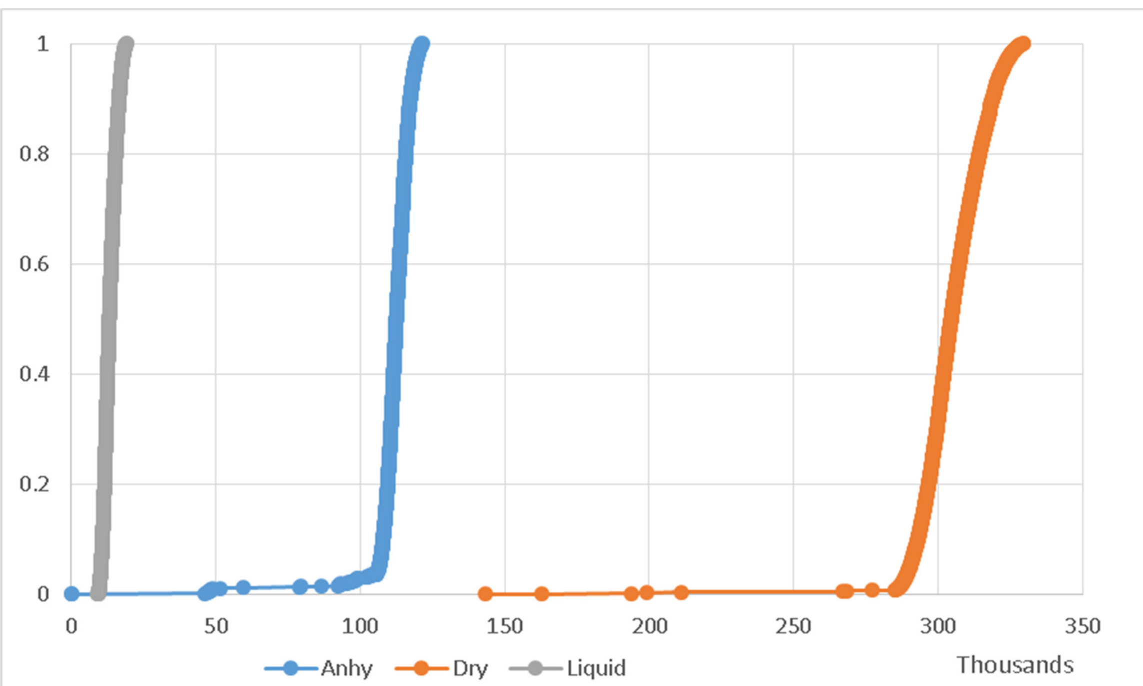

Figure E.43. Cumulative probability for 9163 (POE: Kingsgate, ID) in stochastic linear future case sensitivity.

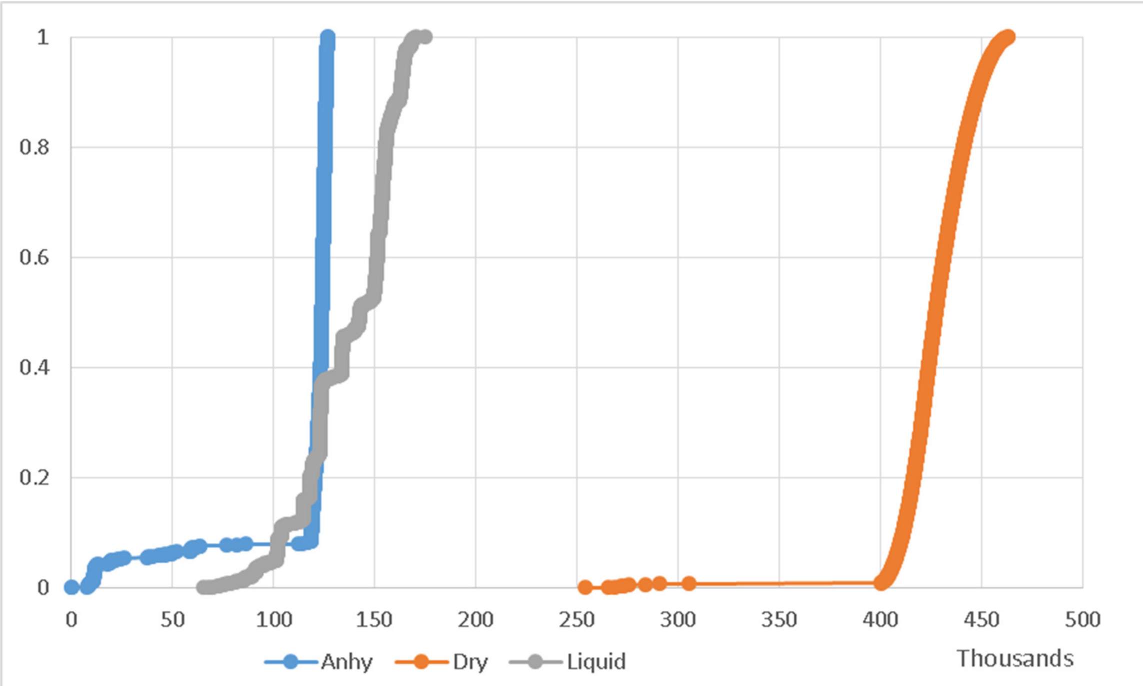

Figure E.44. Cumulative probability for 9303 (POE: Coutts, MT) in stochastic linear future case sensitivity.

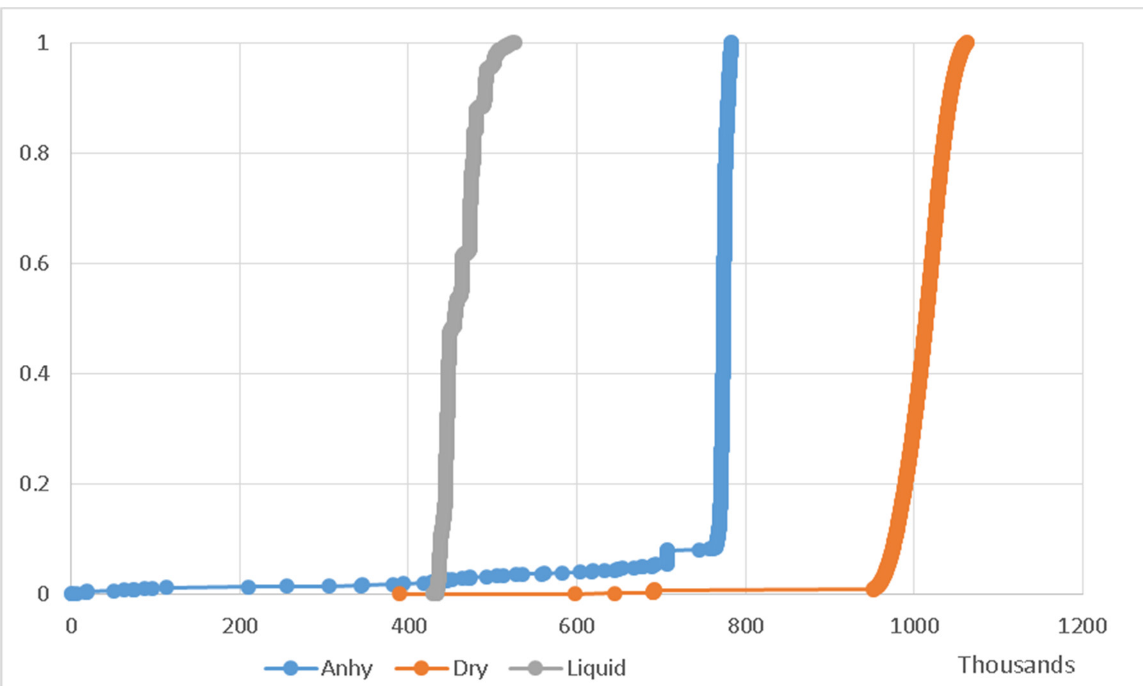

Figure E.45. Cumulative probability for 9384 (POE: Portal, ND) in stochastic linear future case sensitivity.

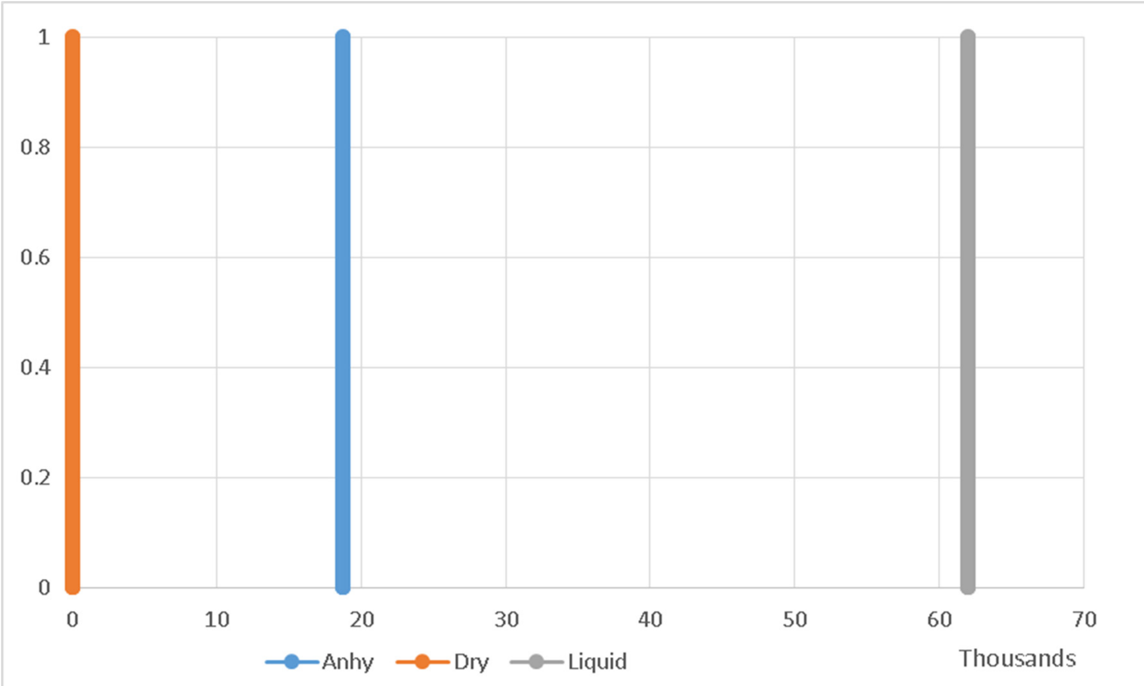

Figure E.46. Cumulative probability for 97051 (St. Helens, OR) in stochastic linear future case sensitivity.

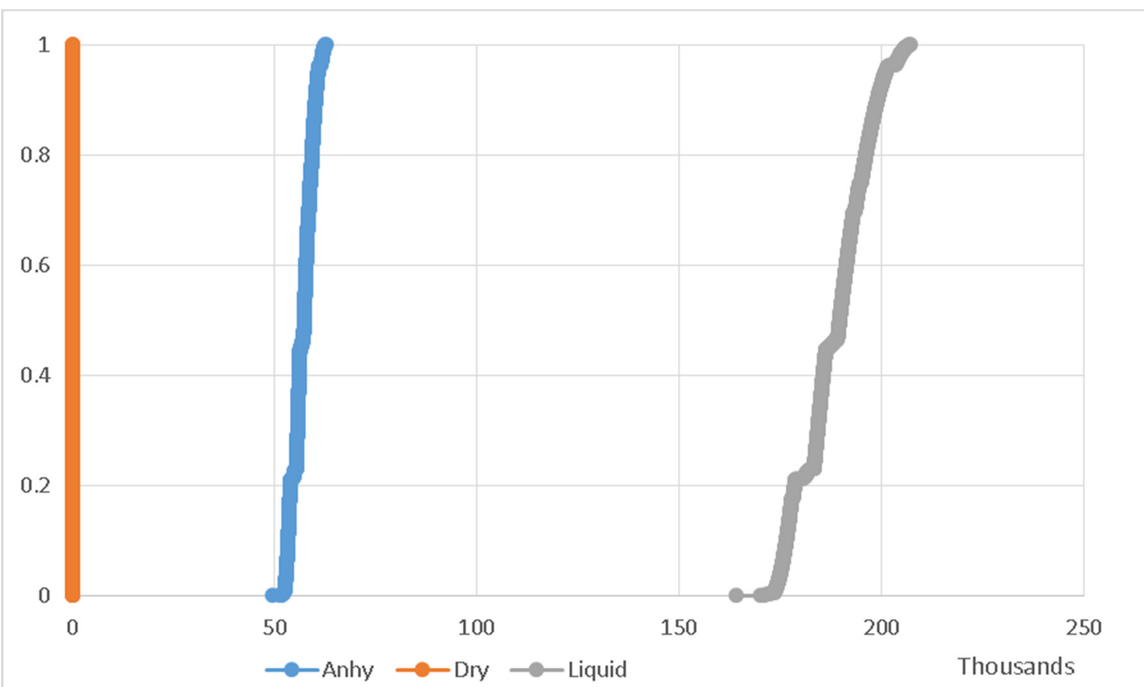

Figure E.47. Cumulative probability for 99337 (Kennewick, WA) in stochastic linear future case sensitivity.

APPENDIX F. STOCHASTIC MIXED-INTEGER FUTURE CASE 2018 SENSITIVITY

F.1. Distribution of Origination Destination Matrix for Stochastic Mixed-Integer Future Case 2018 Sensitivity

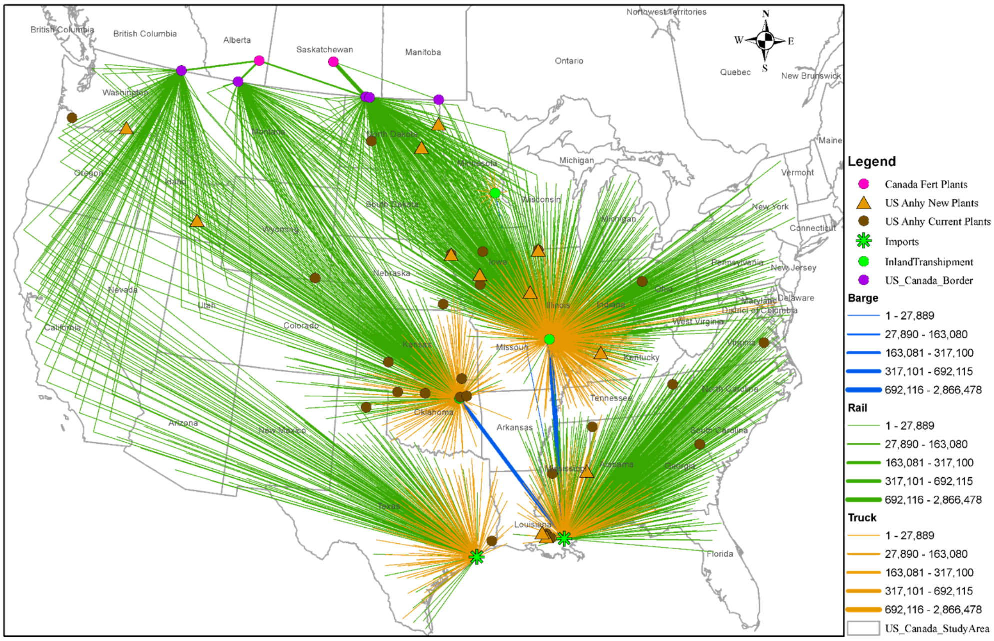

Figure F.1. Structure of supply chain for anhydrous ammonia for future case mixed-integer sensitivity by mode (Rail=Green, Truck=Orange, Barge=Blue).

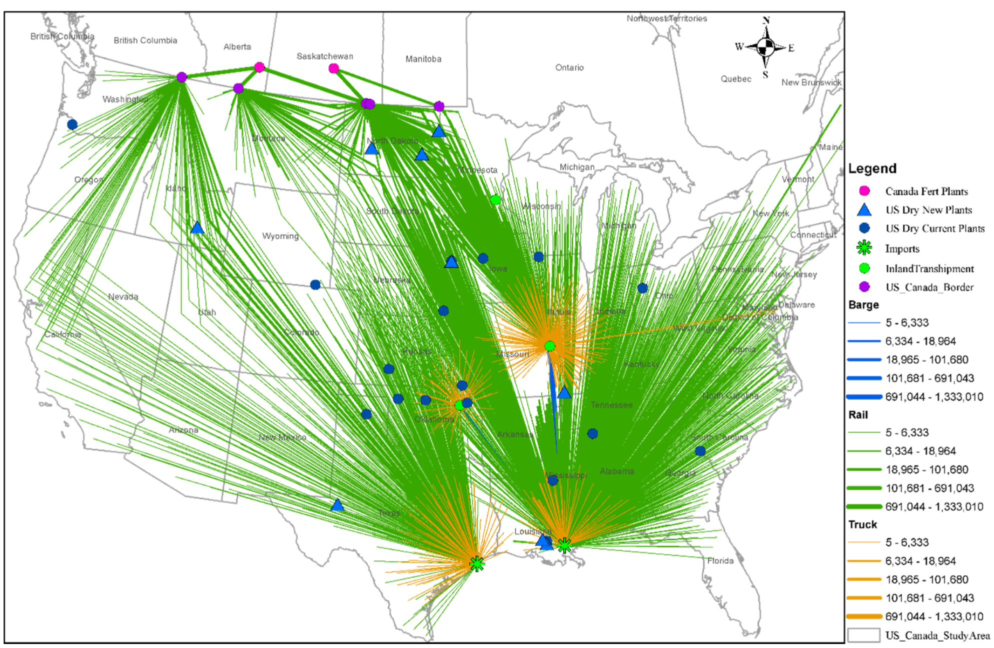

Figure F.2. Structure of supply chain for anhydrous ammonia for future case mixed-integer sensitivity by mode (Rail=Green, Truck=Orange, Barge=Blue).

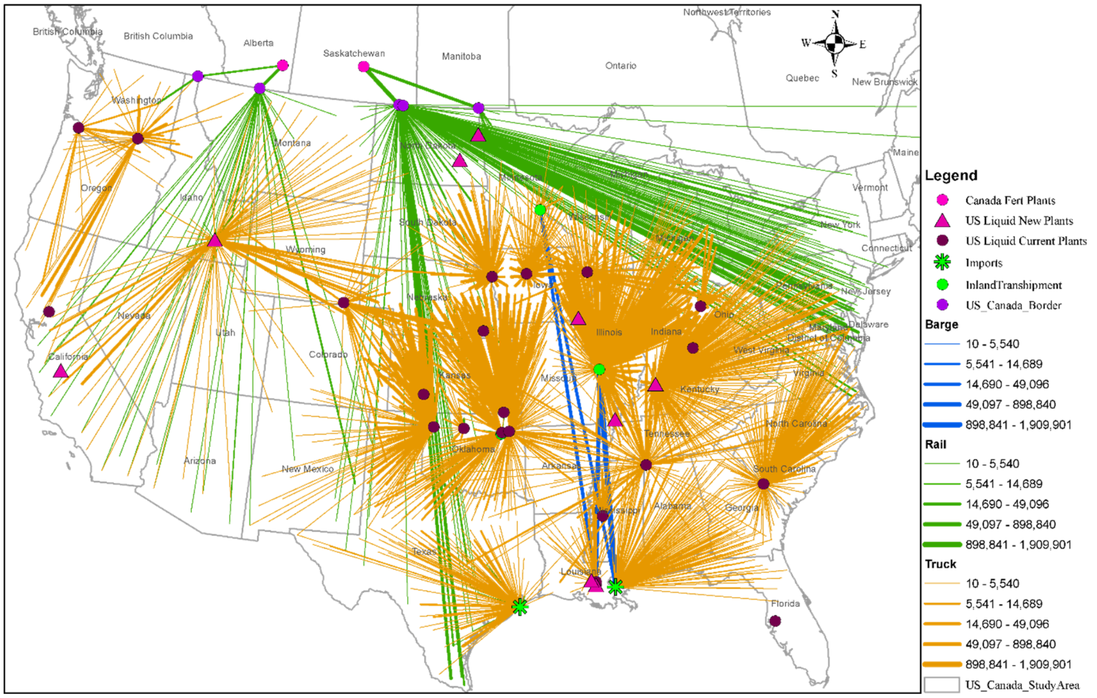

Figure F.3. Structure of supply chain for anhydrous ammonia for future case mixed-integer sensitivity by mode (Rail=Green, Truck=Orange, Barge=Blue).

F.2. Market Boundaries for Selective Plants by Probability of Shipping for 1000 Iterations in Stochastic Mixed-Integer Future Case 2018 Sensitivity

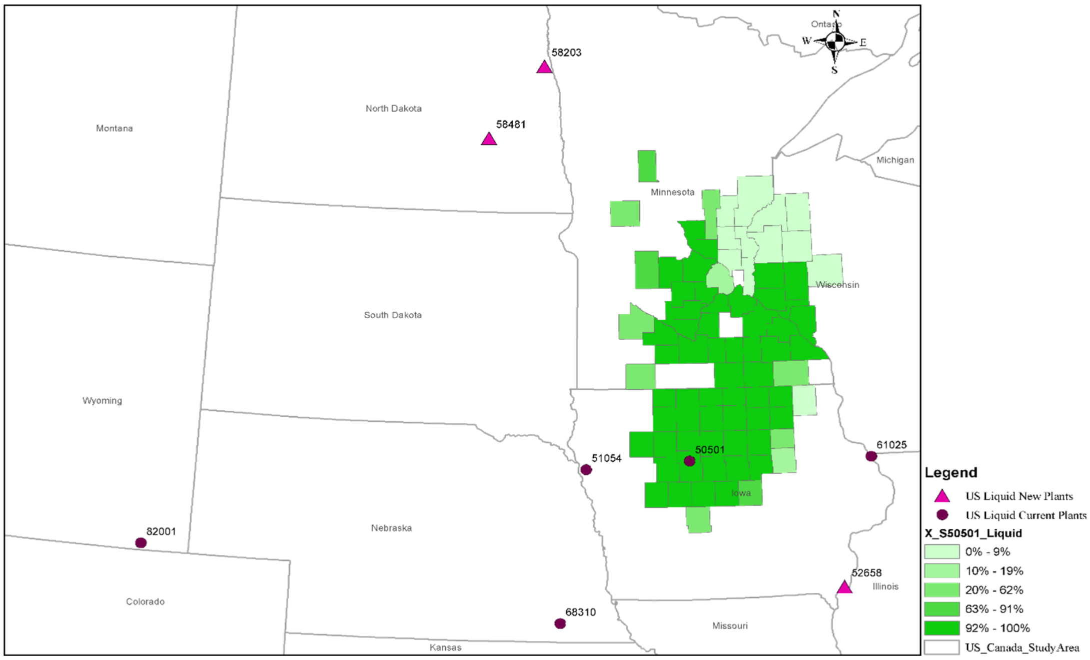

Figure F.4. Market boundaries for plant j=50501 for UAN (probability of shipping for 1000 iterations) in future case mixed-integer sensitivity.

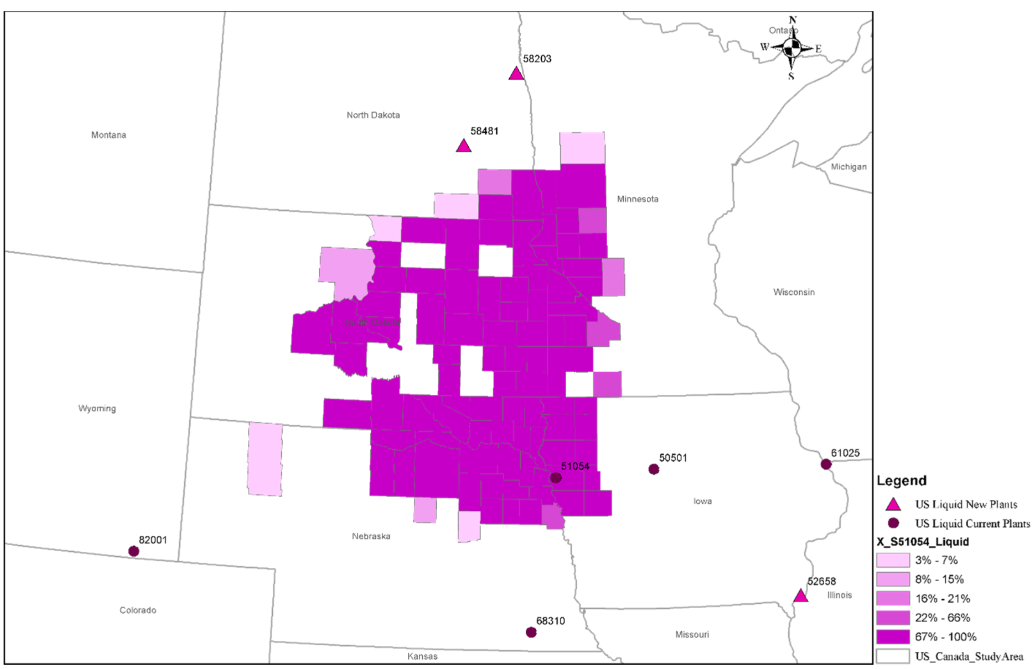

Figure F.5. Market boundaries for plant j=51054 for UAN (probability of shipping for 1000 iterations) in future case mixed-integer sensitivity.

F.3. Market Boundaries for Selective Plants by Mean Quantity of Shipping for 1000 Iterations in Stochastic Mixed-Integer Future Case 2018 Sensitivity

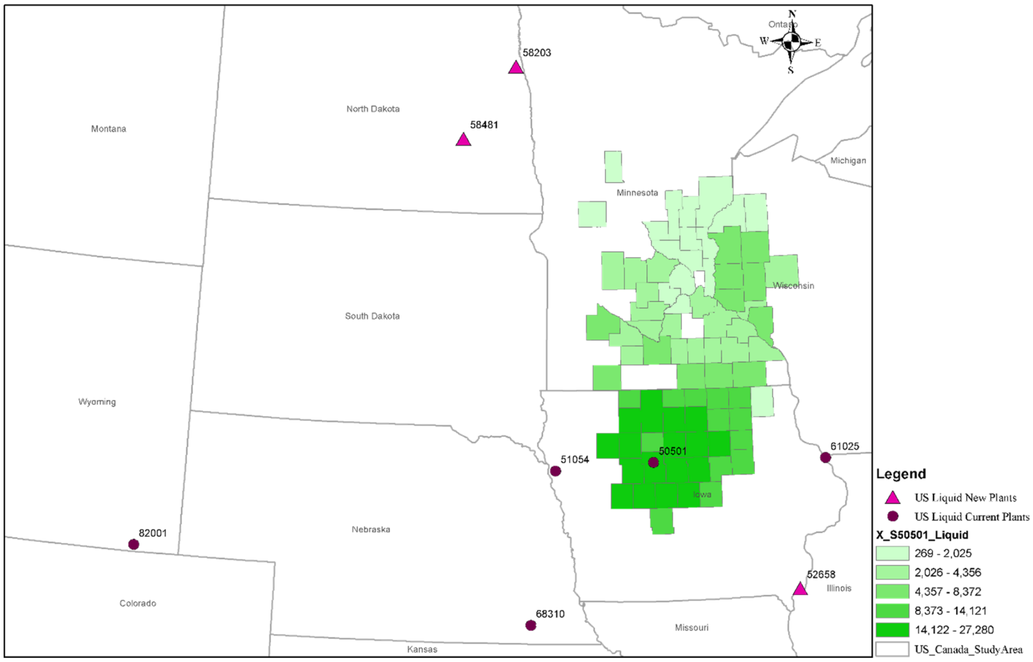

Figure F.6. Market boundaries for plant j=50501 for UAN (mean quantity of shipping for 1000 iterations) in future case mixed-integer sensitivity.

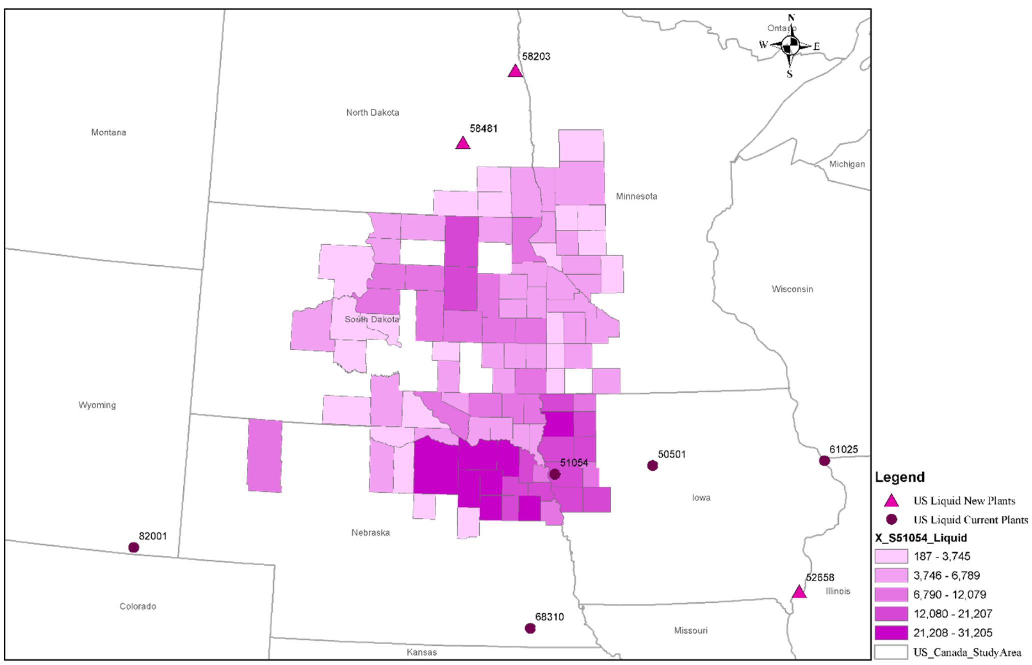

Figure F.7. Market boundaries for plant j=51054 for UAN (mean quantity of shipping for 1000 iterations) in future case mixed-integer sensitivity.

F.4. CDFs by Nodes in Stochastic Mixed-Integer Future Case 2018 Sensitivity

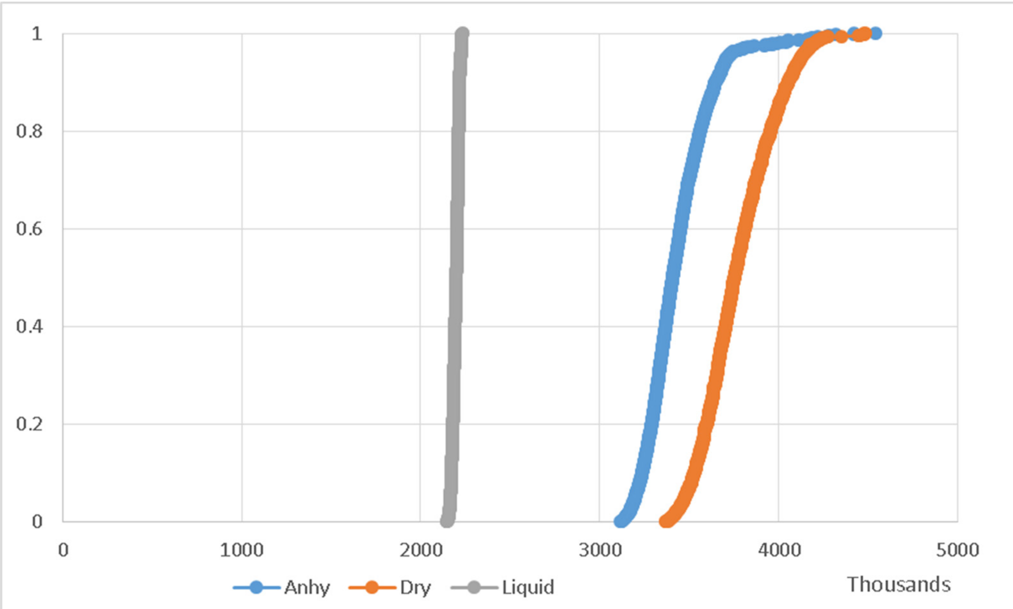

Figure F.8. Cumulative probability for 2200374 (New Orleans, LA) in stochastic mixed-integer future case sensitivity.

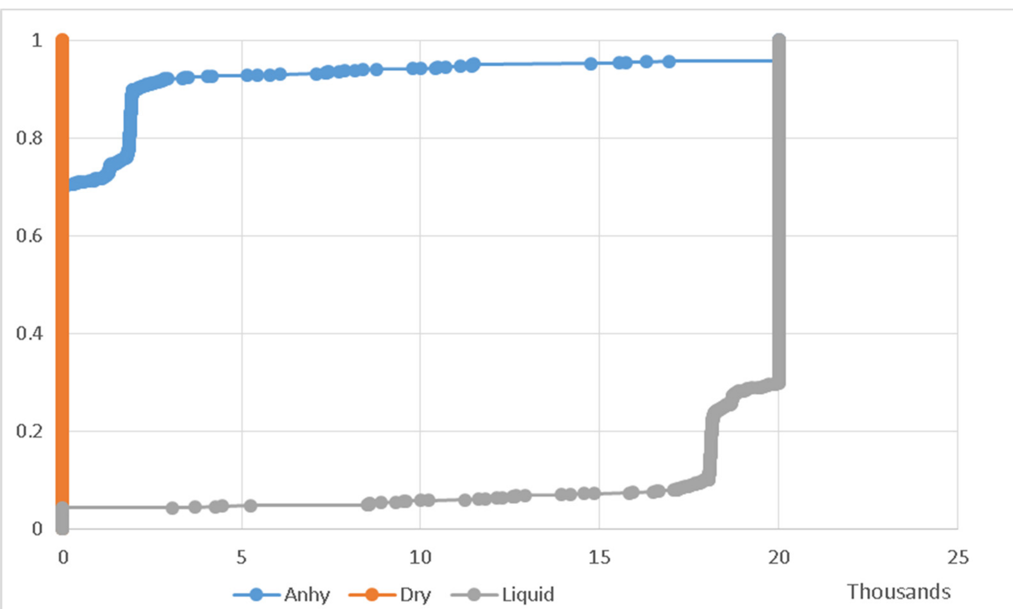

Figure F.9. Cumulative probability for 2700093 (Minneapolis, MN) in stochastic mixed-integer future case sensitivity.

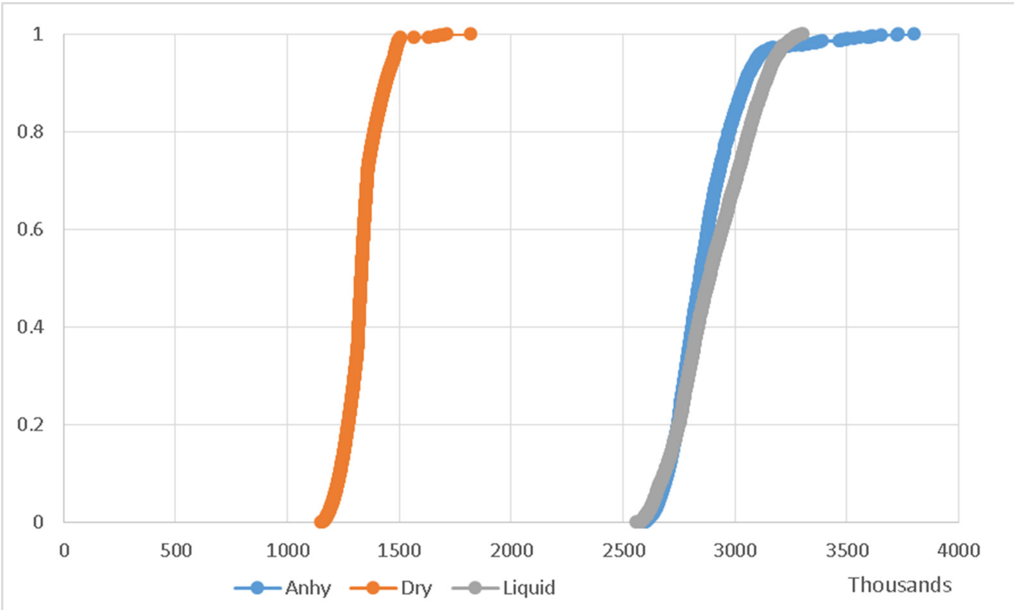

Figure F.10. Cumulative probability for 2900310 (St Louis, MO) in stochastic mixed-integer future case sensitivity.

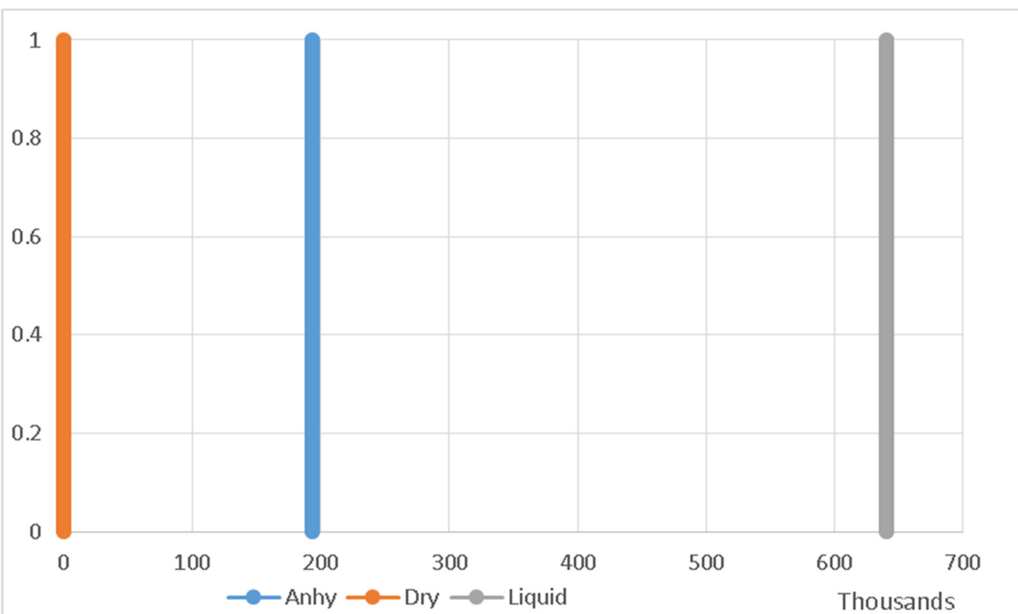

Figure F.11. Cumulative probability for 30901 (Augusta, GA) for in stochastic mixed-integer future case sensitivity.

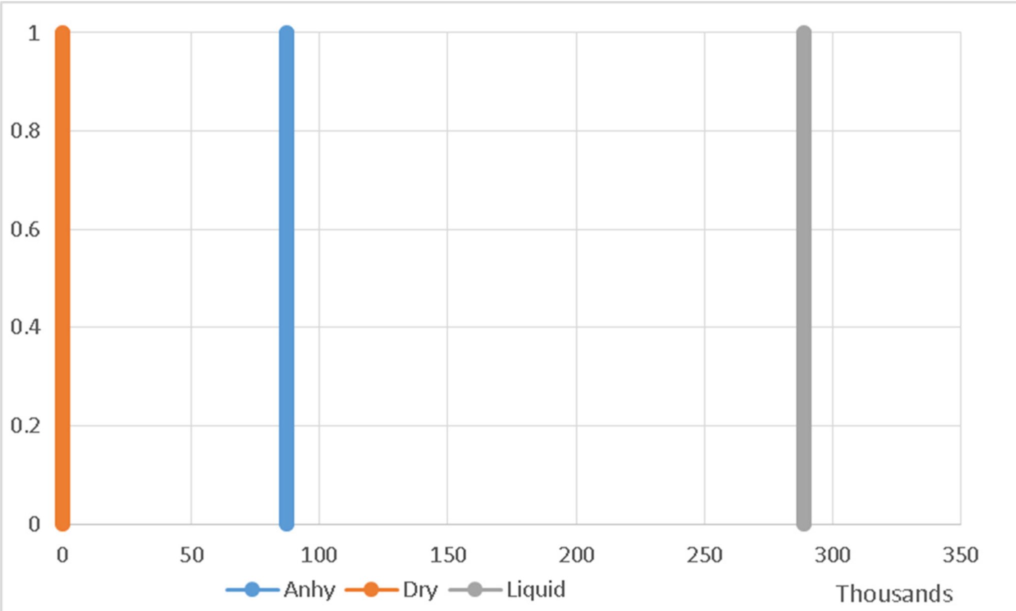

Figure F.12. Cumulative probability for 35616 (Cherokee, AL) for in stochastic mixed-integer future case sensitivity.

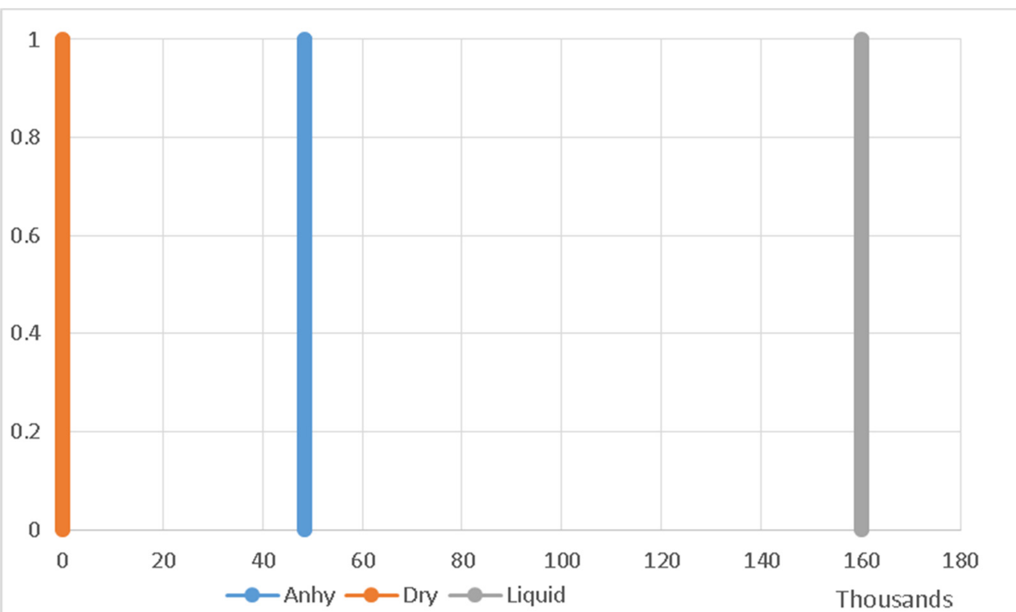

Figure F.13. Cumulative probability for 39194 (Yazoo City, MS) for in stochastic mixed-integer future case sensitivity.

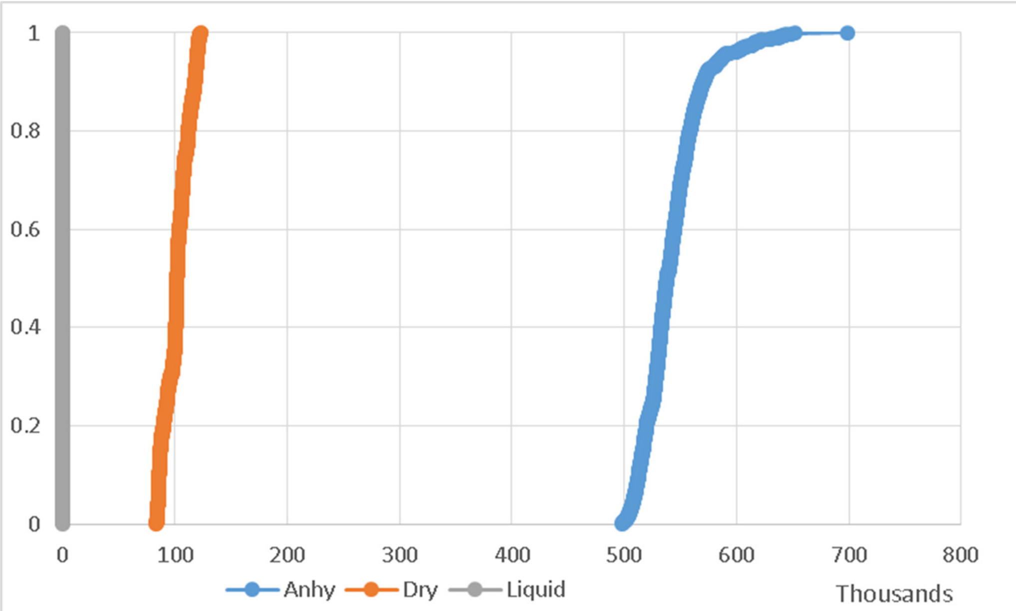

Figure F.14. Cumulative probability for 4000131 (Catoosa, OK) for in stochastic mixed-integer future case sensitivity.

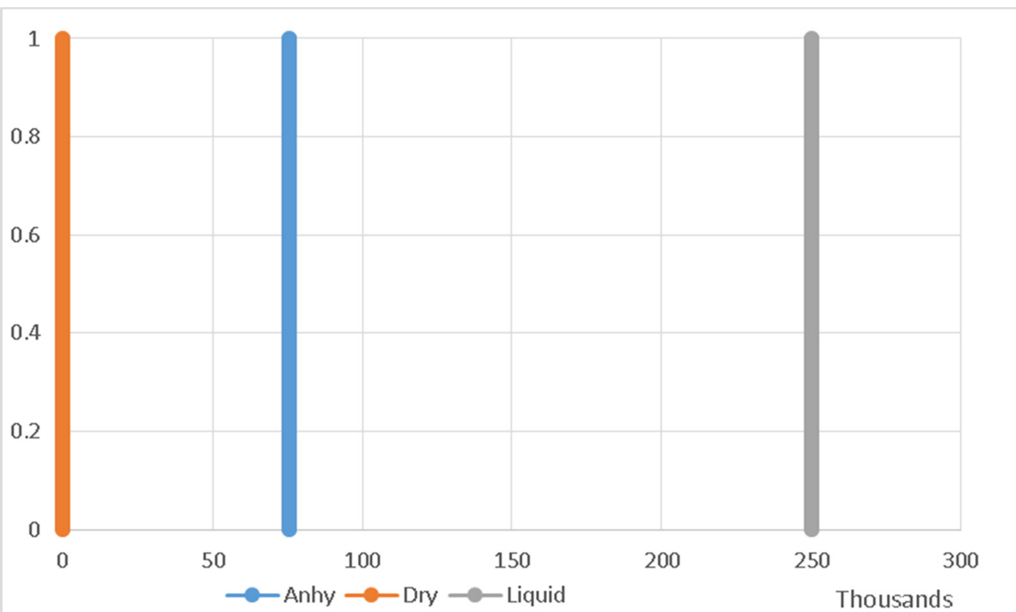

Figure F.15. Cumulative probability for 45804 (Lima, OH) for in stochastic mixed-integer future case sensitivity.

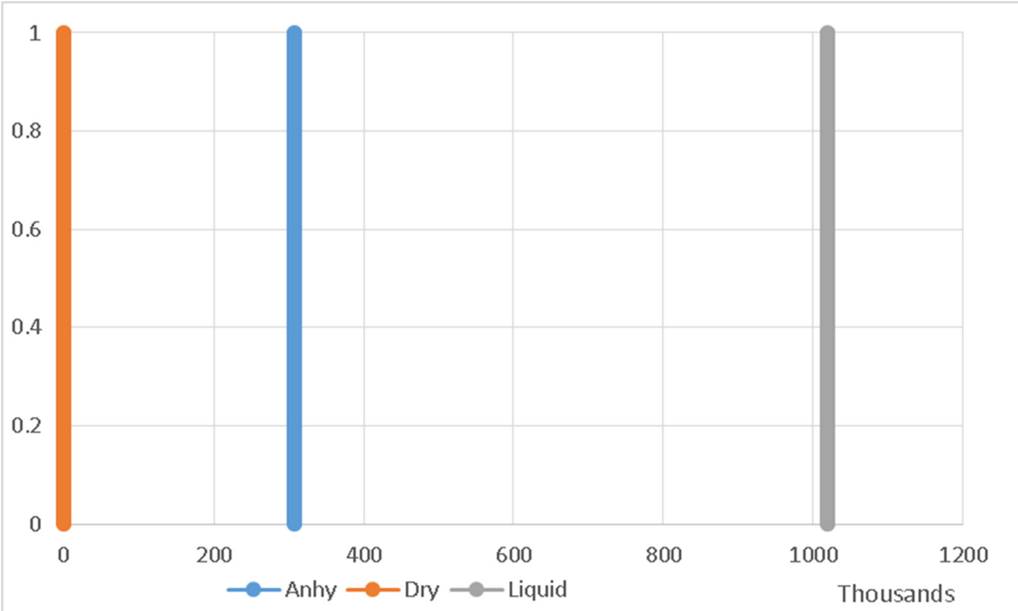

Figure F.16. Cumulative probability for 47635 (Rockport, IN) for in stochastic mixed-integer future case sensitivity.

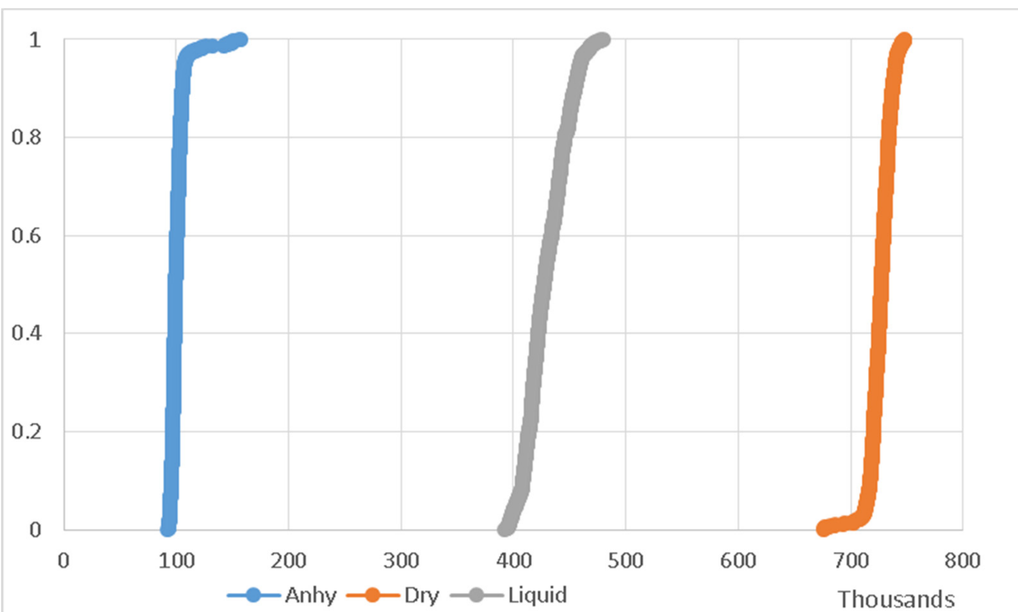

Figure F.17. Cumulative probability for 4800608 (Galveston, TX) for in stochastic mixed-integer future case sensitivity.

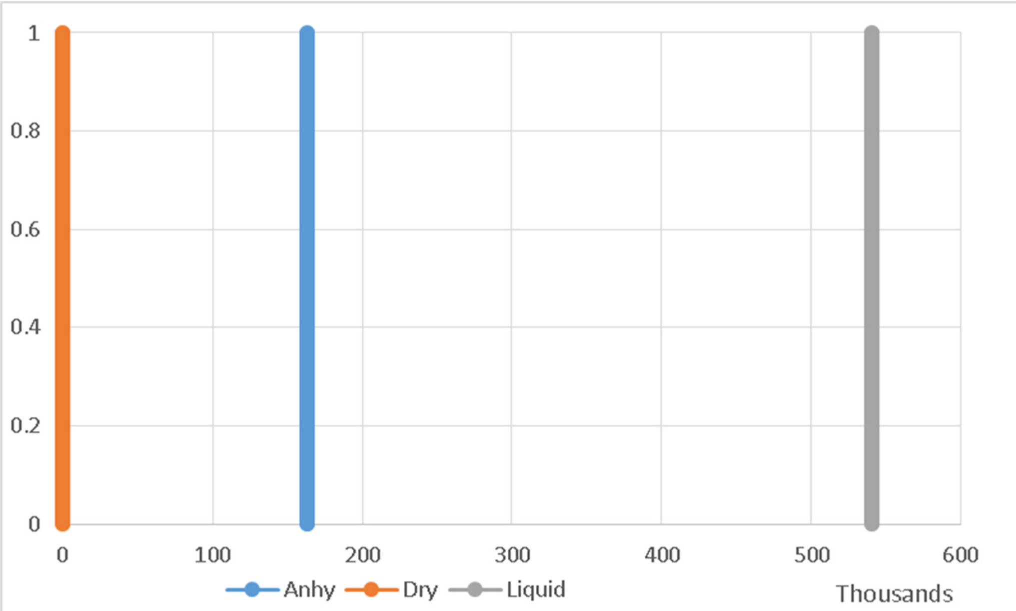

Figure F.18. Cumulative probability for 50501 (Fort Dodge, IA) for in stochastic mixed-integer future case sensitivity.

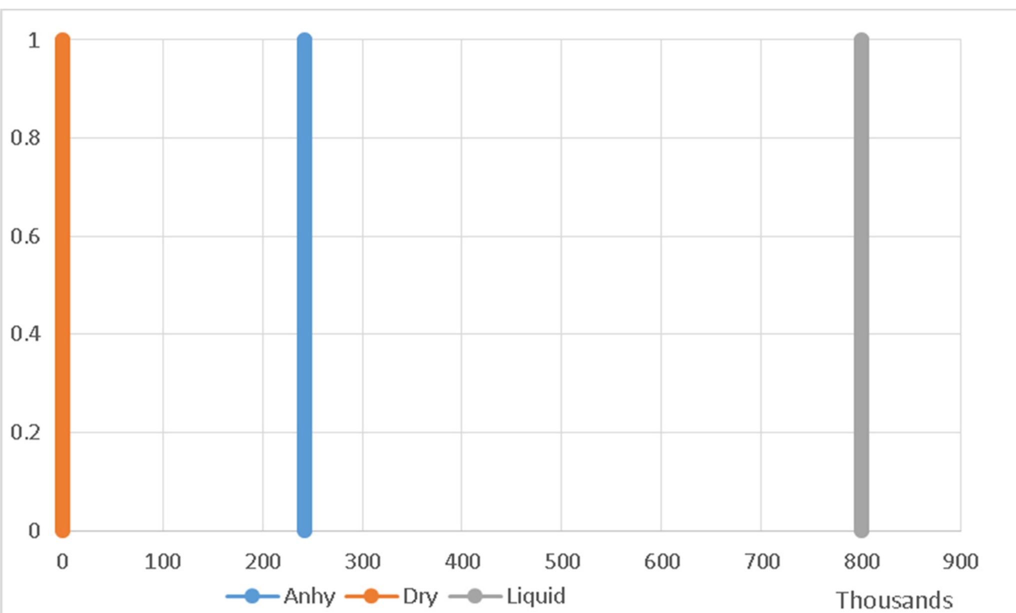

Figure F.19. Cumulative probability for 51054 (Port Neal, IA) for in stochastic mixed-integer future case sensitivity.

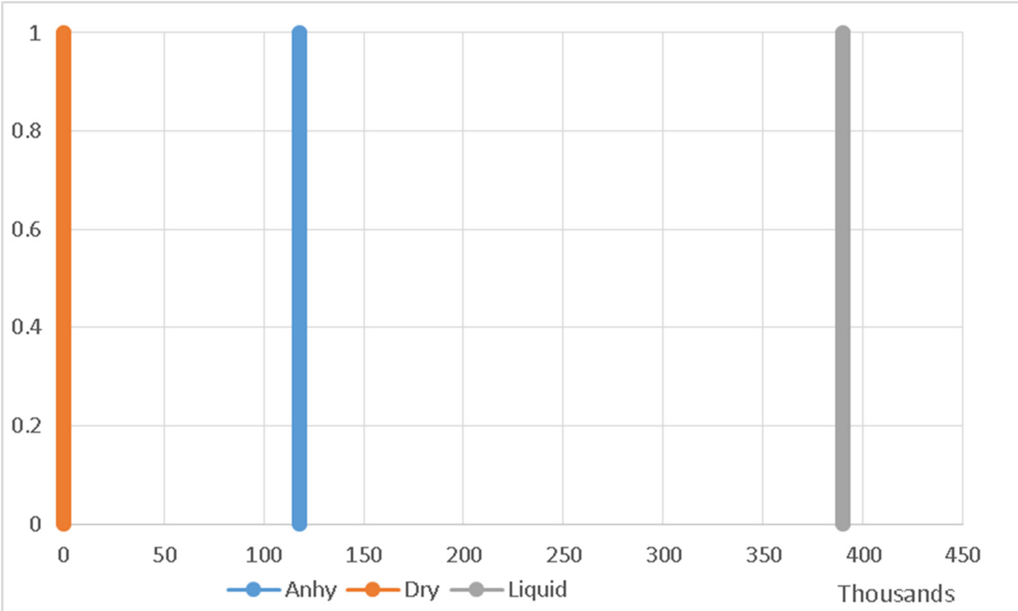

Figure F.20. Cumulative probability for 61025 (East Dubuque, IL) for in stochastic mixed-integer future case sensitivity.

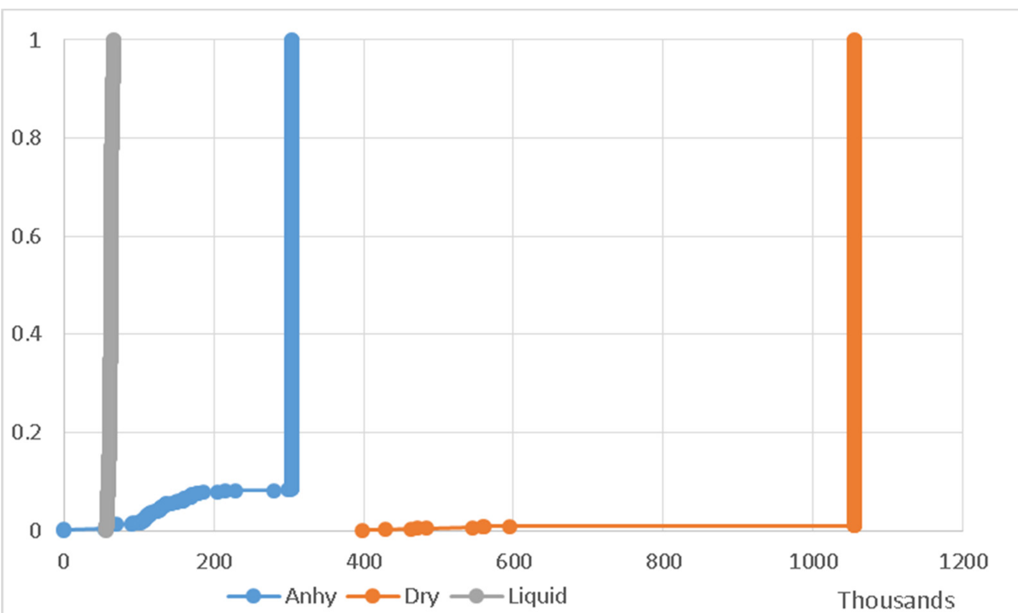

Figure F.21. Cumulative probability for 612 (Medicine Hat, AB) for in stochastic mixed-integer future case sensitivity.

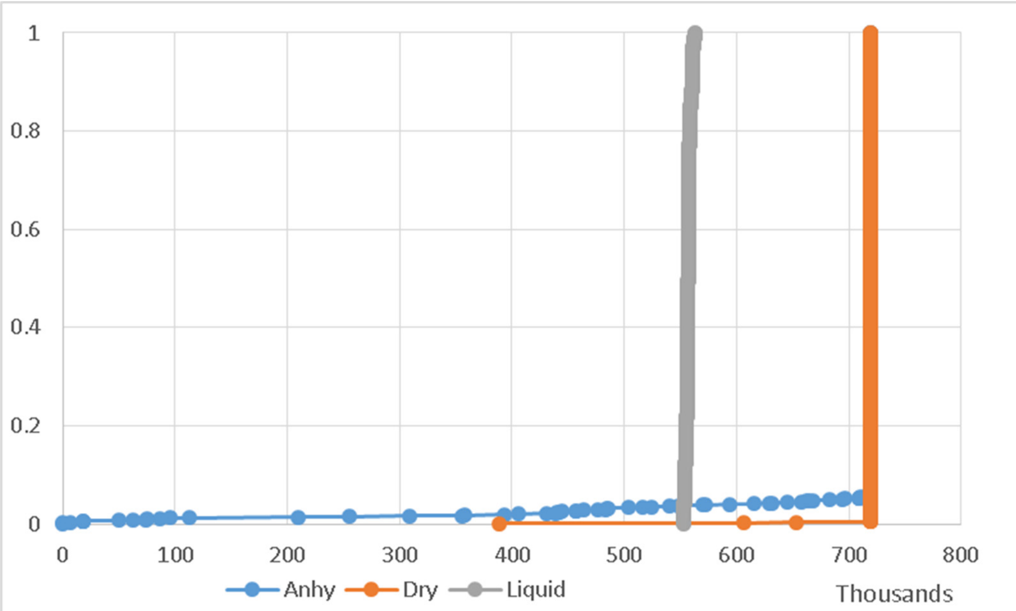

Figure F.22. Cumulative probability for 644 (Belle Plaine, SK) for in stochastic mixed-integer future case sensitivity.

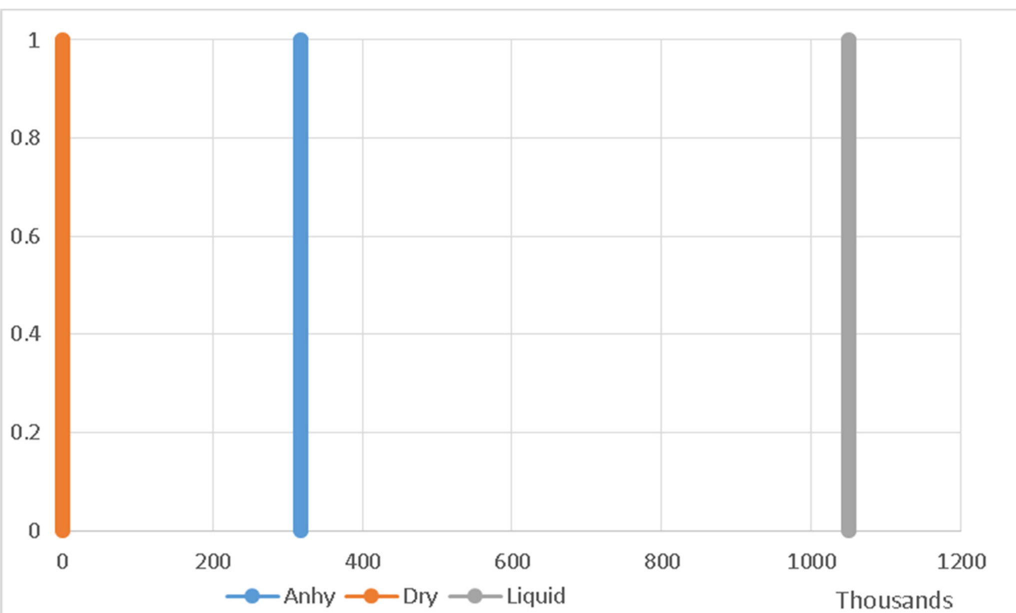

Figure F.23. Cumulative probability for 67337 (Coffeyville, KS) for in stochastic mixed-integer future case sensitivity.

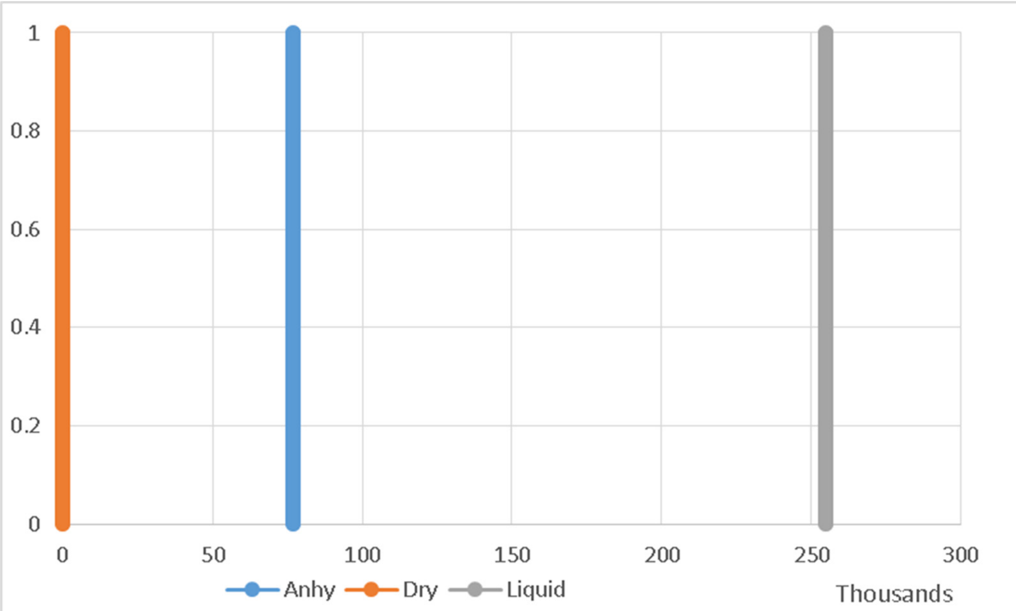

Figure F.24. Cumulative probability for 67801 (Dodge City, KS) for in stochastic mixed-integer future case sensitivity.

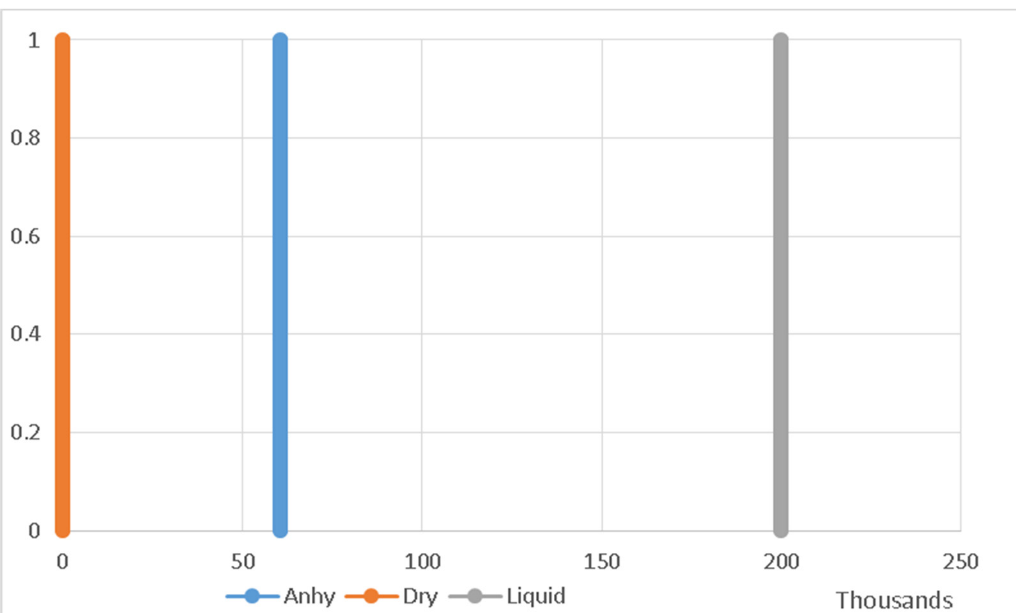

Figure F.25. Cumulative probability for 68310 (Beatrice, NE) for in stochastic mixed-integer future case sensitivity.

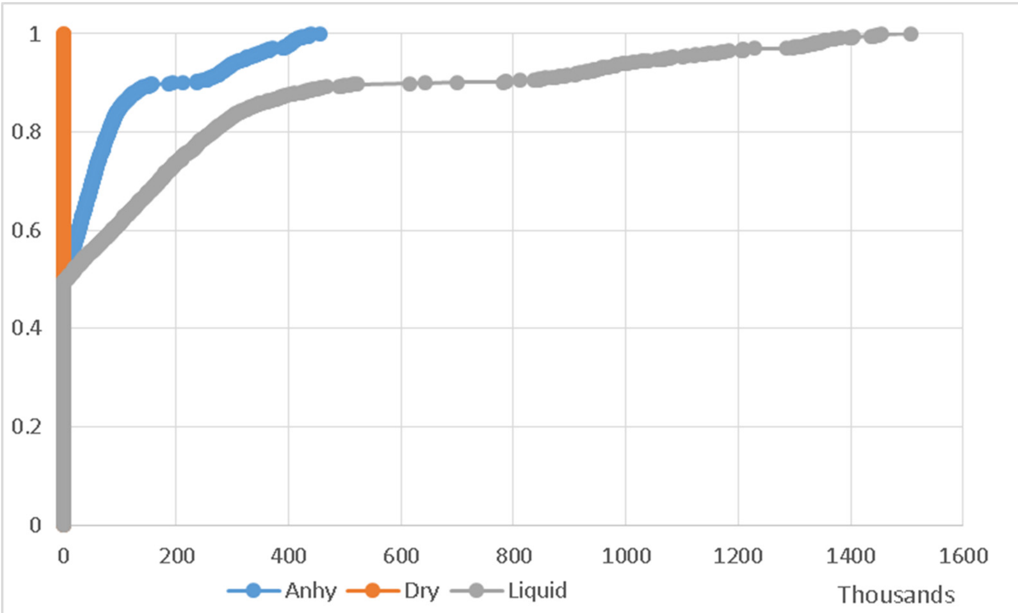

Figure F.26. Cumulative probability for 70346 (Donaldsonville, LA) for in stochastic mixed-integer future case sensitivity.

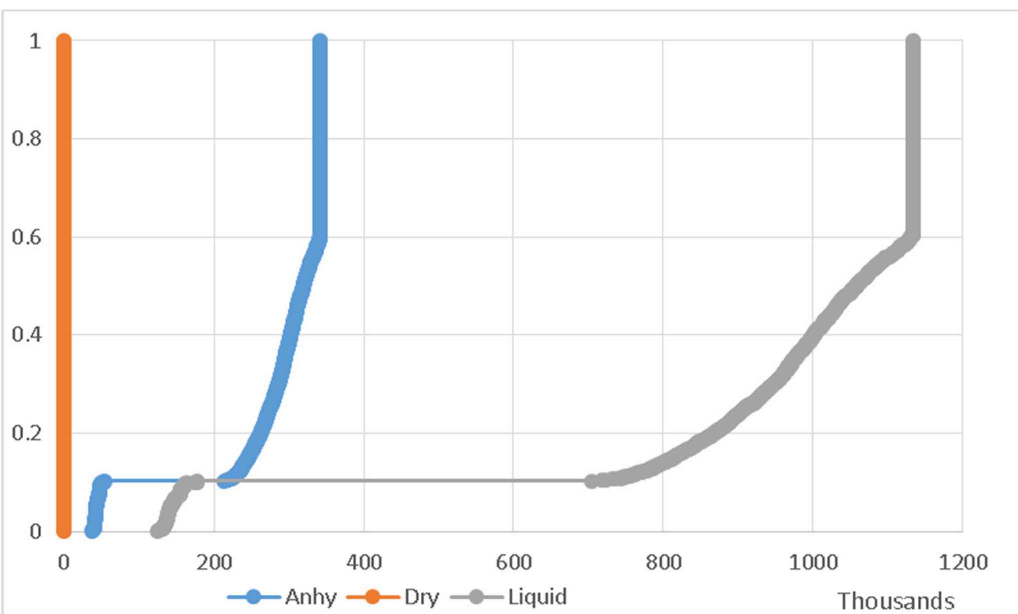

Figure F.27. Cumulative probability for 70734 (Geismar, LA) for in stochastic mixed-integer future case sensitivity.

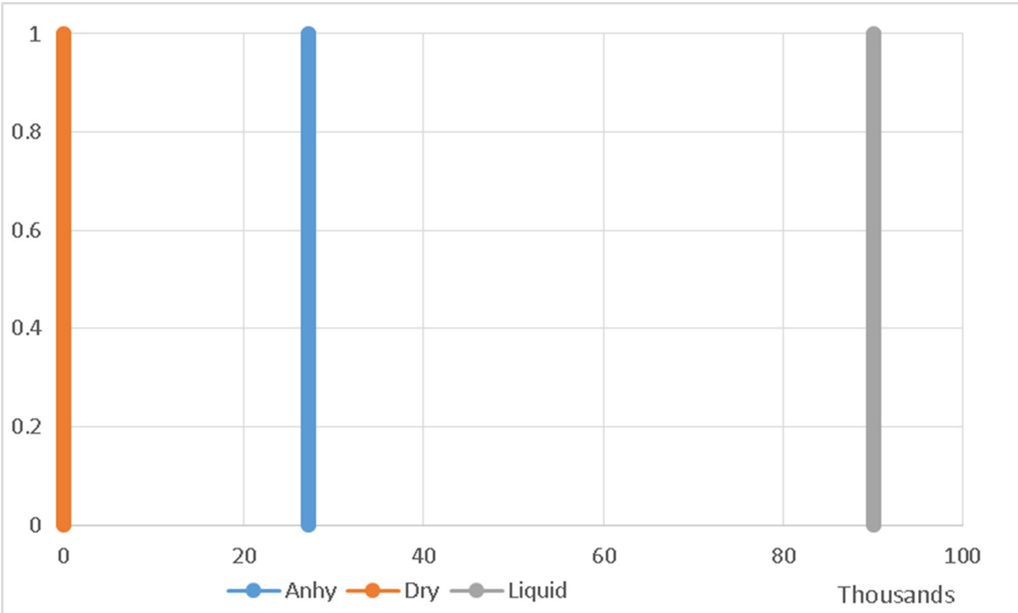

Figure F.28. Cumulative probability for 73701 (Enid, OK) for in stochastic mixed-integer future case sensitivity.

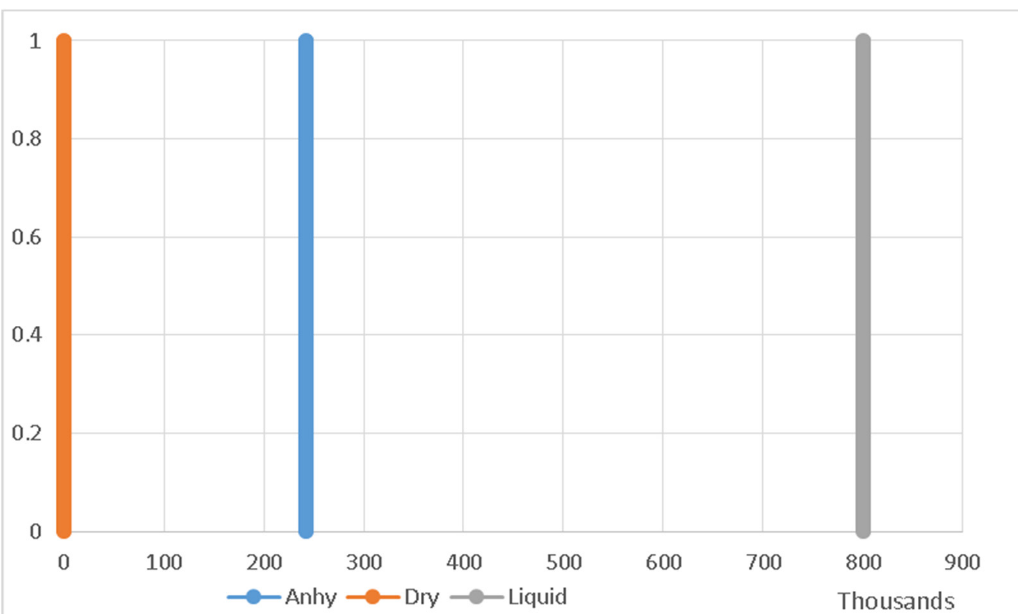

Figure F.29. Cumulative probability for 73801 (Woodward, OK) for in stochastic mixed-integer future case sensitivity.

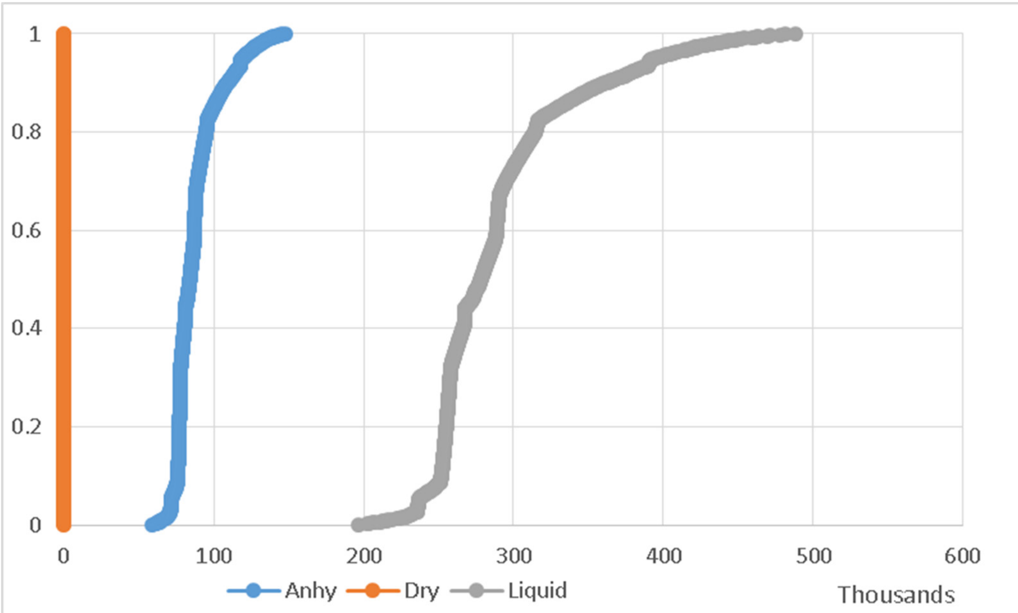

Figure F.30. Cumulative probability for 74019 (Verdigris, OK) for in stochastic mixed-integer future case sensitivity.

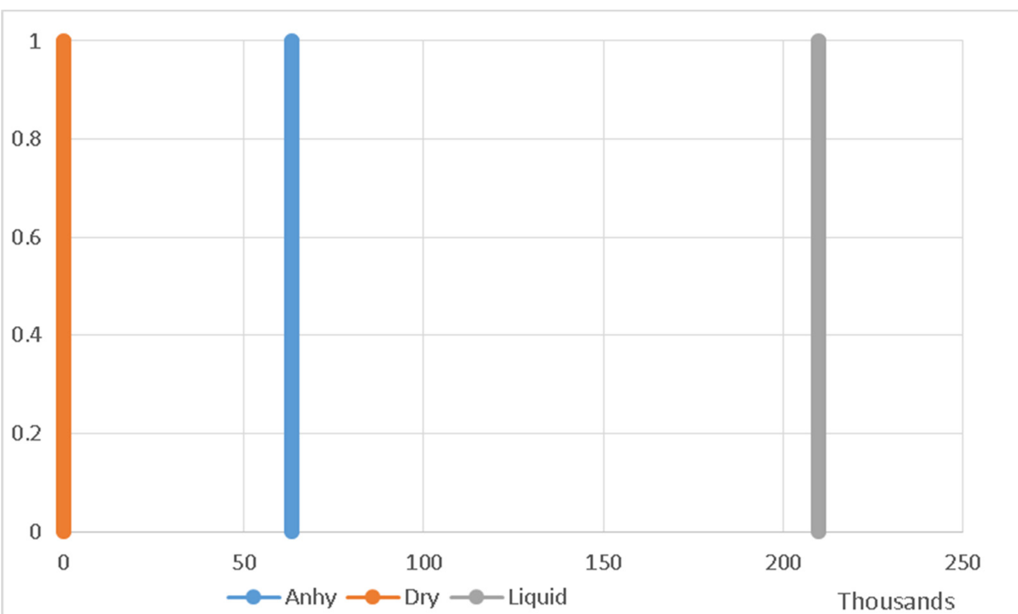

Figure F.31. Cumulative probability for 82001 (Cheyenne, WY) for in stochastic mixed-integer future case sensitivity.

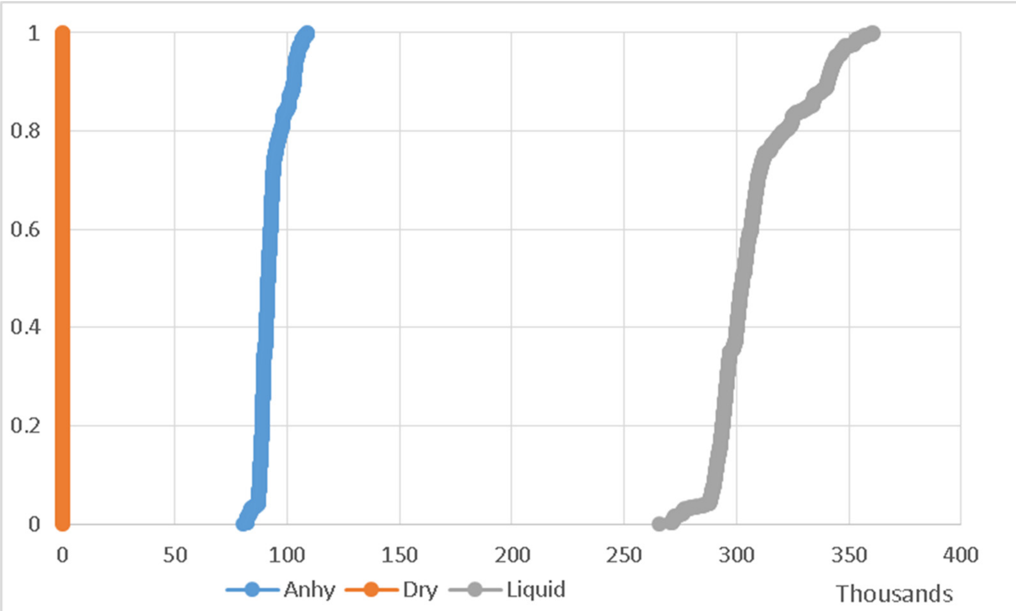

Figure F.32. Cumulative probability for 83211 (American Falls, ID) for in stochastic mixed-integer future case sensitivity.

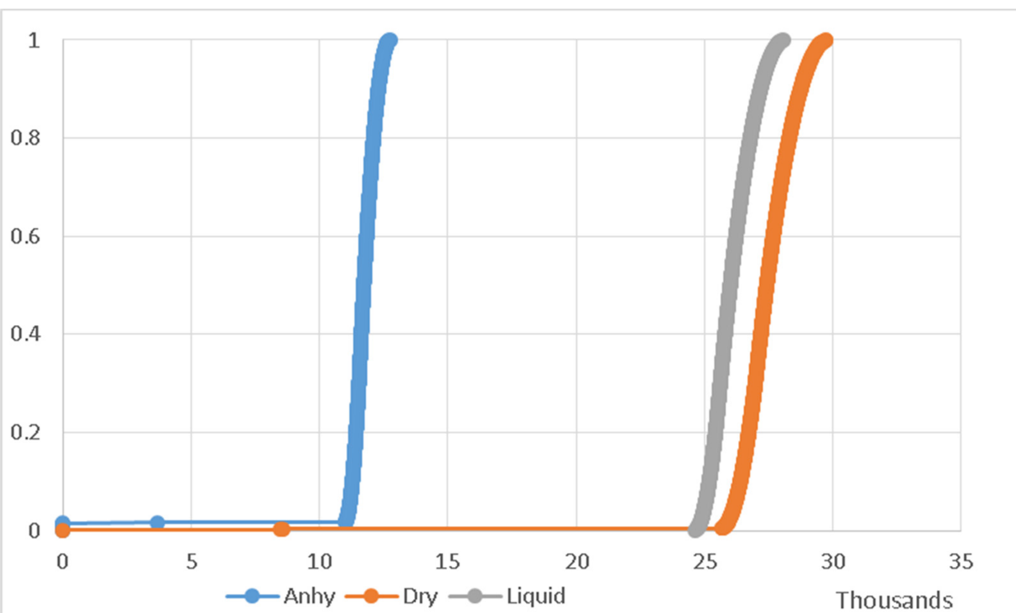

Figure F.33. Cumulative probability for 8800451 (POE: Emerson, ND) for in stochastic mixed-integer future case sensitivity.

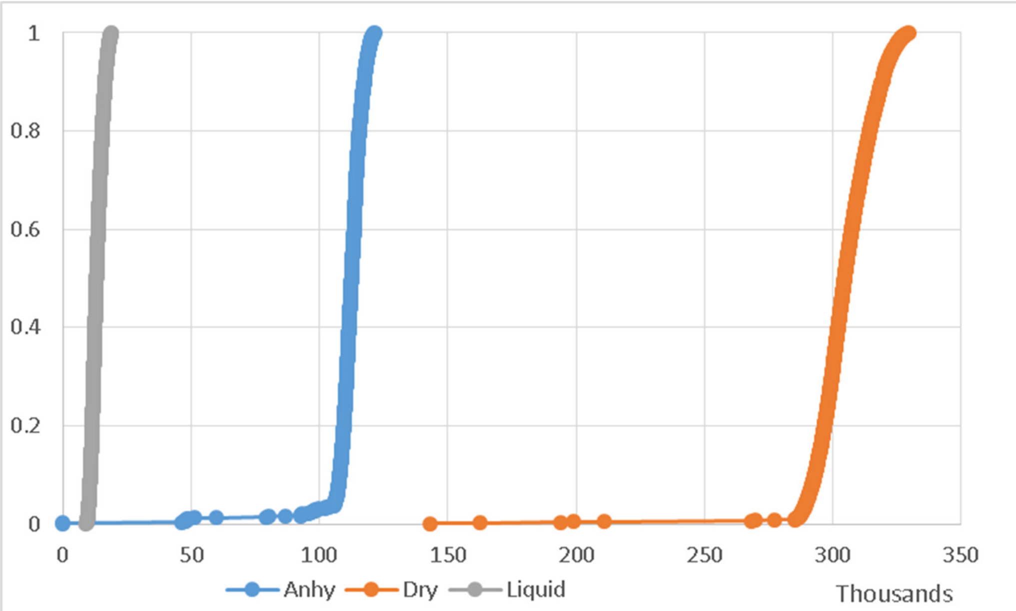

Figure F.34. Cumulative probability for 9163 (POE: Kingsgate, ID) for in stochastic mixed-integer future case sensitivity.

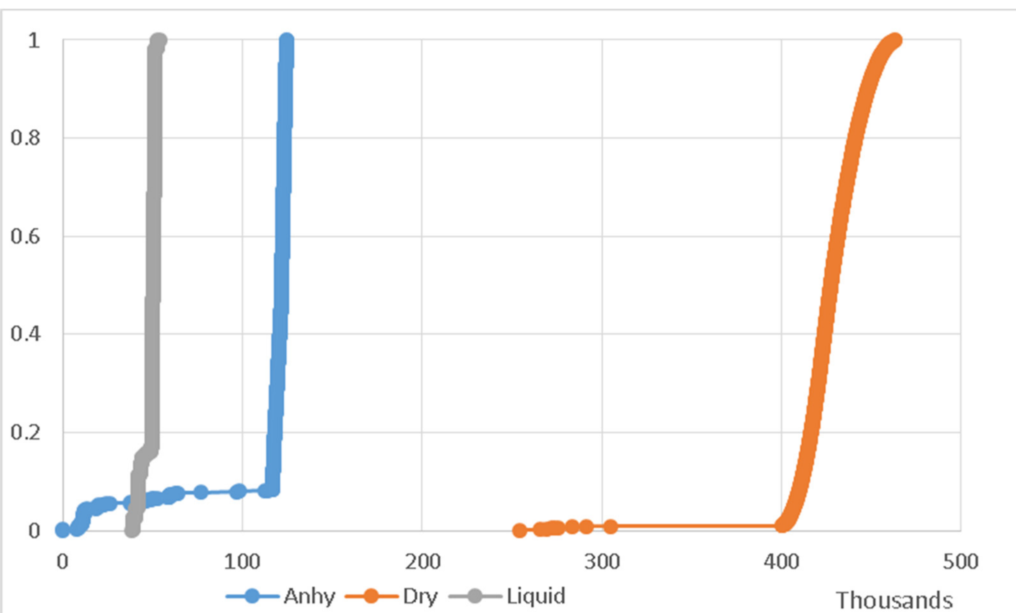

Figure F.35. Cumulative probability for 9303 (POE: Coutts, MT) for in stochastic mixed-integer future case sensitivity.

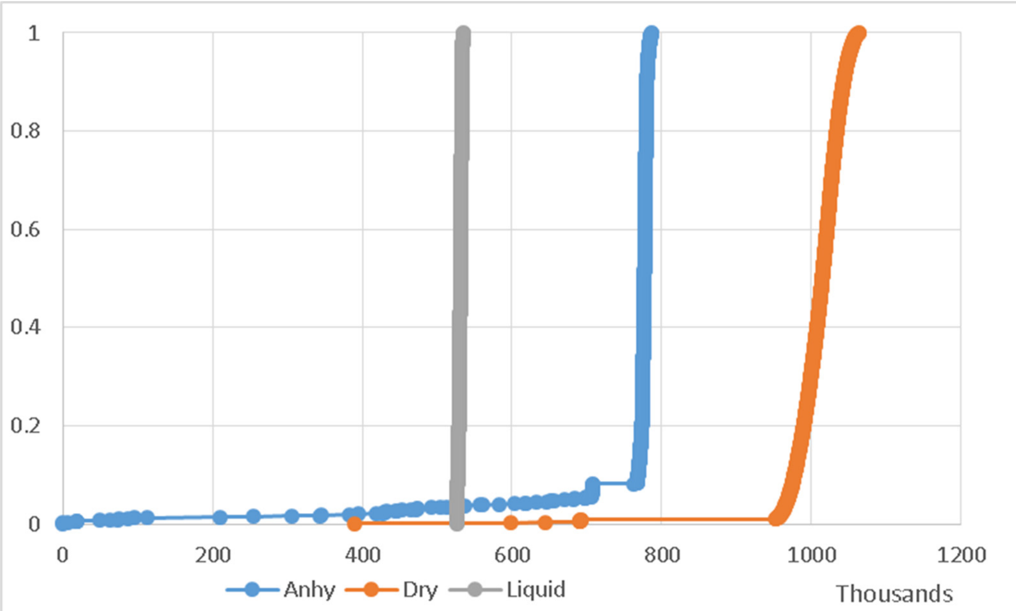

Figure F.36. Cumulative probability for 9384 (POE: Portal, ND) for in stochastic mixed-integer future case sensitivity.

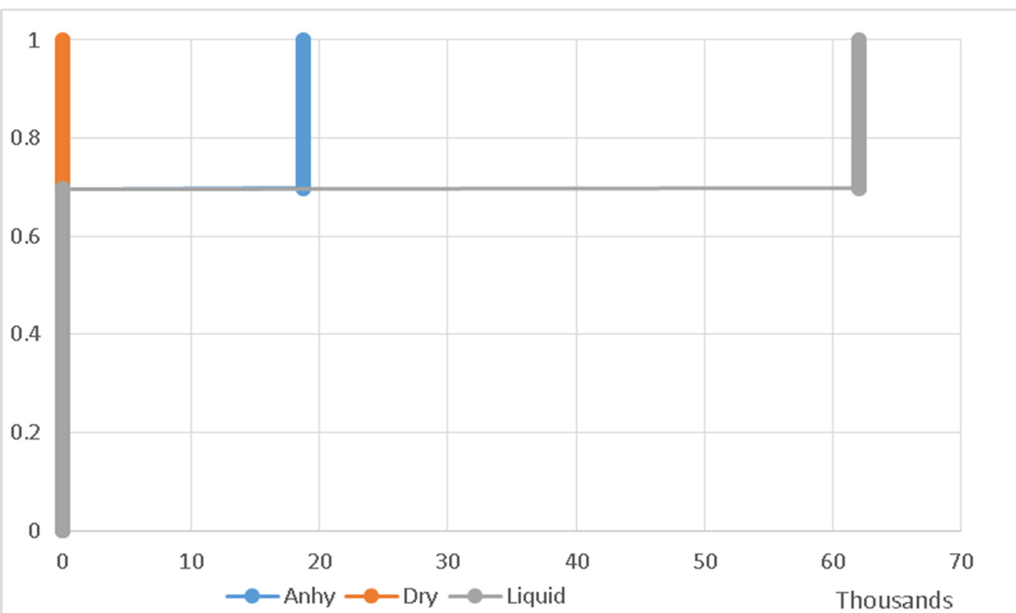

Figure F.37. Cumulative probability for 97051 (St. Helens, OR) for in stochastic mixed-integer future case sensitivity.

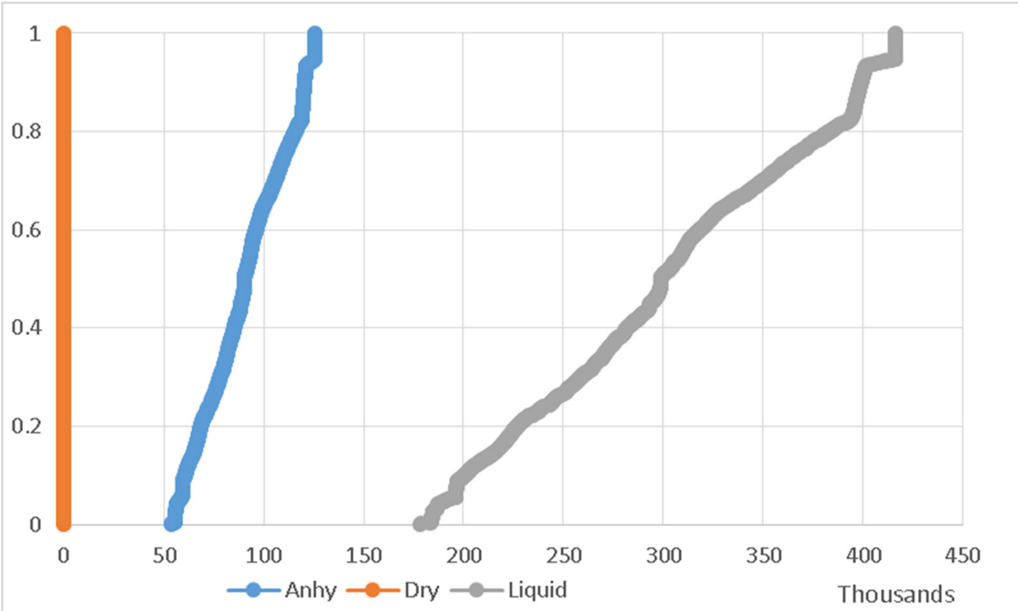

Figure F.38. Cumulative probability for 74362 (Pryor OK) for in stochastic mixed-integer future case sensitivity.

APPENDIX G. SUMMARY RESULTS ACROSS SCENARIOS

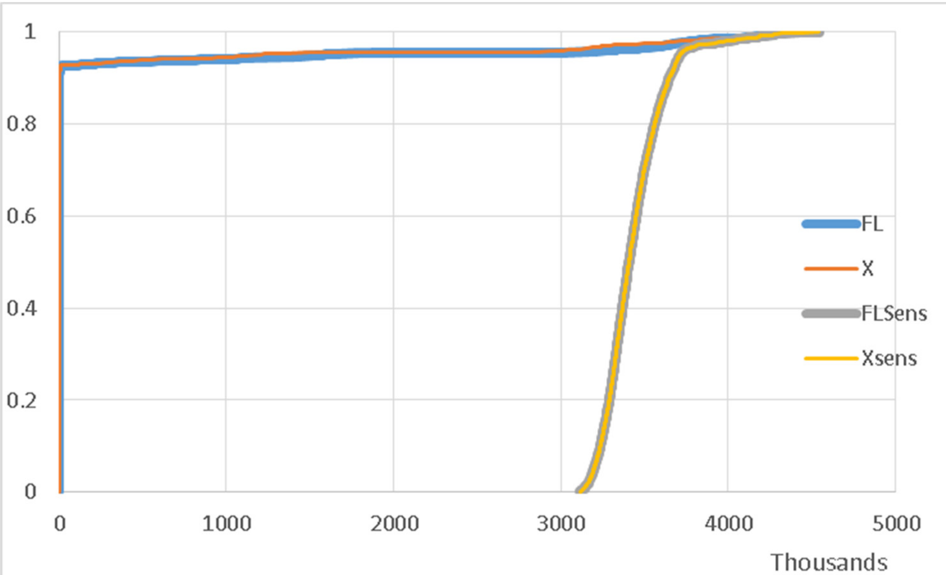

Figure G.1. Cumulative probability of anhydrous ammonia production for 2200374 (New Orleans, LA) across scenarios of stochastic future linear (FL), future mixed-integer (X), future linear sensitivity (FLSens) and future mixed-integer sensitivity (Xsens).

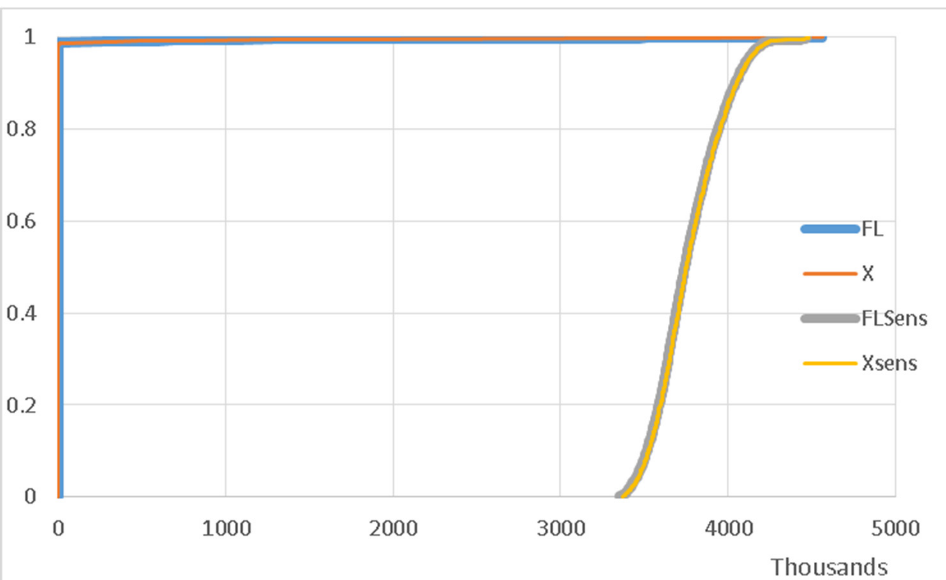

Figure G.2. Cumulative probability of urea production for 2200374 (New Orleans, LA) across scenarios of stochastic future linear (FL), future mixed-integer (X), future linear sensitivity (FLSens) and future mixed-integer sensitivity (Xsens).

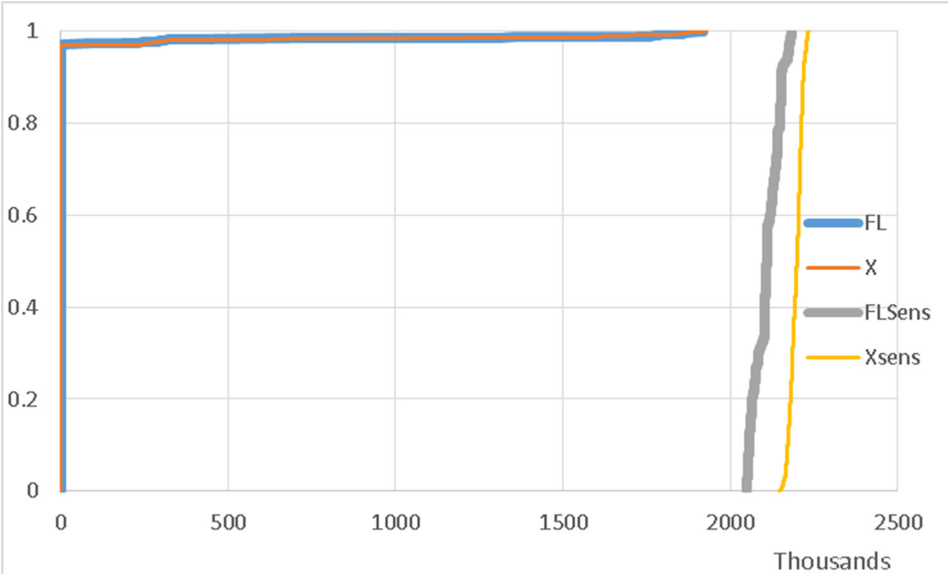

Figure G.3. Cumulative probability of UAN production for 2200374 (New Orleans, LA) across scenarios of stochastic future linear (FL), future mixed-integer (X), future linear sensitivity (FLSens) and future mixed-integer sensitivity (Xsens).

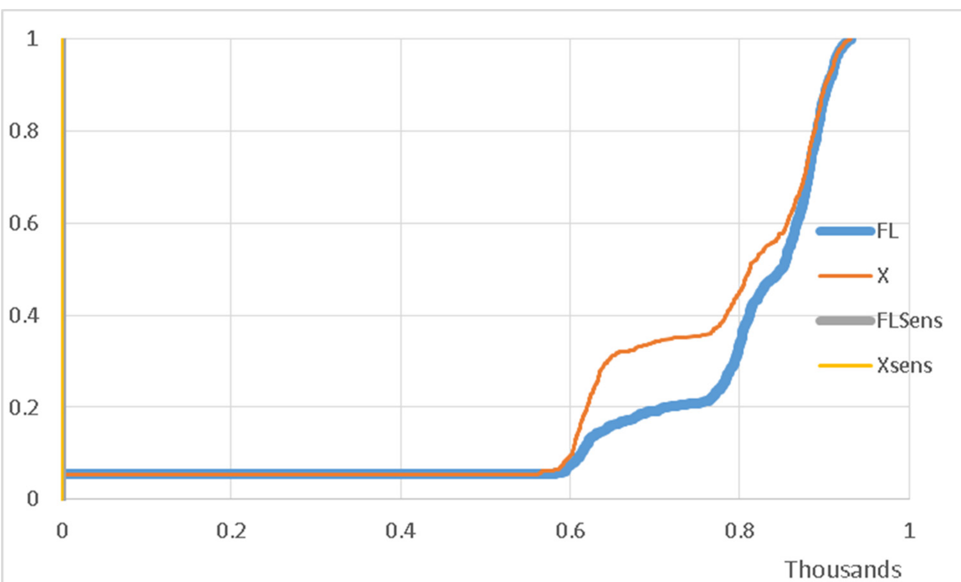

Figure G.4. Cumulative probability of anhydrous ammonia production for 23860 (Hopewell, VA) across scenarios of stochastic future linear (FL), future mixed-integer (X), future linear sensitivity (FLSens) and future mixed-integer sensitivity (Xsens).

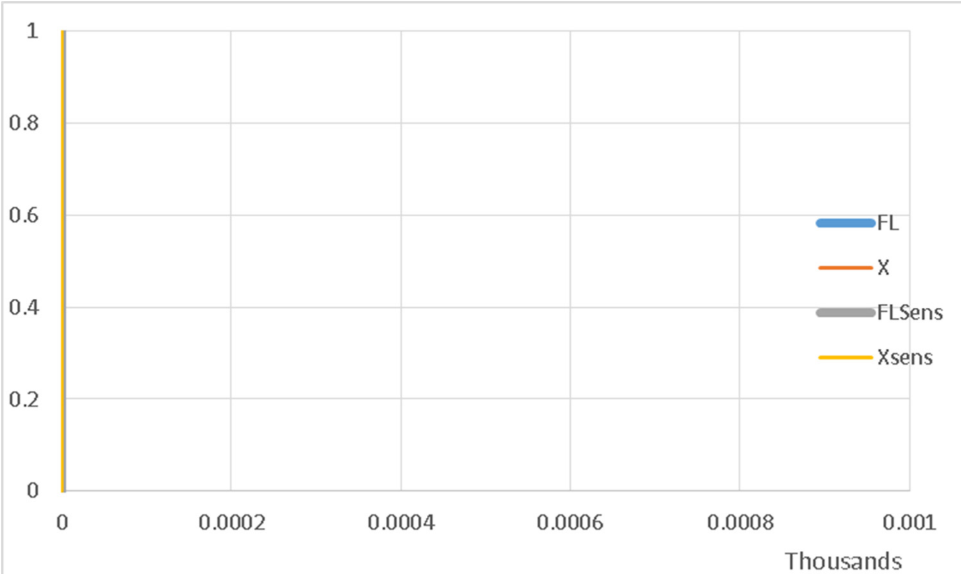

Figure G.5. Cumulative probability of urea production for 23860 (Hopewell, VA) across scenarios of stochastic future linear (FL), future mixed-integer (X), future linear sensitivity (FLSens) and future mixed-integer sensitivity (Xsens).

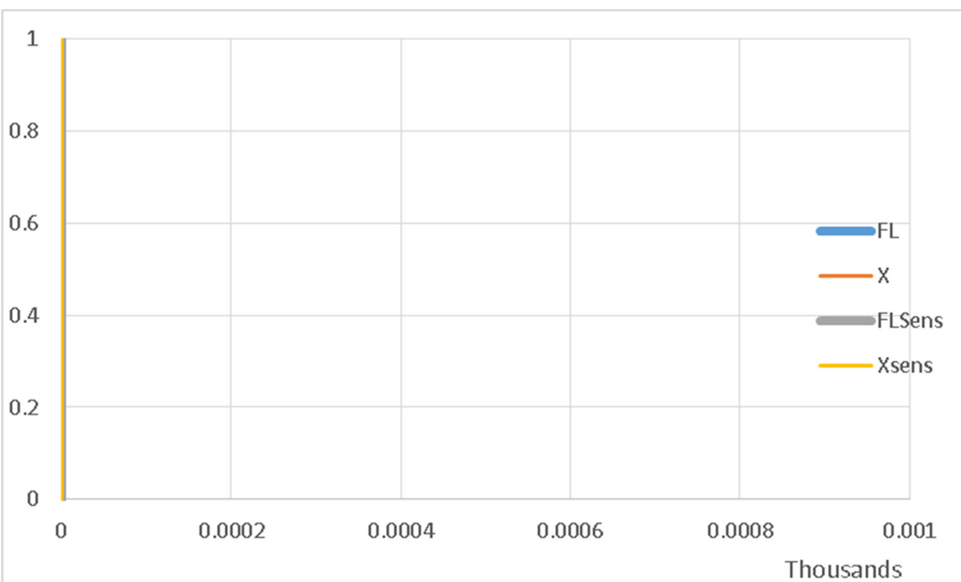

Figure G.6. Cumulative probability of UAN production for 23860 (Hopewell, VA) across scenarios of stochastic future linear (FL), future mixed-integer (X), future linear sensitivity (FLSens) and future mixed-integer sensitivity (Xsens).

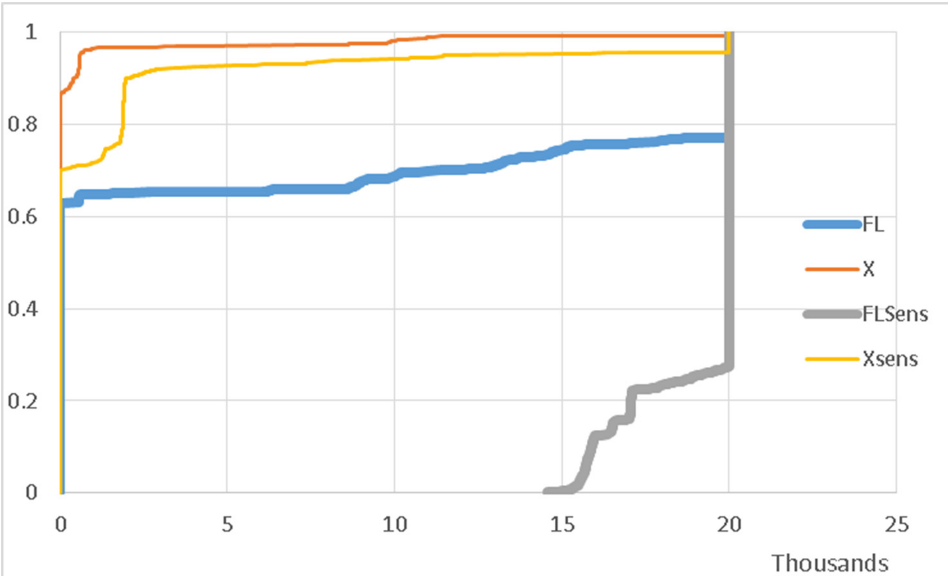

Figure G.7. Cumulative probability of anhydrous ammonia production for 2700093 (Minneapolis, MN) across scenarios of stochastic future linear (FL), future mixed-integer (X), future linear sensitivity (FLSens) and future mixed-integer sensitivity (Xsens).

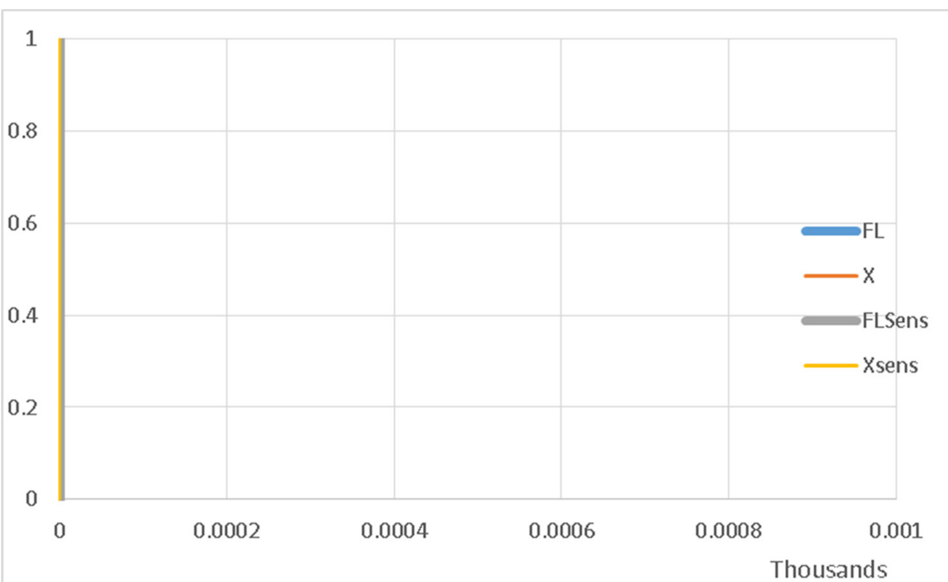

Figure G.8. Cumulative probability of urea production for 2700093 (Minneapolis, MN) across scenarios of stochastic future linear (FL), future mixed-integer (X), future linear sensitivity (FLSens) and future mixed-integer sensitivity (Xsens).

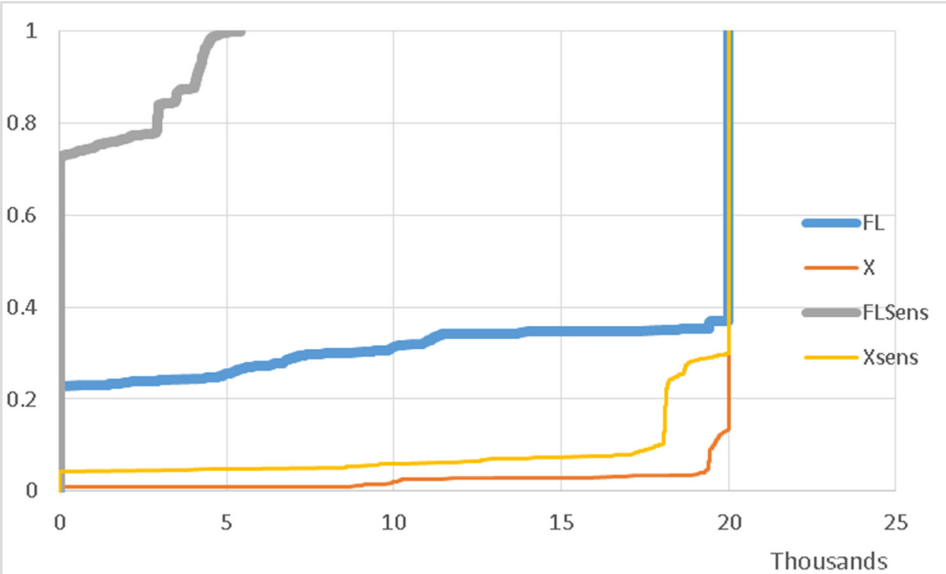

Figure G.9. Cumulative probability of UAN production for 2700093 (Minneapolis, MN) across scenarios of stochastic future linear (FL), future mixed-integer (X), future linear sensitivity (FLSens) and future mixed-integer sensitivity (Xsens).

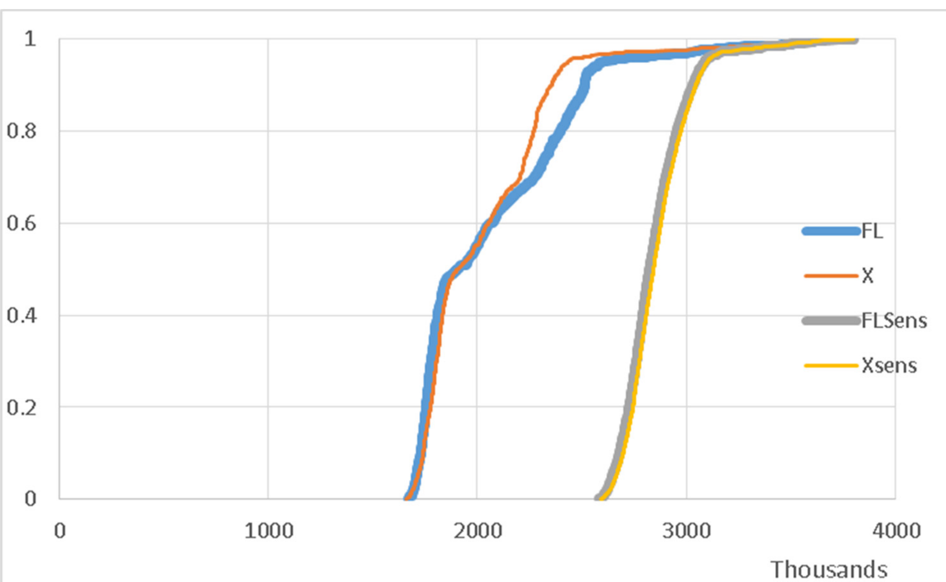

Figure G.10. Cumulative probability of anhydrous ammonia production for 2900310 (St Louis, MO) across scenarios of stochastic future linear (FL), future mixed-integer (X), future linear sensitivity (FLSens) and future mixed-integer sensitivity (Xsens).

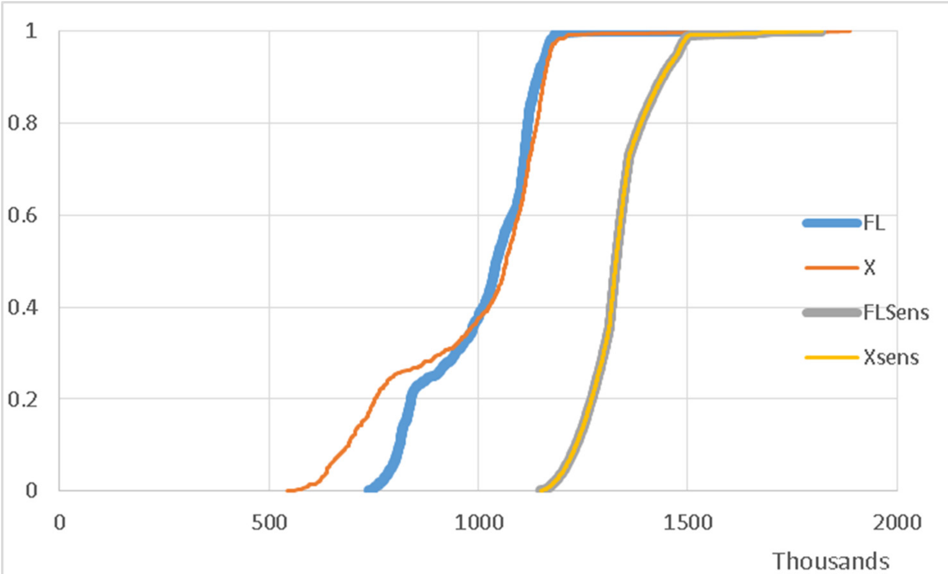

Figure G.11. Cumulative probability of urea production for 2900310 (St Louis, MO) across scenarios of stochastic future linear (FL), future mixed-integer (X), future linear sensitivity (FLSens) and future mixed-integer sensitivity (Xsens).

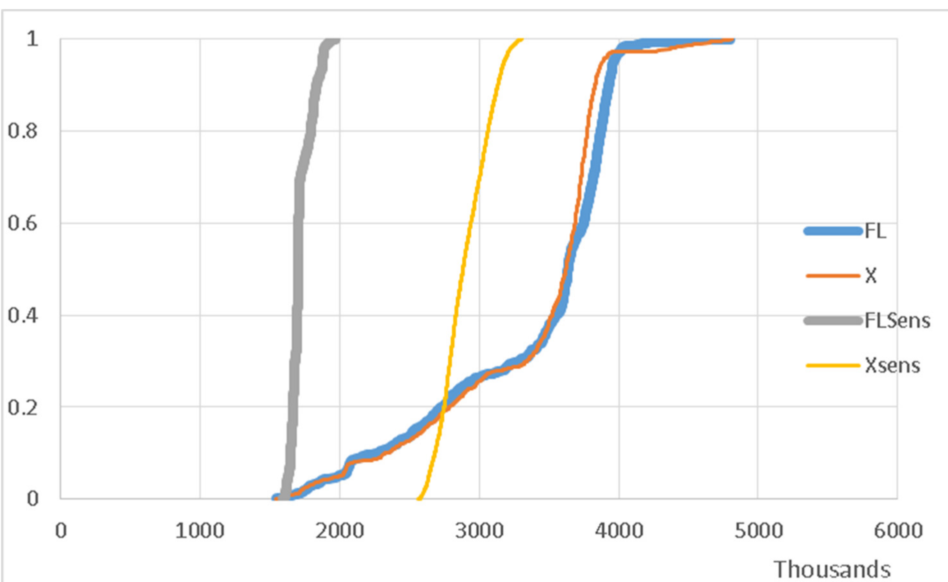

Figure G.12. Cumulative probability of UAN production for 2900310 (St Louis, MO) across scenarios of stochastic future linear (FL), future mixed-integer (X), future linear sensitivity (FLSens) and future mixed-integer sensitivity (Xsens).

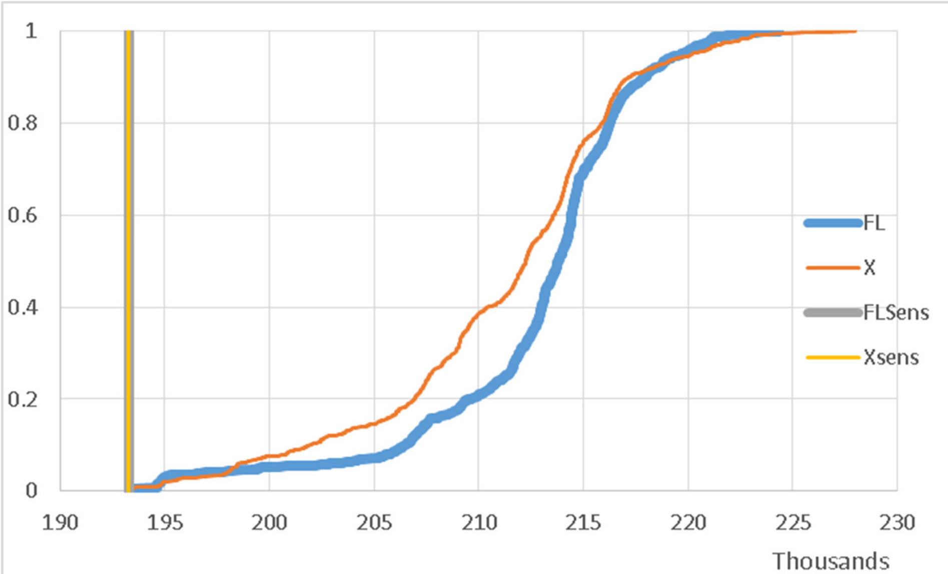

Figure G.13. Cumulative probability of anhydrous ammonia production for 30901 (Augusta, GA) across scenarios of stochastic future linear (FL), future mixed-integer (X), future linear sensitivity (FLSens) and future mixed-integer sensitivity (Xsens).

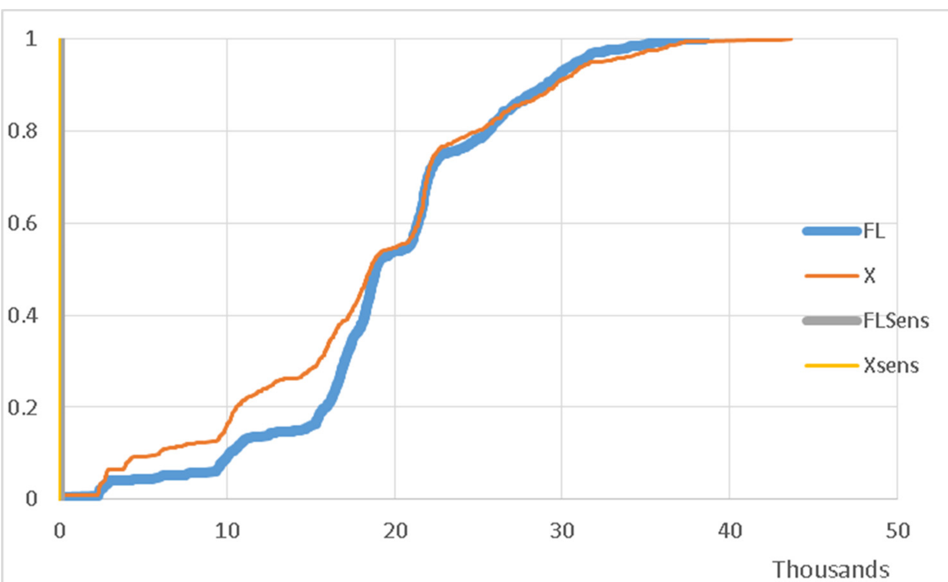

Figure G.14. Cumulative probability of urea production for 30901 (Augusta, GA) across scenarios of stochastic future linear (FL), future mixed-integer (X), future linear sensitivity (FLSens) and future mixed-integer sensitivity (Xsens).

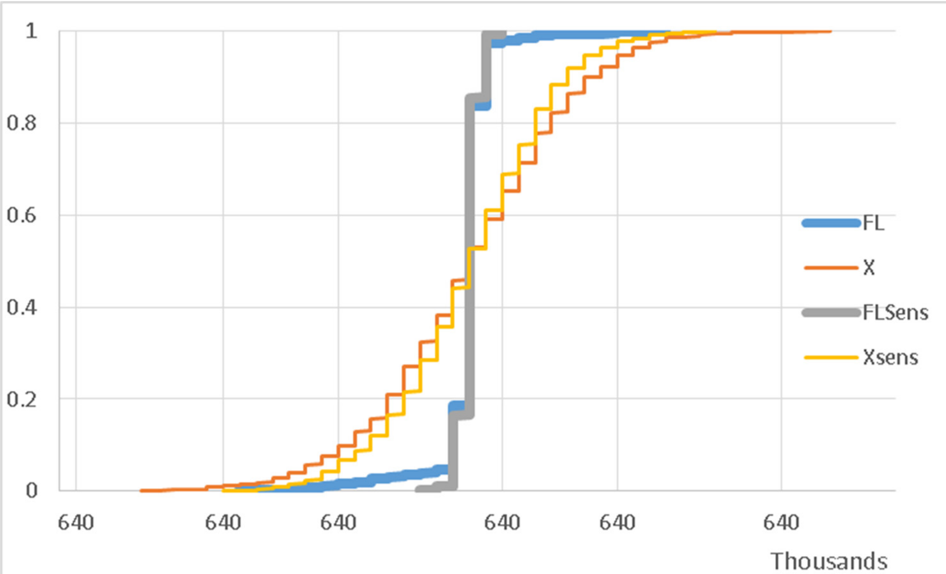

Figure G.15. Cumulative probability of UAN production for 30901 (Augusta, GA) across scenarios of stochastic future linear (FL), future mixed-integer (X), future linear sensitivity (FLSens) and future mixed-integer sensitivity (Xsens).

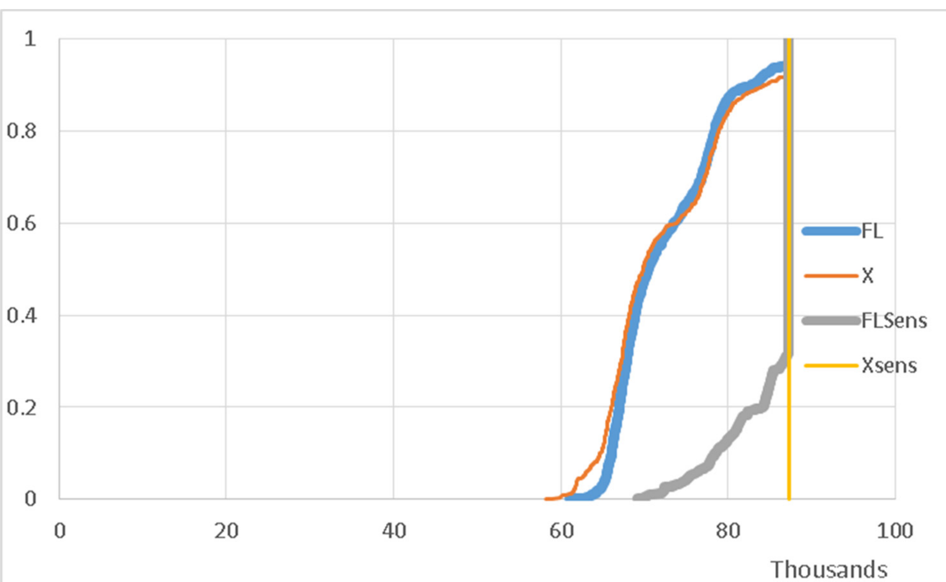

Figure G.16. Cumulative probability of anhydrous ammonia production for 35616 (Cherokee, AL) across scenarios of stochastic future linear (FL), future mixed-integer (X), future linear sensitivity (FLSens) and future mixed-integer sensitivity (Xsens).

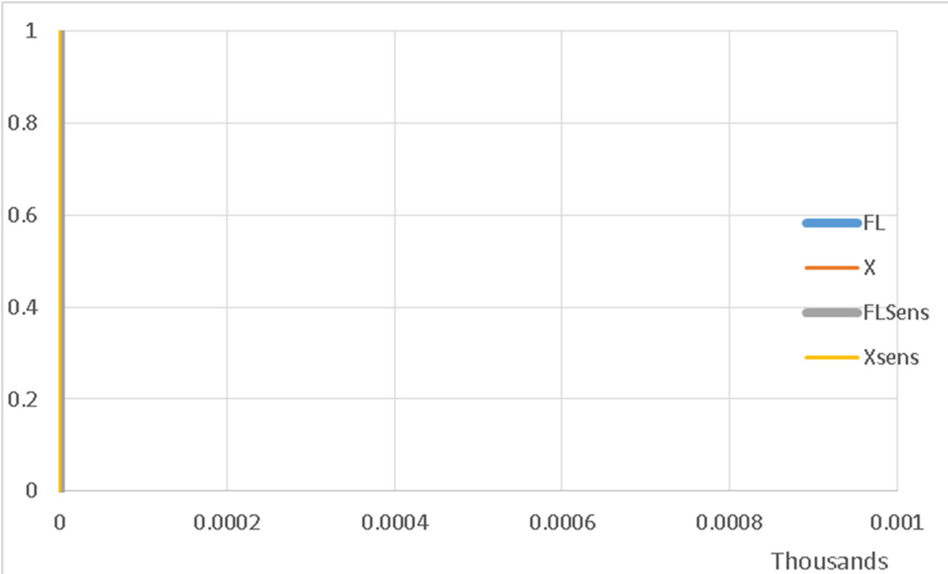

Figure G.17. Cumulative probability of urea production for 35616 (Cherokee, AL) across scenarios of stochastic future linear (FL), future mixed-integer (X), future linear sensitivity (FLSens) and future mixed-integer sensitivity (Xsens).

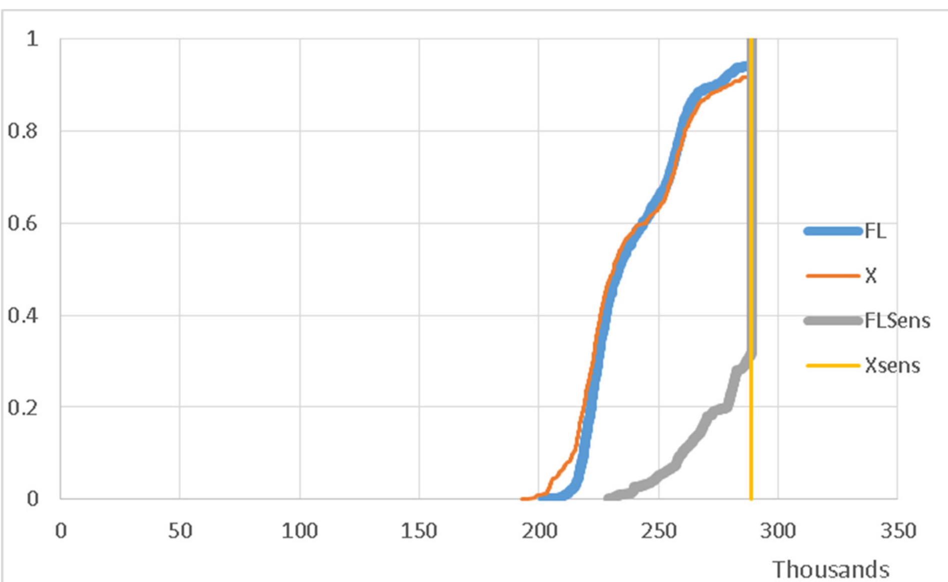

Figure G.18. Cumulative probability of UAN production for 35616 (Cherokee, AL) across scenarios of stochastic future linear (FL), future mixed-integer (X), future linear sensitivity (FLSens) and future mixed-integer sensitivity (Xsens).

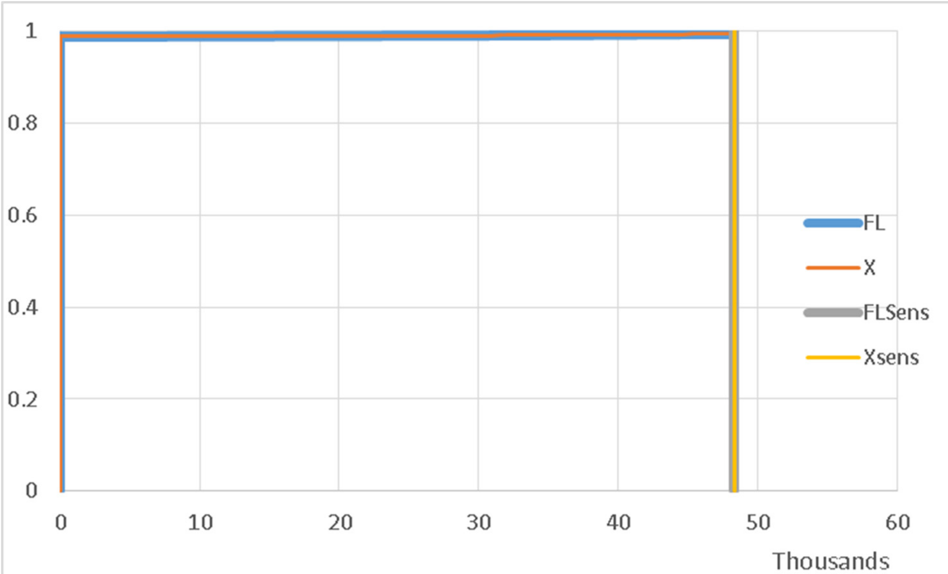

Figure G.19. Cumulative probability of anhydrous ammonia production for 39194 (Yazoo City, MS) across scenarios of stochastic future linear (FL), future mixed-integer (X), future linear sensitivity (FLSens) and future mixed-integer sensitivity (Xsens).

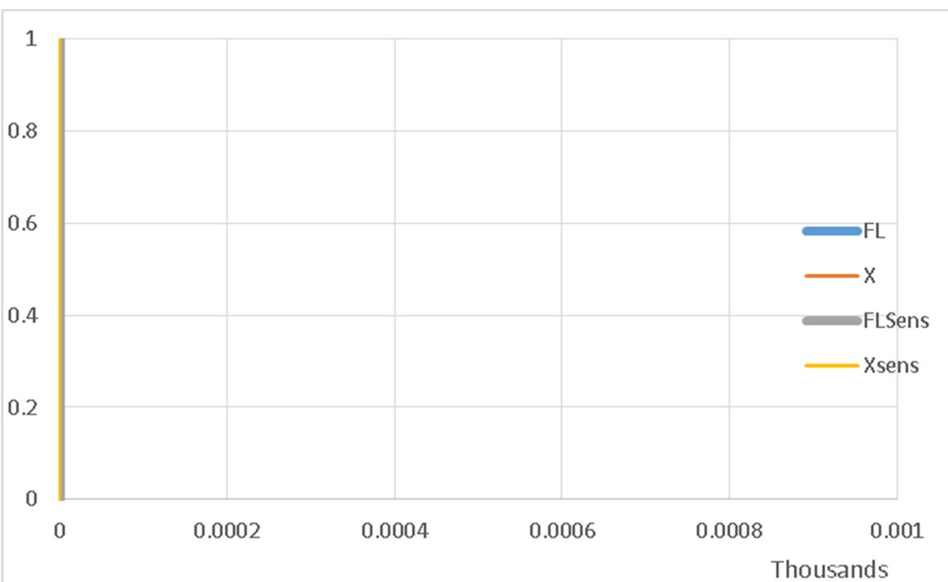

Figure G.20. Cumulative probability of urea production for 39194 (Yazoo City, MS) across scenarios of stochastic future linear (FL), future mixed-integer (X), future linear sensitivity (FLSens) and future mixed-integer sensitivity (Xsens).

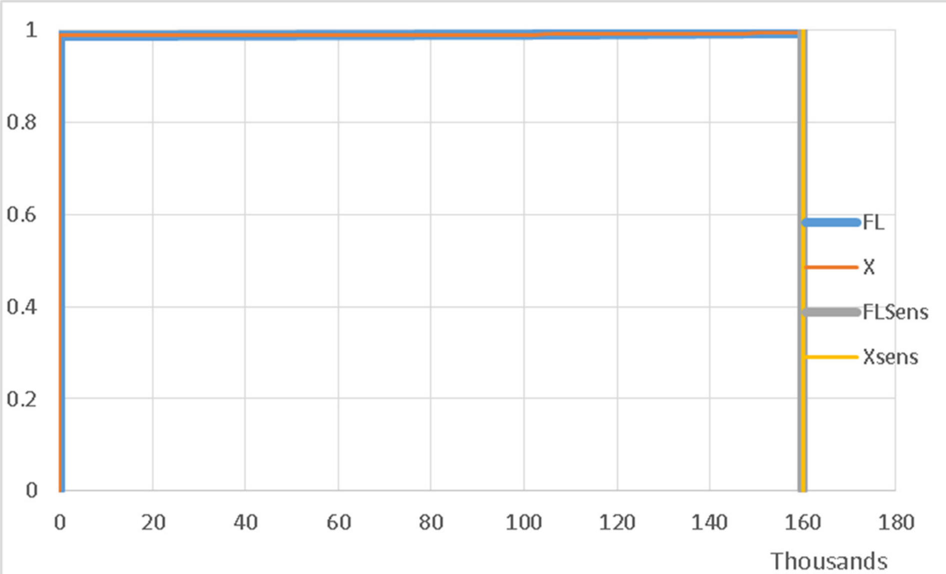

Figure G.21. Cumulative probability of UAN production for 39194 (Yazoo City, MS) across scenarios of stochastic future linear (FL), future mixed-integer (X), future linear sensitivity (FLSens) and future mixed-integer sensitivity (Xsens).

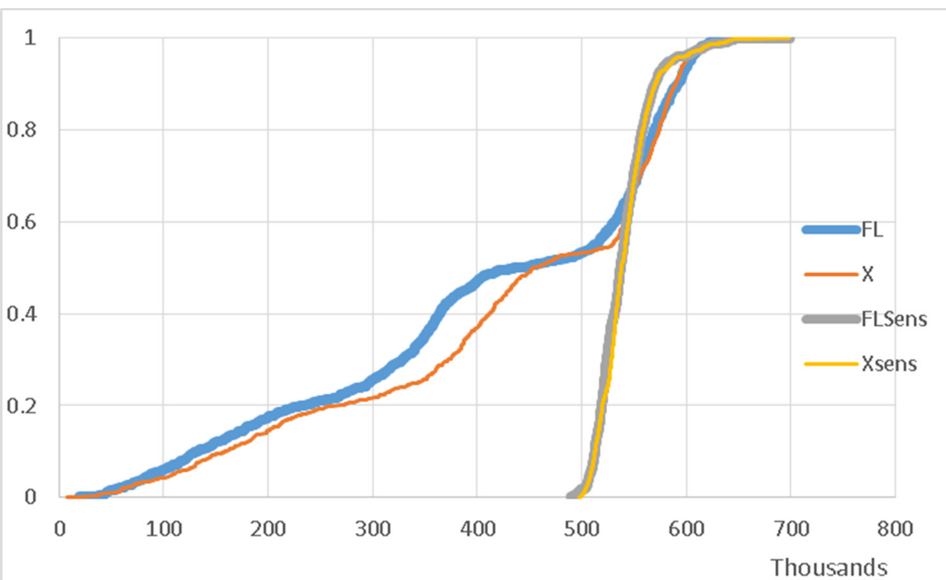

Figure G.22. Cumulative probability of anhydrous ammonia production for 4000131 (Catoosa, OK) across scenarios of stochastic future linear (FL), future mixed-integer (X), future linear sensitivity (FLSens) and future mixed-integer sensitivity (Xsens).

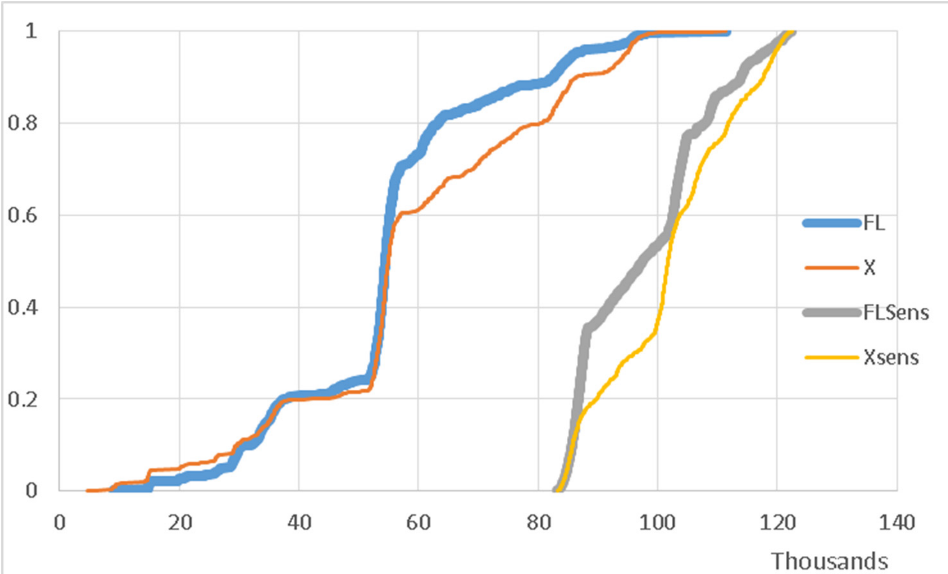

Figure G.23. Cumulative probability of urea production for 4000131 (Catoosa, OK) across scenarios of stochastic future linear (FL), future mixed-integer (X), future linear sensitivity (FLSens) and future mixed-integer sensitivity (Xsens).

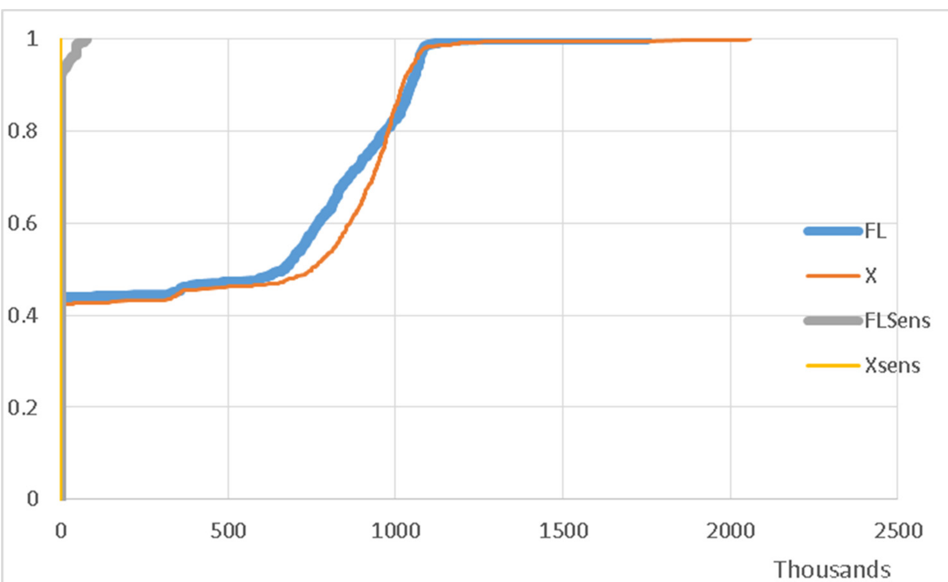

Figure G.24. Cumulative probability of UAN production for 4000131 (Catoosa, OK) across scenarios of stochastic future linear (FL), future mixed-integer (X), future linear sensitivity (FLSens) and future mixed-integer sensitivity (Xsens).

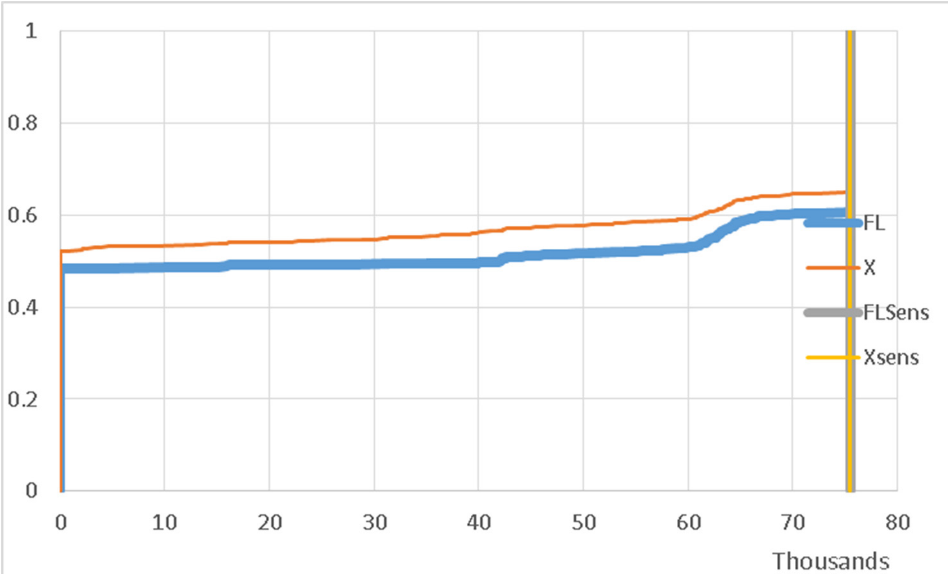

Figure G.25. Cumulative probability of anhydrous ammonia production for 45804 (Lima, OH) across scenarios of stochastic future linear (FL), future mixed-integer (X), future linear sensitivity (FLSens) and future mixed-integer sensitivity (Xsens).

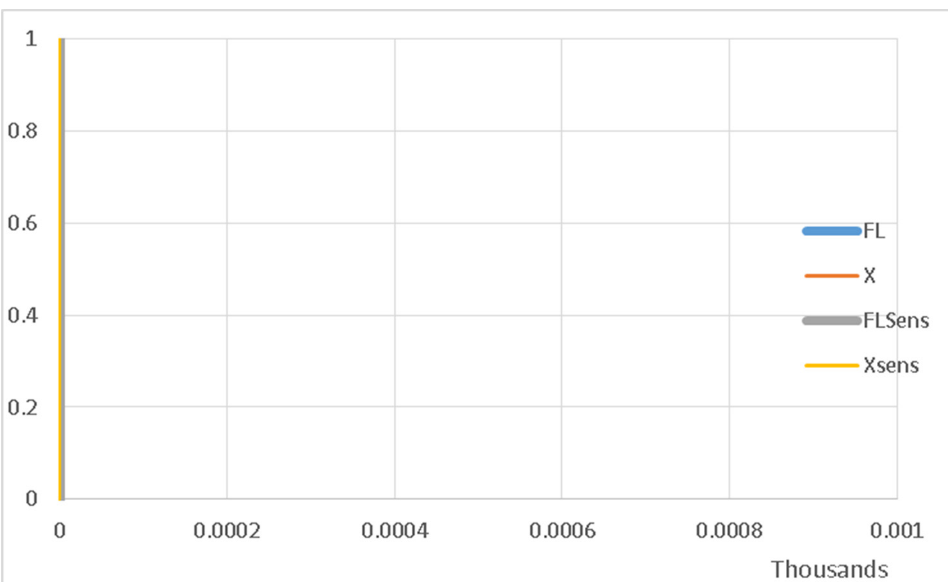

Figure G.26. Cumulative probability of urea production for 45804 (Lima, OH) across scenarios of stochastic future linear (FL), future mixed-integer (X), future linear sensitivity (FLSens) and future mixed-integer sensitivity (Xsens).

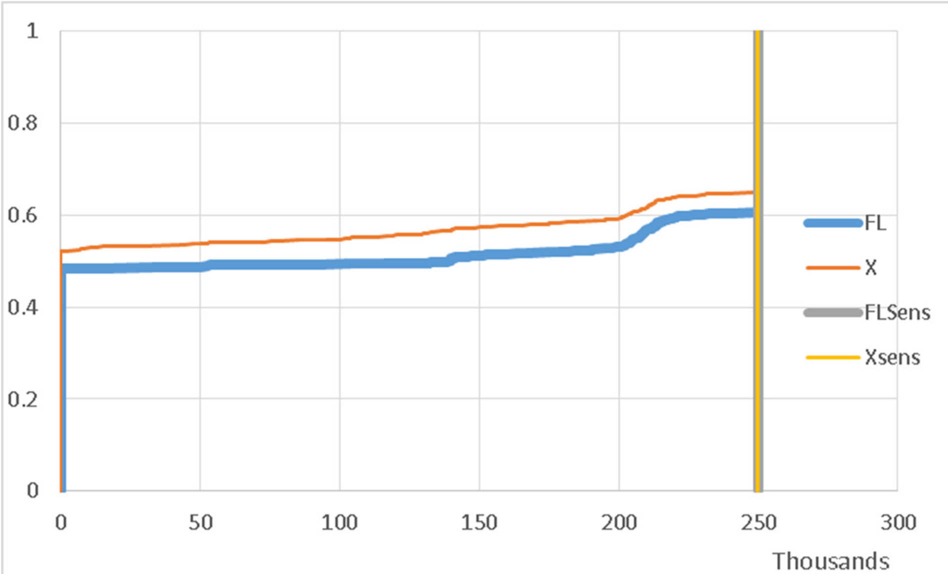

Figure G.27. Cumulative probability of UAN production for 45804 (Lima, OH) across scenarios of stochastic future linear (FL), future mixed-integer (X), future linear sensitivity (FLSens) and future mixed-integer sensitivity (Xsens).

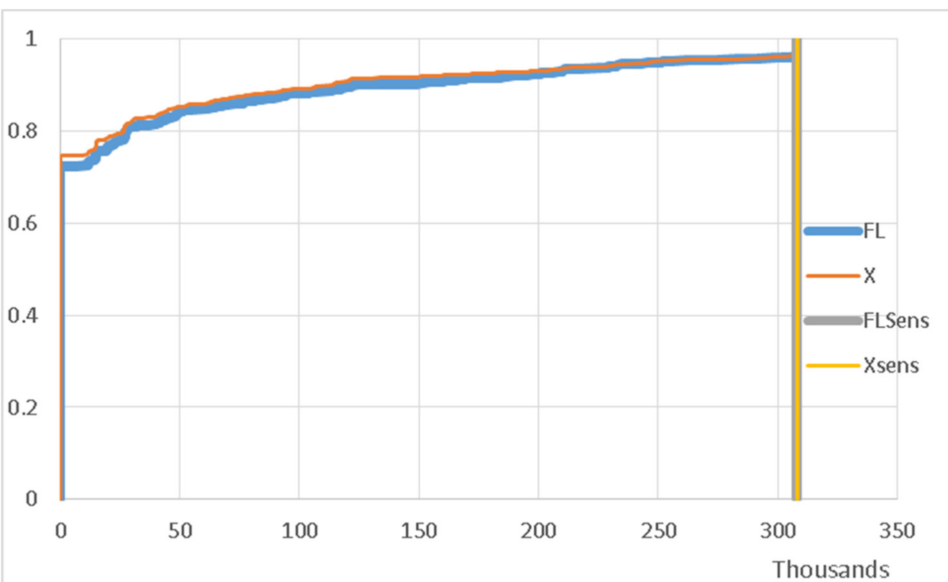

Figure G.28. Cumulative probability of anhydrous ammonia production for 47635 (Rockport, IN) across scenarios of stochastic future linear (FL), future mixed-integer (X), future linear sensitivity (FLSens) and future mixed-integer sensitivity (Xsens).

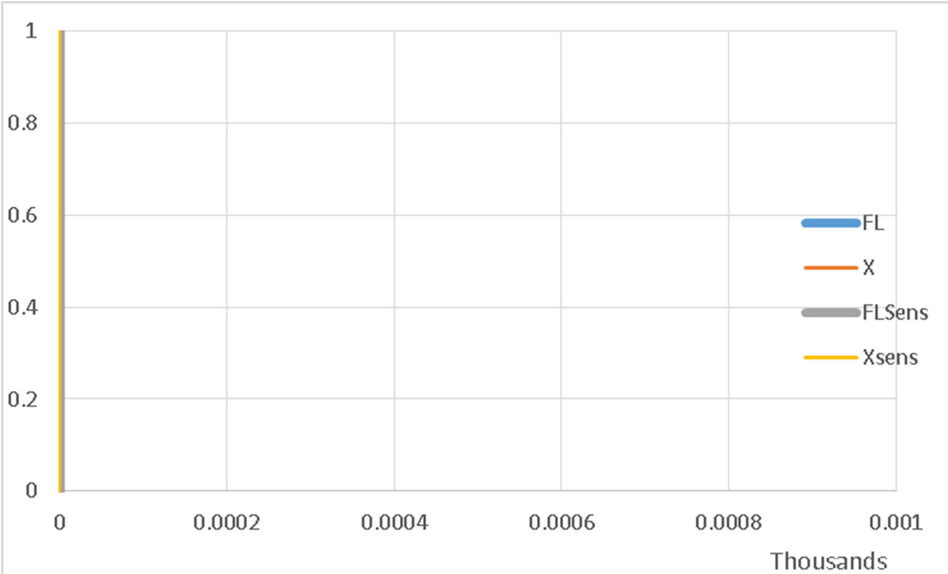

Figure G.29. Cumulative probability of urea production for 47635 (Rockport, IN) across scenarios of stochastic future linear (FL), future mixed-integer (X), future linear sensitivity (FLSens) and future mixed-integer sensitivity (Xsens).

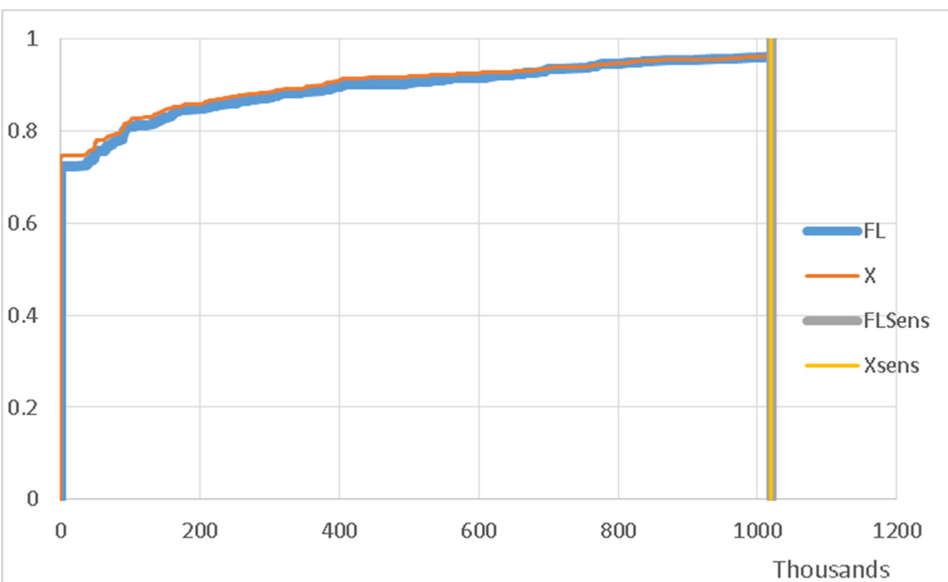

Figure G.30. Cumulative probability of UAN production for 47635 (Rockport, IN) across scenarios of stochastic future linear (FL), future mixed-integer (X), future linear sensitivity (FLSens) and future mixed-integer sensitivity (Xsens).

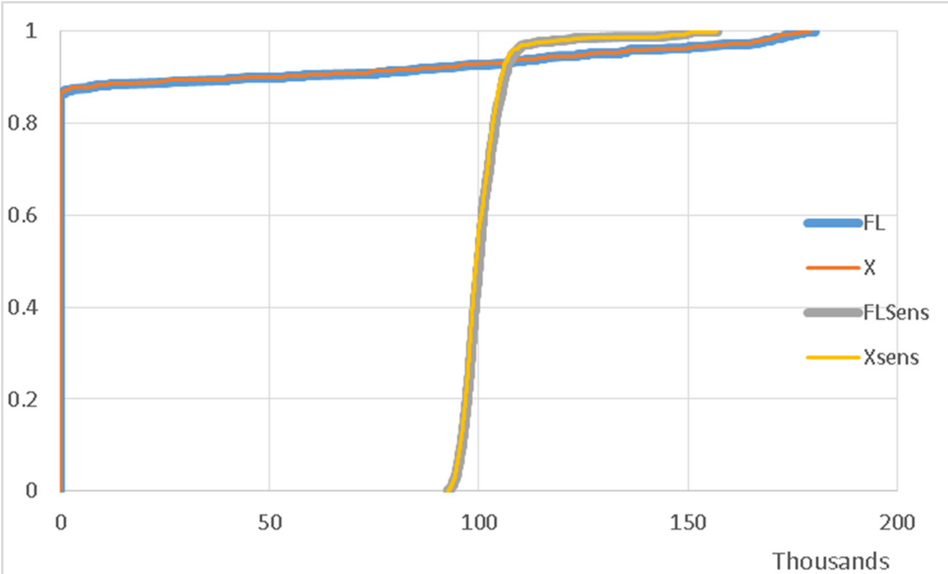

Figure G.31. Cumulative probability of anhydrous ammonia production for 4800608 (Galveston, TX) across scenarios of stochastic future linear (FL), future mixed-integer (X), future linear sensitivity (FLSens) and future mixed-integer sensitivity (Xsens).

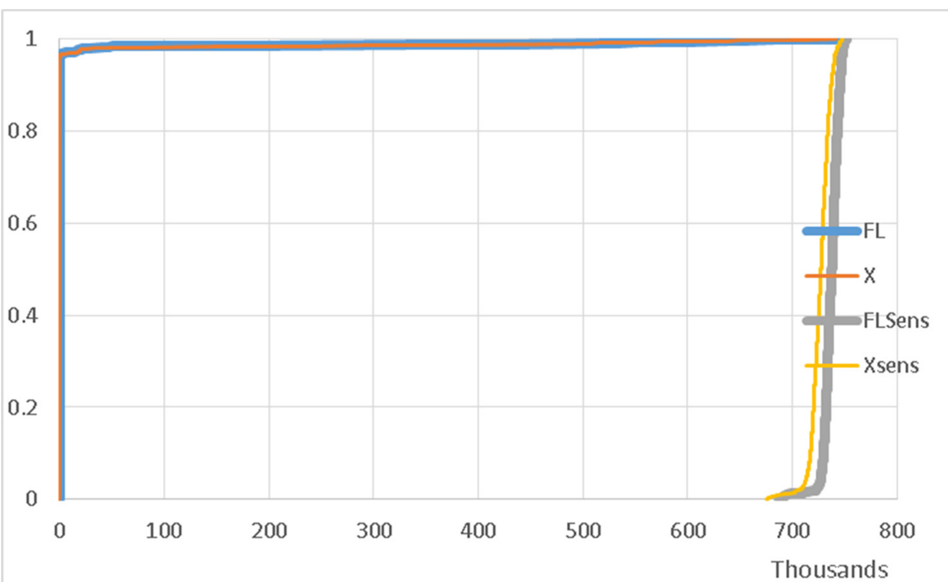

Figure G.32. Cumulative probability of urea production for 4800608 (Galveston, TX) across scenarios of stochastic future linear (FL), future mixed-integer (X), future linear sensitivity (FLSens) and future mixed-integer sensitivity (Xsens).

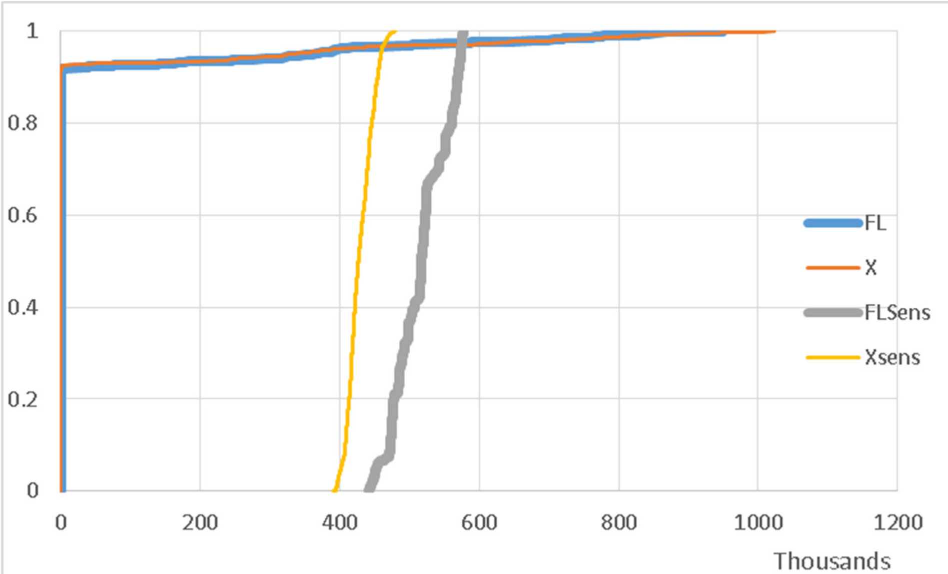

Figure G.33. Cumulative probability of UAN production for 4800608 (Galveston, TX) across scenarios of stochastic future linear (FL), future mixed-integer (X), future linear sensitivity (FLSens) and future mixed-integer sensitivity (Xsens).

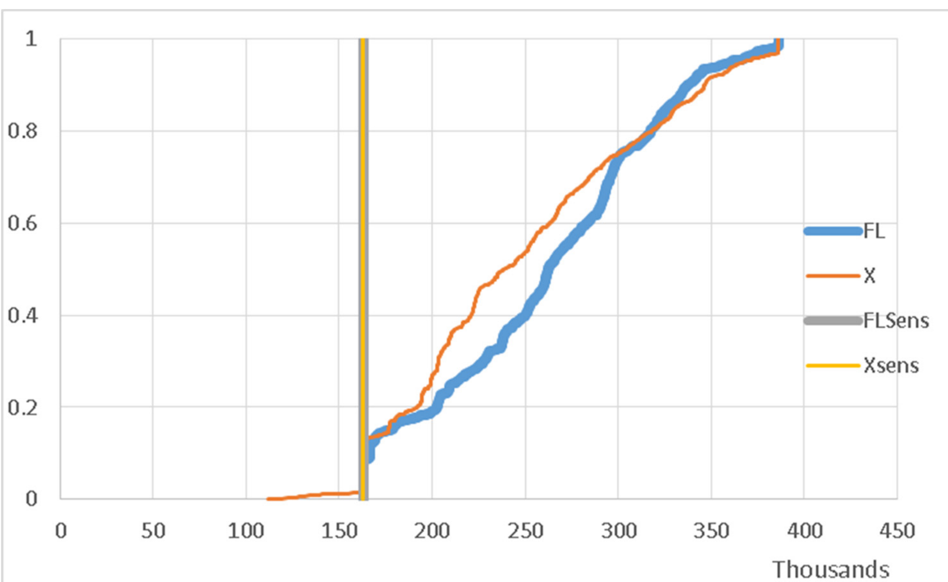

Figure G.34. Cumulative probability of anhydrous ammonia production for 50501 (Fort Dodge, IA) across scenarios of stochastic future linear (FL), future mixed-integer (X), future linear sensitivity (FLSens) and future mixed-integer sensitivity (Xsens).

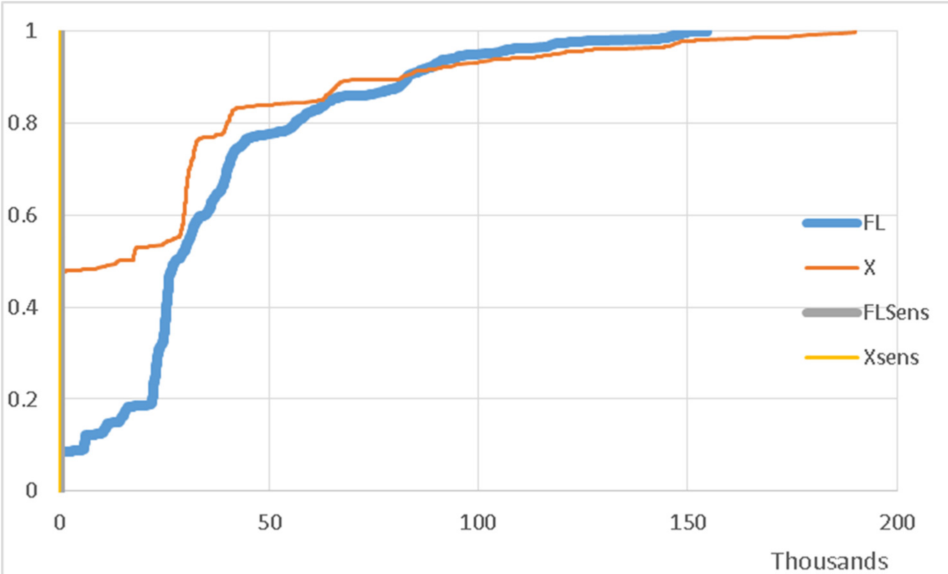

Figure G.35. Cumulative probability of urea production for 50501 (Fort Dodge, IA) across scenarios of stochastic future linear (FL), future mixed-integer (X), future linear sensitivity (FLSens) and future mixed-integer sensitivity (Xsens).

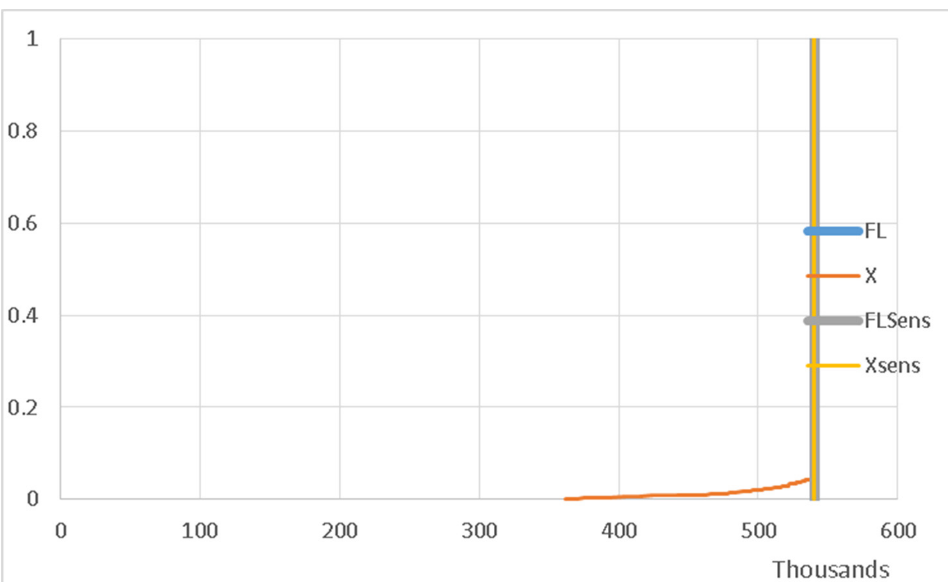

Figure G.36. Cumulative probability of UAN production for 50501 (Fort Dodge, IA) across scenarios of stochastic future linear (FL), future mixed-integer (X), future linear sensitivity (FLSens) and future mixed-integer sensitivity (Xsens).

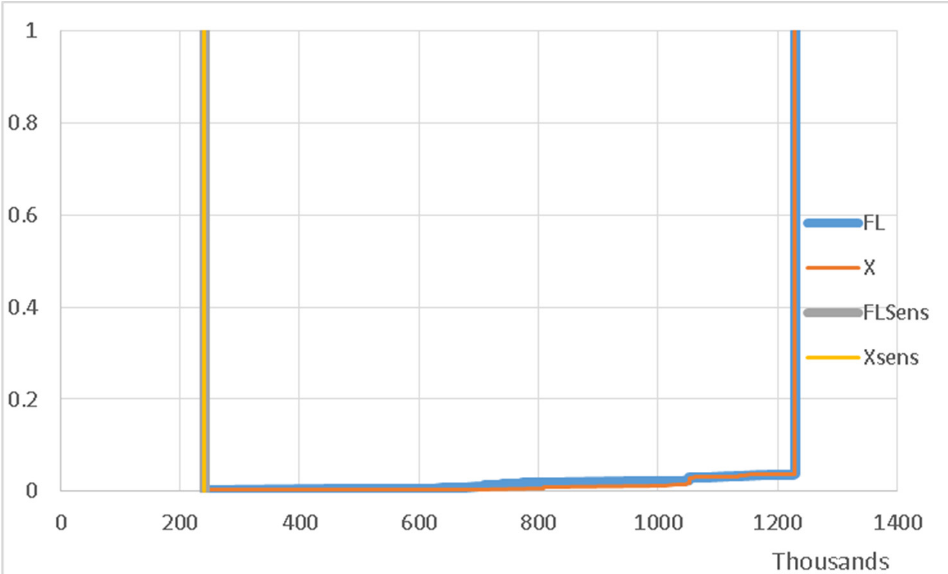

Figure G.37. Cumulative probability of anhydrous ammonia production for 51054 (Port Neal, IA) across scenarios of stochastic future linear (FL), future mixed-integer (X), future linear sensitivity (FLSens) and future mixed-integer sensitivity (Xsens).

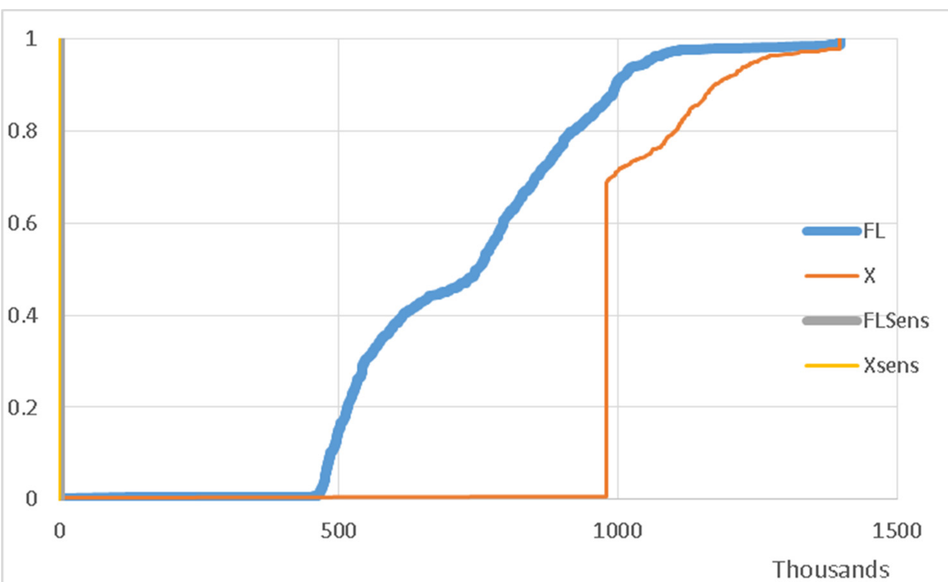

Figure G.38. Cumulative probability of urea production for 51054 (Port Neal, IA) across scenarios of stochastic future linear (FL), future mixed-integer (X), future linear sensitivity (FLSens) and future mixed-integer sensitivity (Xsens).

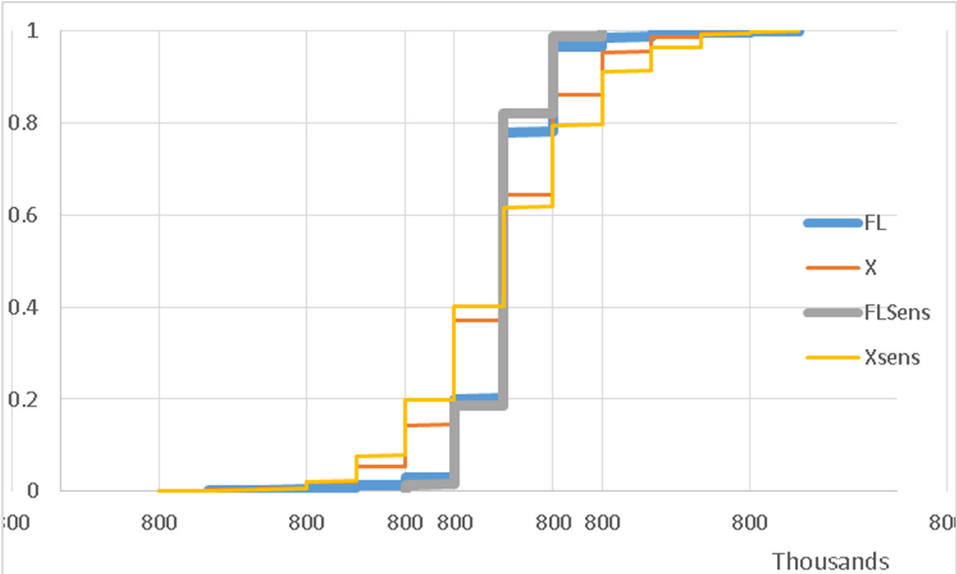

Figure G.39. Cumulative probability of UAN production for 51054 (Port Neal, IA) across scenarios of stochastic future linear (FL), future mixed-integer (X), future linear sensitivity (FLSens) and future mixed-integer sensitivity (Xsens).

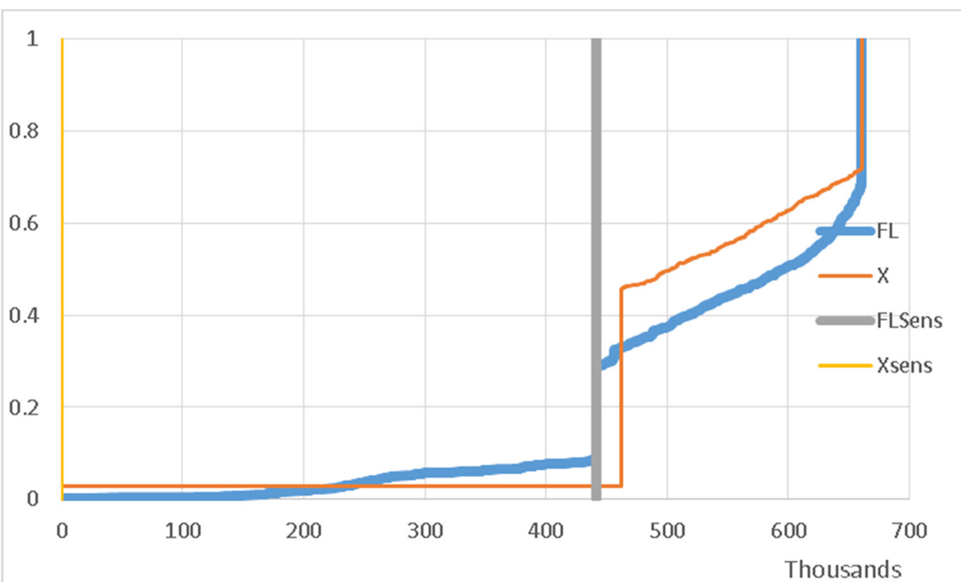

Figure G.40. Cumulative probability of anhydrous ammonia production for 52658 (Wever, IA) across scenarios of stochastic future linear (FL), future mixed-integer (X), future linear sensitivity (FLSens) and future mixed-integer sensitivity (Xsens).

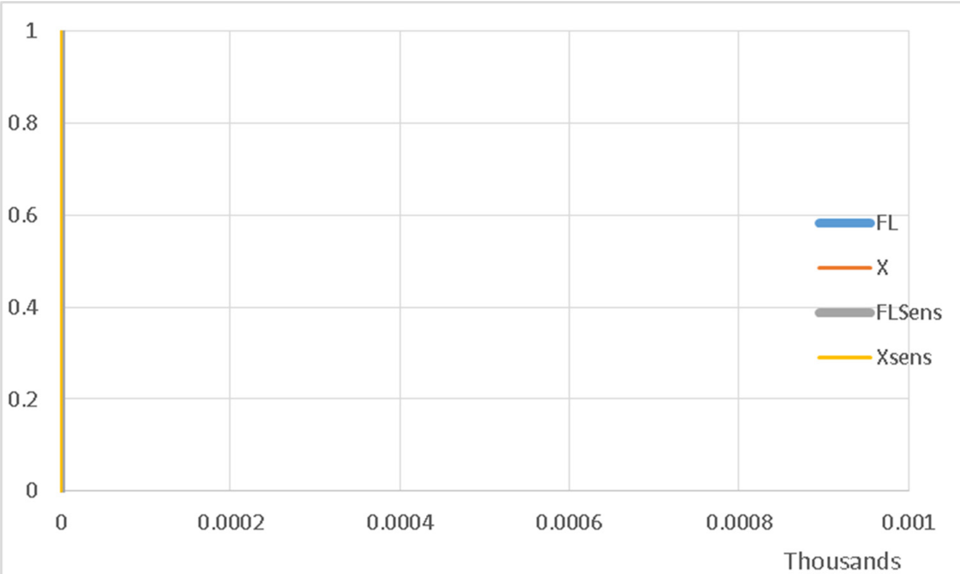

Figure G.41. Cumulative probability of urea production for 52658 (Wever, IA) across scenarios of stochastic future linear (FL), future mixed-integer (X), future linear sensitivity (FLSens) and future mixed-integer sensitivity (Xsens).

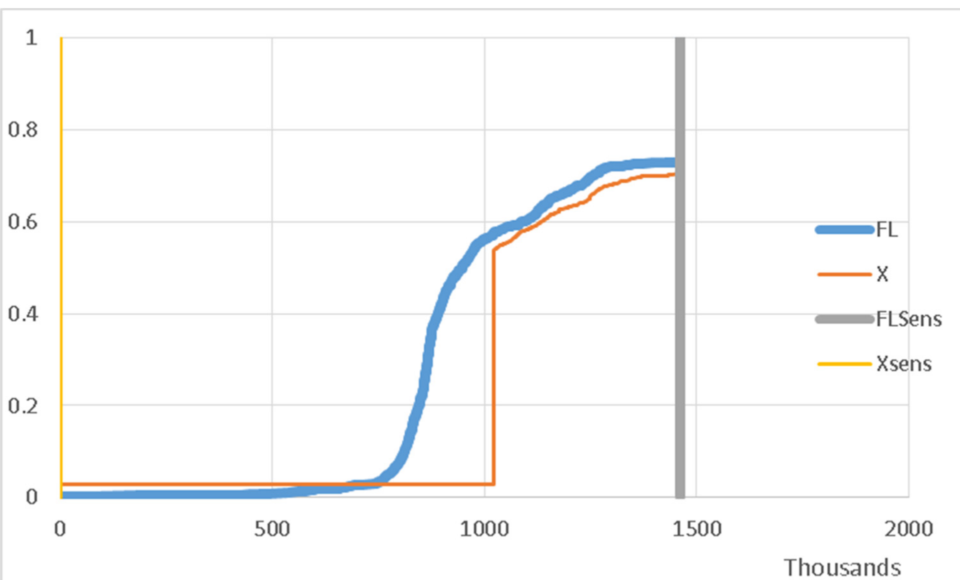

Figure G.42. Cumulative probability of UAN production for 52658 (Wever, IA) across scenarios of stochastic future linear (FL), future mixed-integer (X), future linear sensitivity (FLSens) and future mixed-integer sensitivity (Xsens).

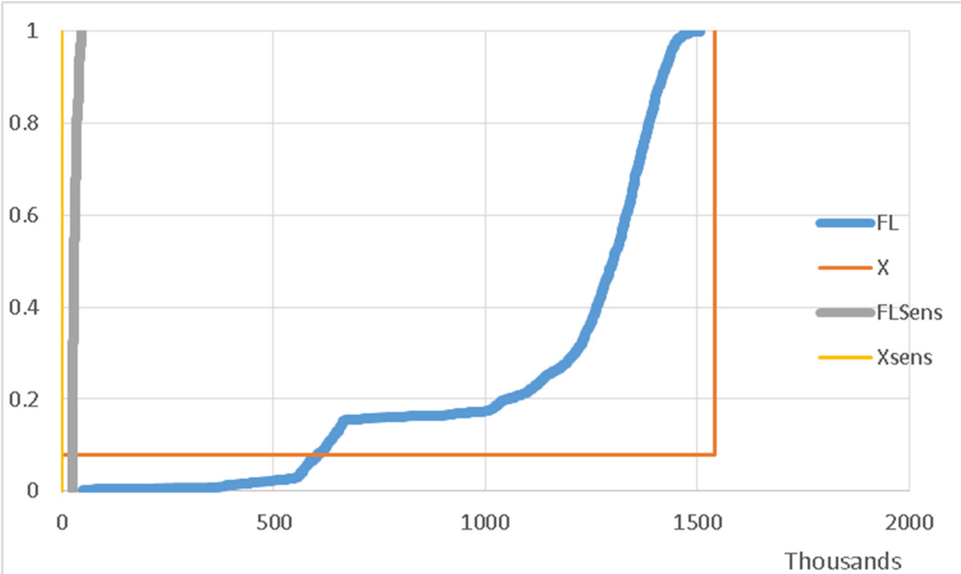

Figure G.43. Cumulative probability of anhydrous ammonia production for 58203 (Grand Forks, ND) across scenarios of stochastic future linear (FL), future mixed-integer (X), future linear sensitivity (FLSens) and future mixed-integer sensitivity (Xsens).

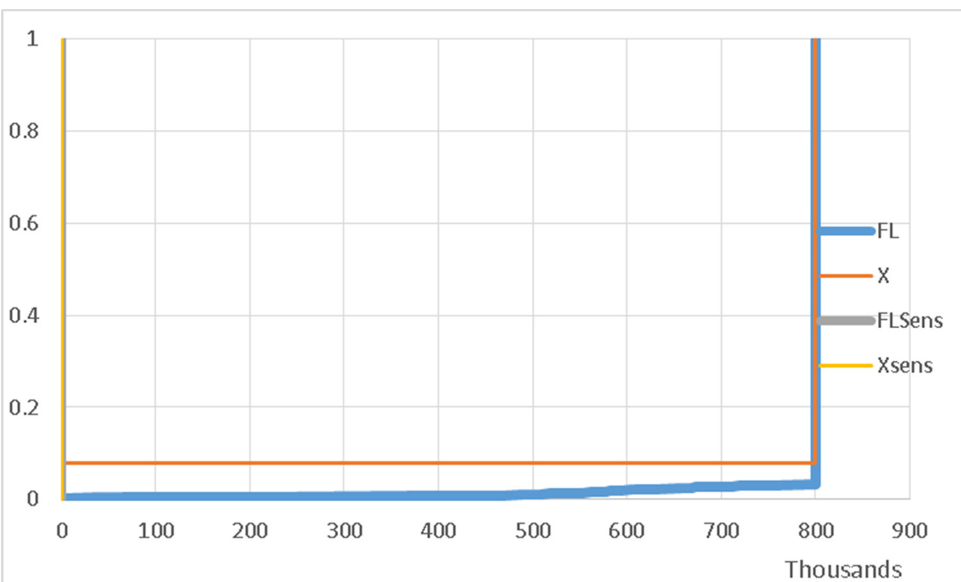

Figure G.44. Cumulative probability of urea production for 58203 (Grand Forks, ND) across scenarios of stochastic future linear (FL), future mixed-integer (X), future linear sensitivity (FLSens) and future mixed-integer sensitivity (Xsens).

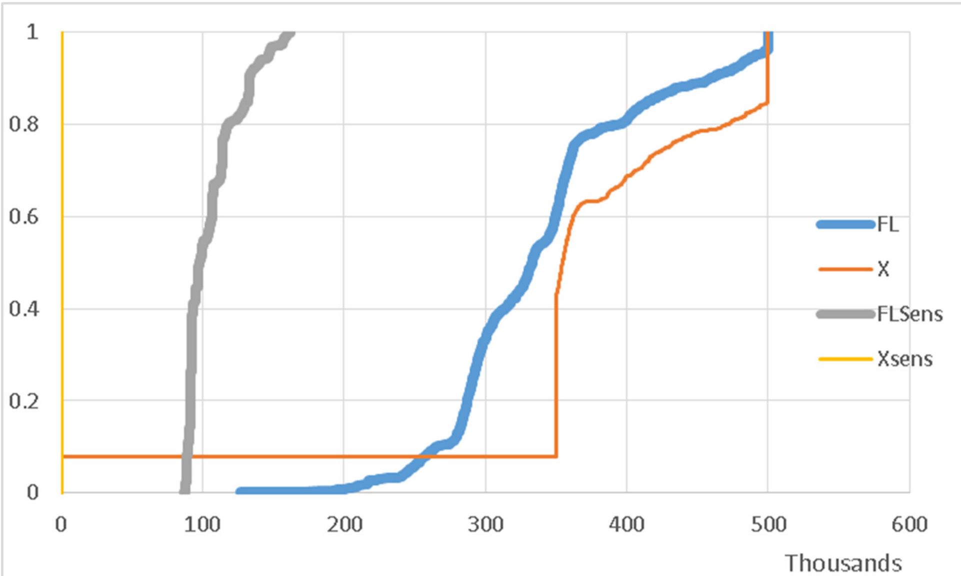

Figure G.45. Cumulative probability of UAN production for 58203 (Grand Forks, ND) across scenarios of stochastic future linear (FL), future mixed-integer (X), future linear sensitivity (FLSens) and future mixed-integer sensitivity (Xsens).

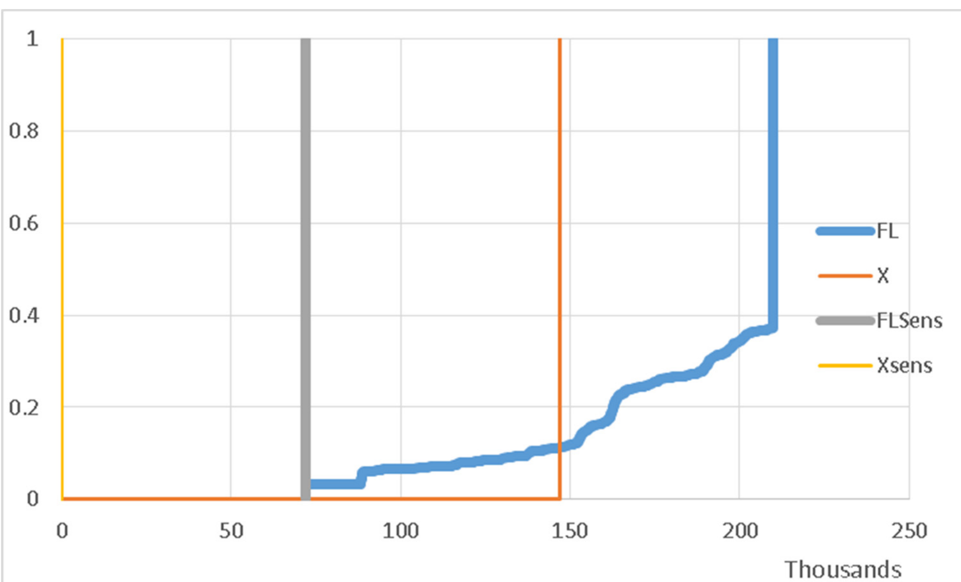

Figure G.46. Cumulative probability of anhydrous ammonia production for 58481 (Jamestown, ND) across scenarios of stochastic future linear (FL), future mixed-integer (X), future linear sensitivity (FLSens) and future mixed-integer sensitivity (Xsens).

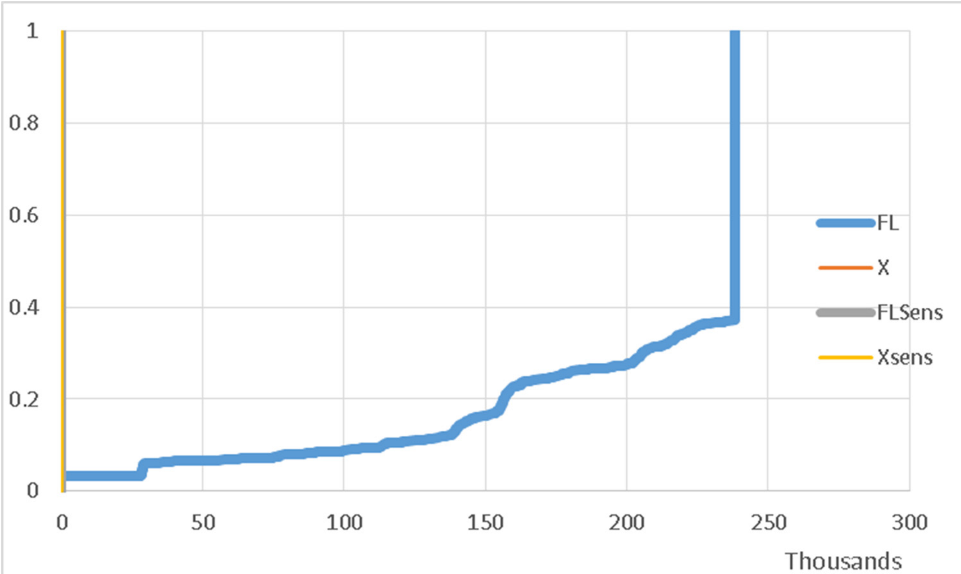

Figure G.47. Cumulative probability of urea production for 58481 (Jamestown, ND) across scenarios of stochastic future linear (FL), future mixed-integer (X), future linear sensitivity (FLSens) and future mixed-integer sensitivity (Xsens).

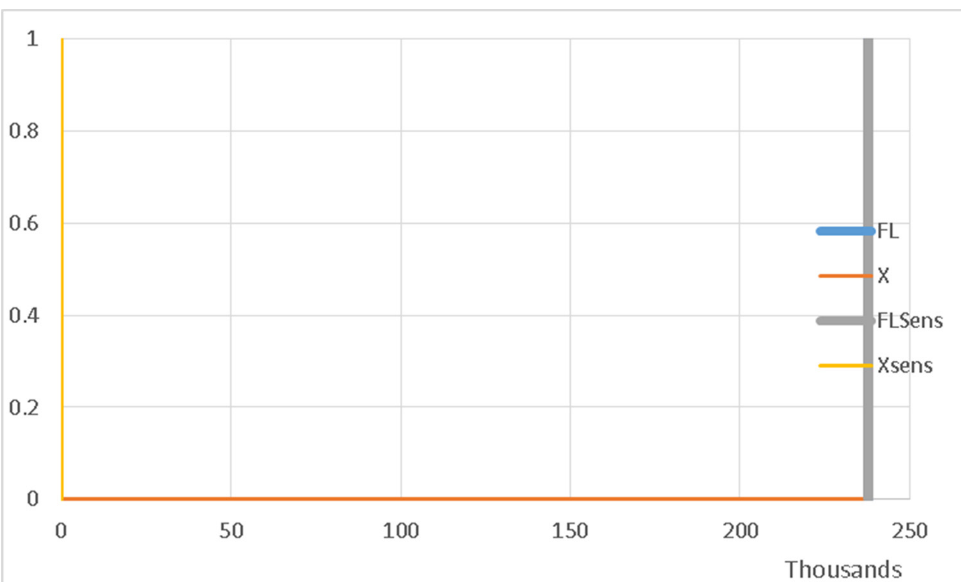

Figure G.48. Cumulative probability of UAN production for 58481 (Jamestown, ND) across scenarios of stochastic future linear (FL), future mixed-integer (X), future linear sensitivity (FLSens) and future mixed-integer sensitivity (Xsens).

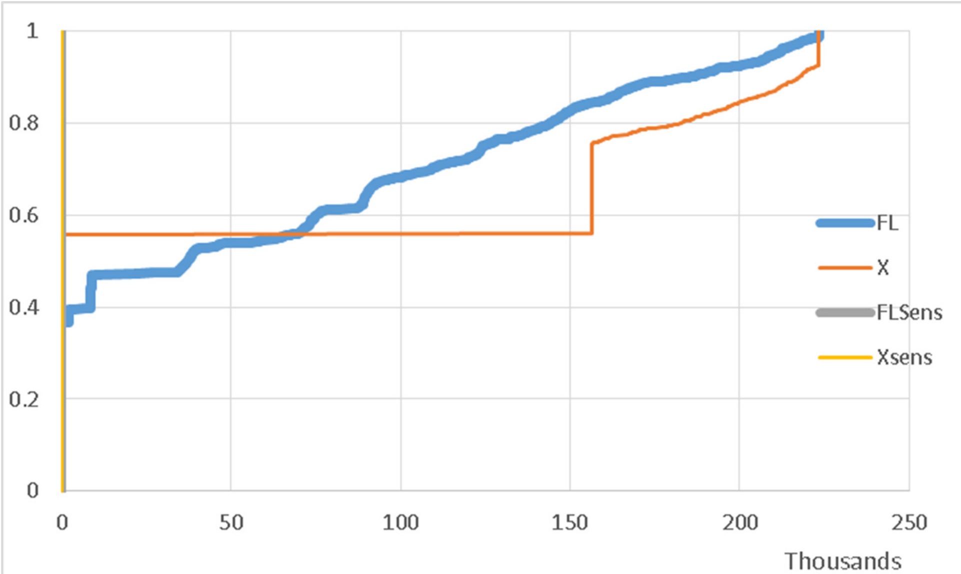

Figure G.49. Cumulative probability of anhydrous ammonia production for 58523 (Beulah, ND) across scenarios of stochastic future linear (FL), future mixed-integer (X), future linear sensitivity (FLSens) and future mixed-integer sensitivity (Xsens).

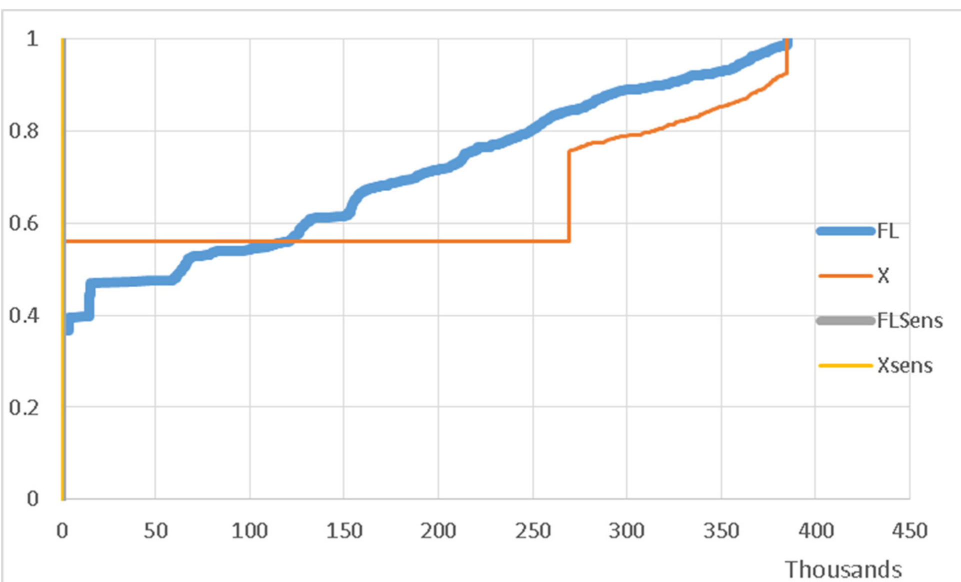

Figure G.50. Cumulative probability of urea production for 58523 (Beulah, ND) across scenarios of stochastic future linear (FL), future mixed-integer (X), future linear sensitivity (FLSens) and future mixed-integer sensitivity (Xsens).

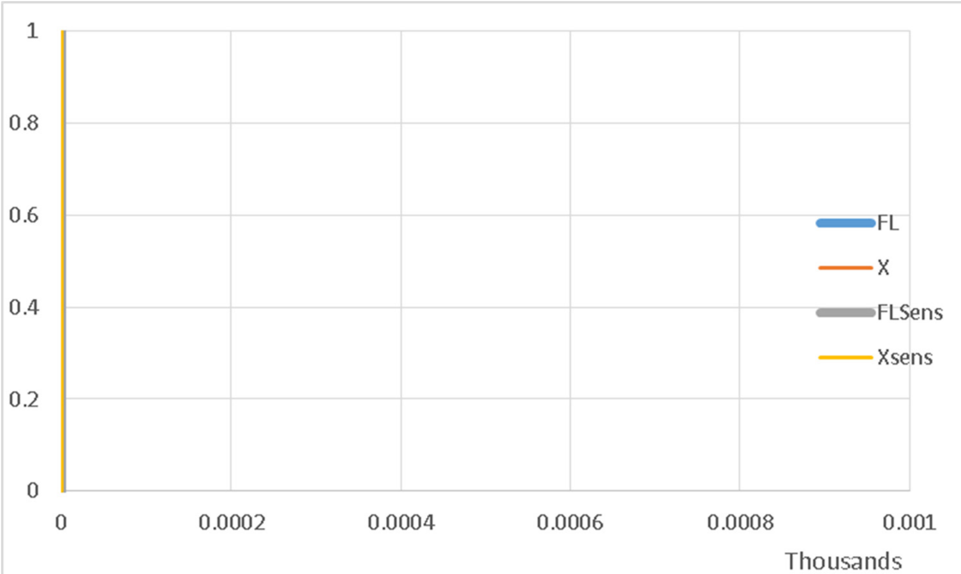

Figure G.51. Cumulative probability of UAN production for 58523 (Beulah, ND) across scenarios of stochastic future linear (FL), future mixed-integer (X), future linear sensitivity (FLSens) and future mixed-integer sensitivity (Xsens).

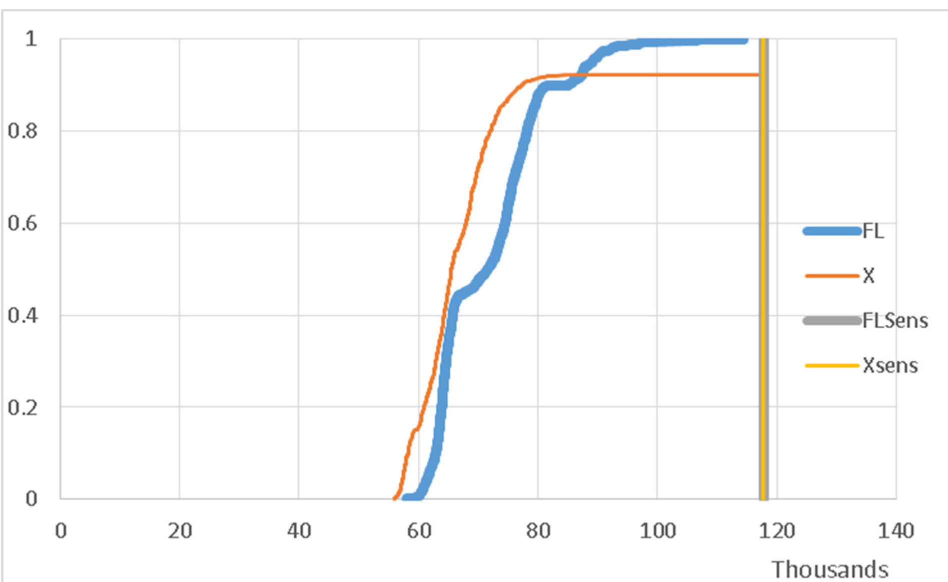

Figure G.52. Cumulative probability of anhydrous ammonia production for 61025 (East Dubuque, IL) across scenarios of stochastic future linear (FL), future mixed-integer (X), future linear sensitivity (FLSens) and future mixed-integer sensitivity (Xsens).

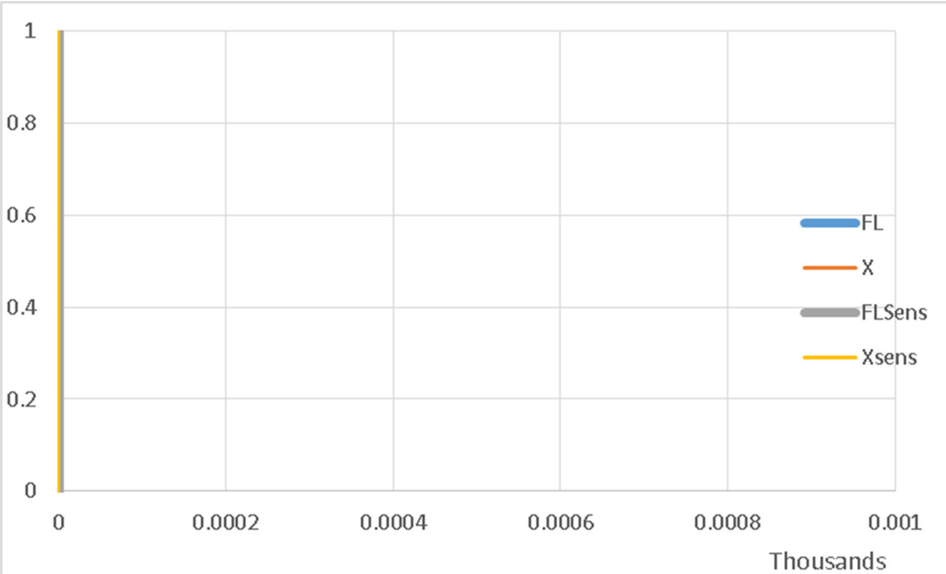

Figure G.53. Cumulative probability of urea production for 61025 (East Dubuque, IL) across scenarios of stochastic future linear (FL), future mixed-integer (X), future linear sensitivity (FLSens) and future mixed-integer sensitivity (Xsens).

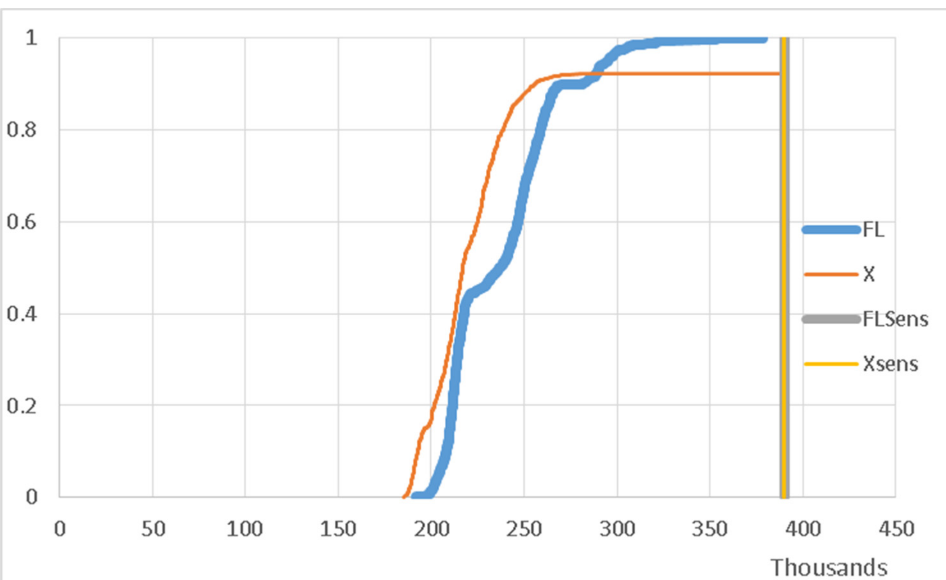

Figure G.54. Cumulative probability of UAN production for 61025 (East Dubuque, IL) across scenarios of stochastic future linear (FL), future mixed-integer (X), future linear sensitivity (FLSens) and future mixed-integer sensitivity (Xsens).

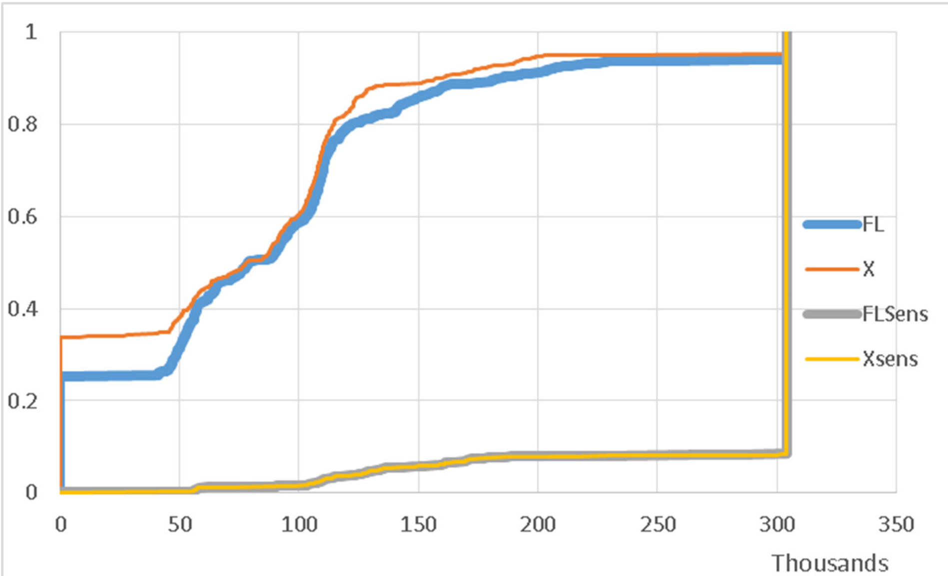

Figure G.55. Cumulative probability of anhydrous ammonia production for 612 (Medicine Hat, AB) across scenarios of stochastic future linear (FL), future mixed-integer (X), future linear sensitivity (FLSens) and future mixed-integer sensitivity (Xsens).

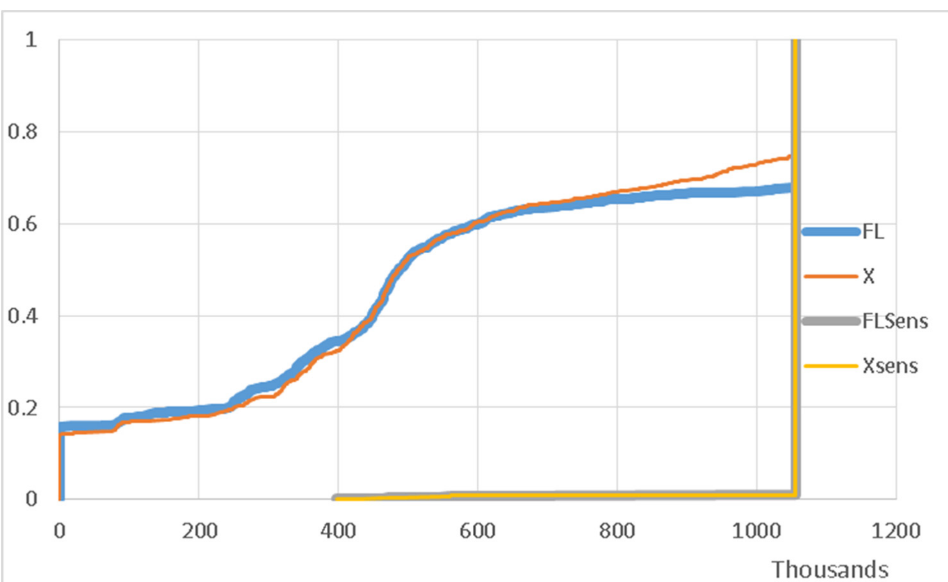

Figure G.56. Cumulative probability of urea production for 612 (Medicine Hat, AB) across scenarios of stochastic future linear (FL), future mixed-integer (X), future linear sensitivity (FLSens) and future mixed-integer sensitivity (Xsens).

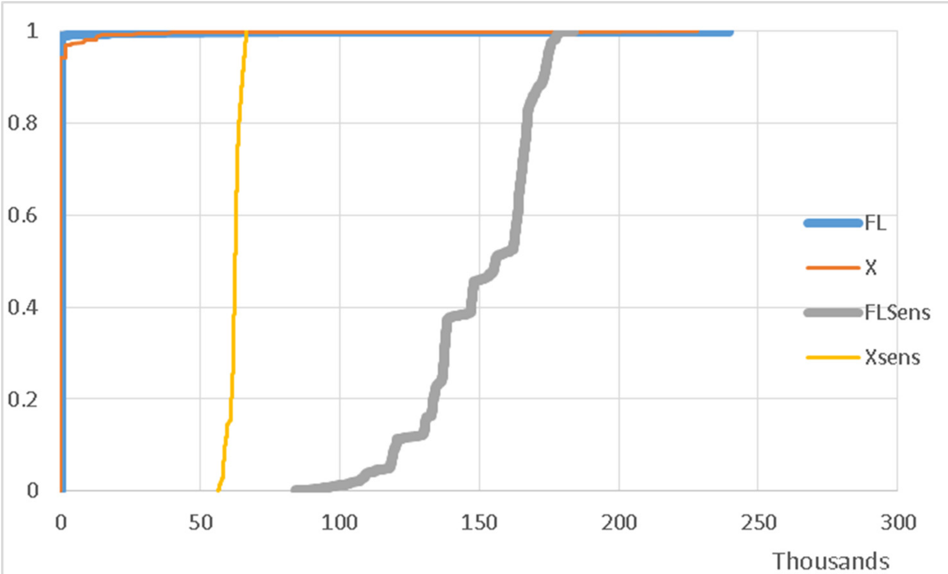

Figure G.57. Cumulative probability of UAN production for 612 (Medicine Hat, AB) across scenarios of stochastic future linear (FL), future mixed-integer (X), future linear sensitivity (FLSens) and future mixed-integer sensitivity (Xsens).

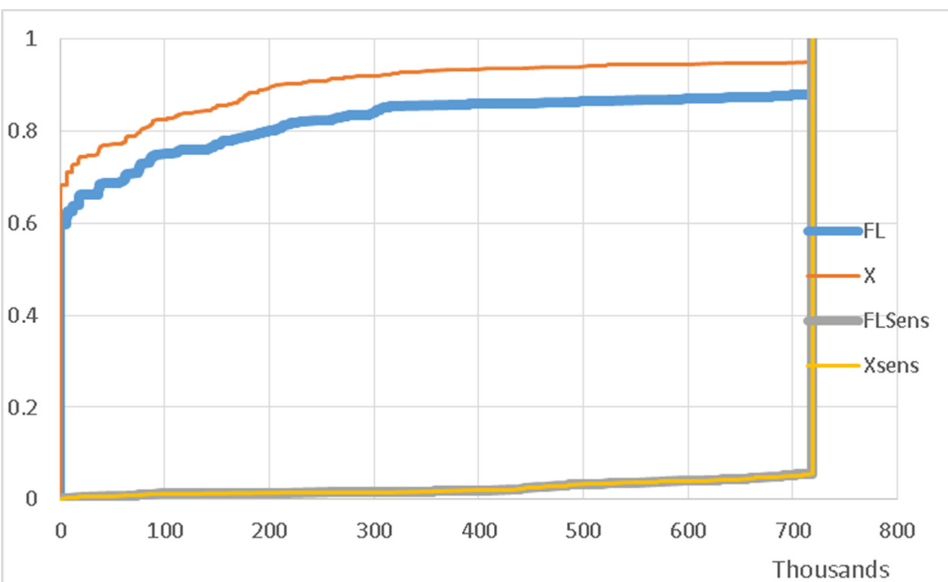

Figure G.58. Cumulative probability of anhydrous ammonia production for 644 (Belle Plaine, SK) across scenarios of stochastic future linear (FL), future mixed-integer (X), future linear sensitivity (FLSens) and future mixed-integer sensitivity (Xsens).

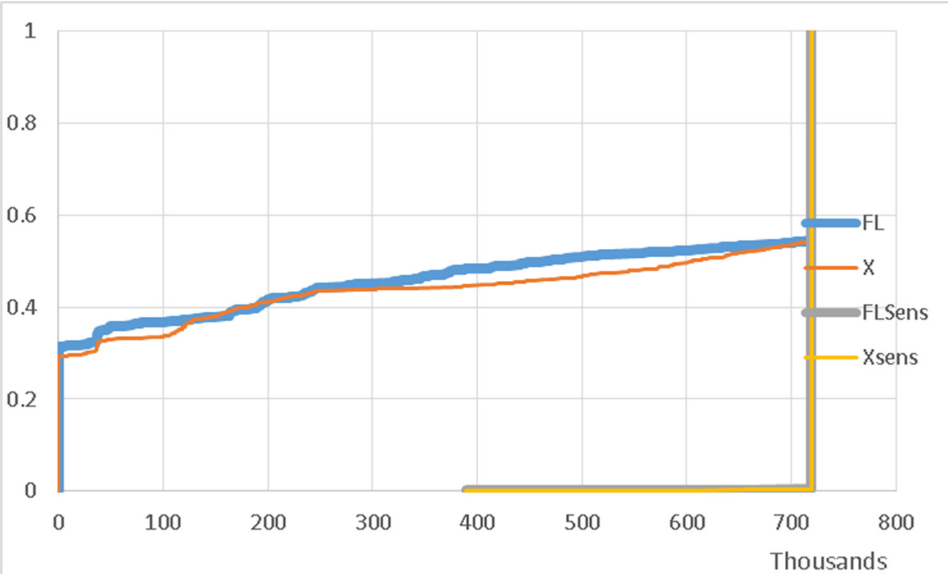

Figure G.59. Cumulative probability of urea production for 644 (Belle Plaine, SK) across scenarios of stochastic future linear (FL), future mixed-integer (X), future linear sensitivity (FLSens) and future mixed-integer sensitivity (Xsens).

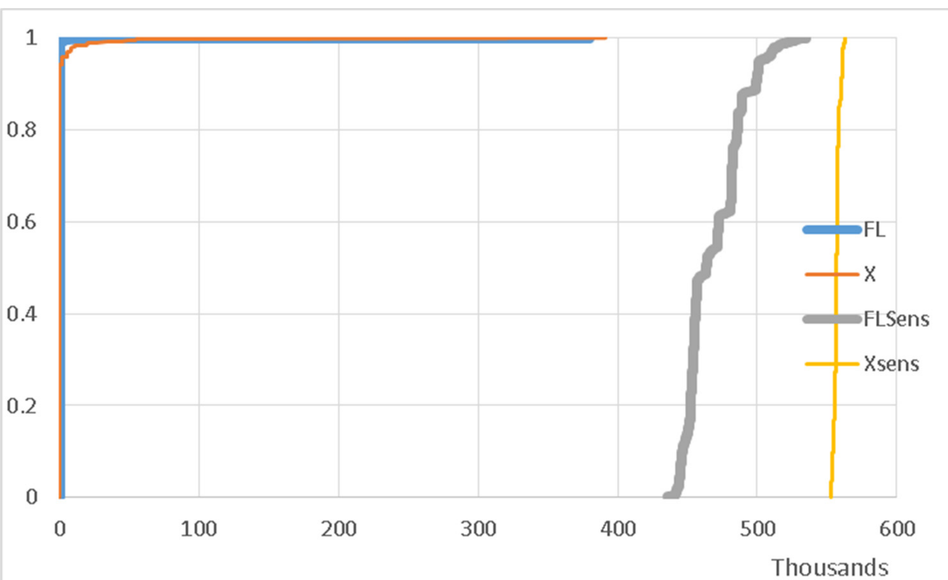

Figure G.60. Cumulative probability of UAN production for 644 (Belle Plaine, SK) across scenarios of stochastic future linear (FL), future mixed-integer (X), future linear sensitivity (FLSens) and future mixed-integer sensitivity (Xsens).

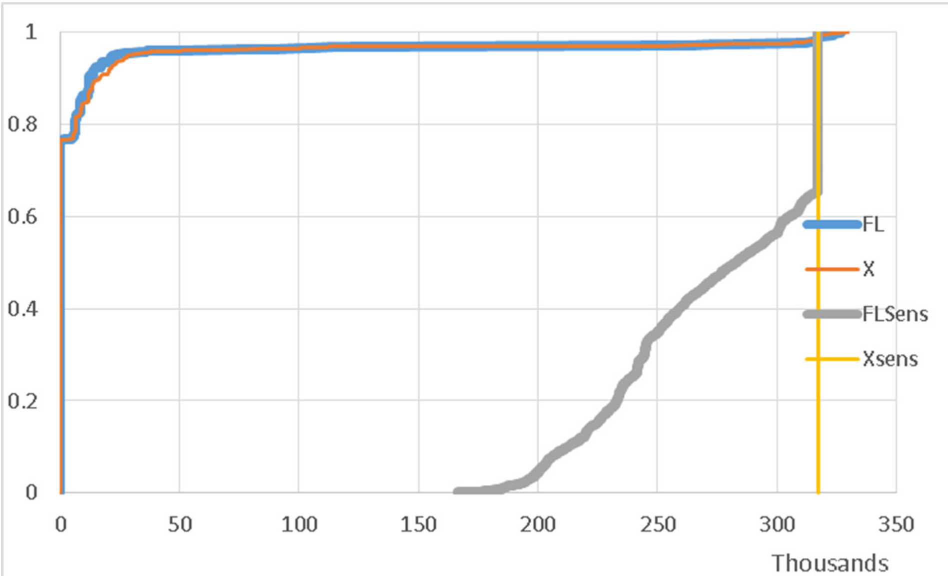

Figure G.61. Cumulative probability of anhydrous ammonia production for 67337 (Coffeyville, KS) across scenarios of stochastic future linear (FL), future mixed-integer (X), future linear sensitivity (FLSens) and future mixed-integer sensitivity (Xsens).

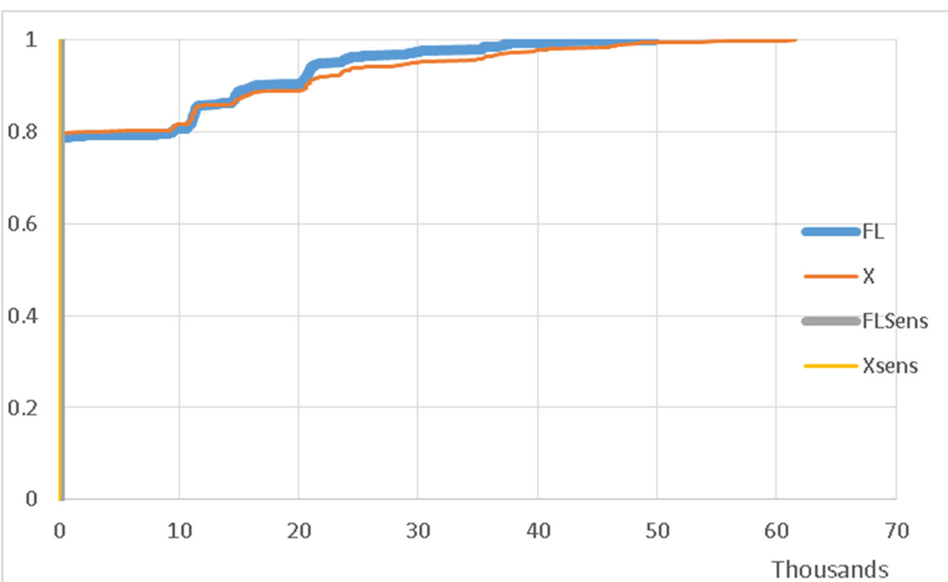

Figure G.62. Cumulative probability of urea production for 67337 (Coffeyville, KS) across scenarios of stochastic future linear (FL), future mixed-integer (X), future linear sensitivity (FLSens) and future mixed-integer sensitivity (Xsens).

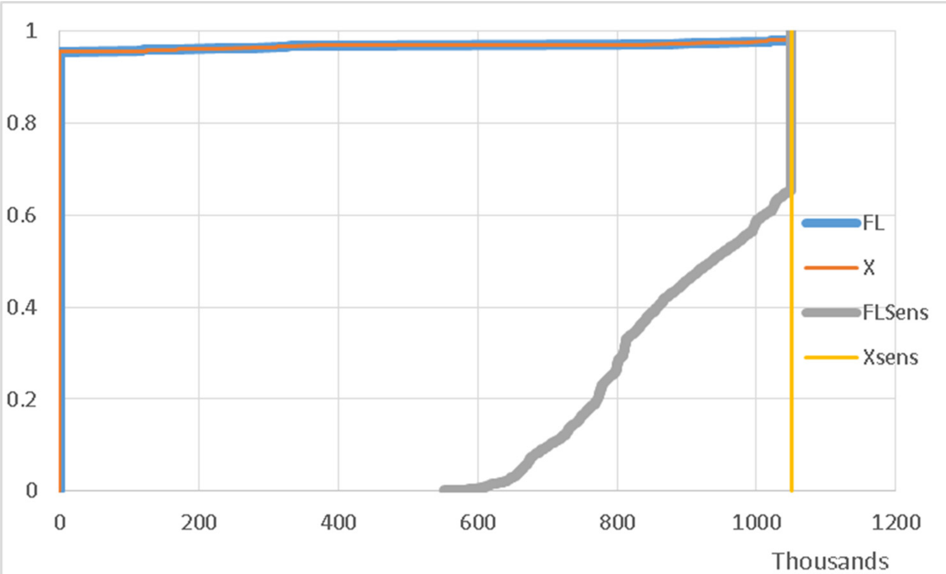

Figure G.63. Cumulative probability of UAN production for 67337 (Coffeyville, KS) across scenarios of stochastic future linear (FL), future mixed-integer (X), future linear sensitivity (FLSens) and future mixed-integer sensitivity (Xsens).

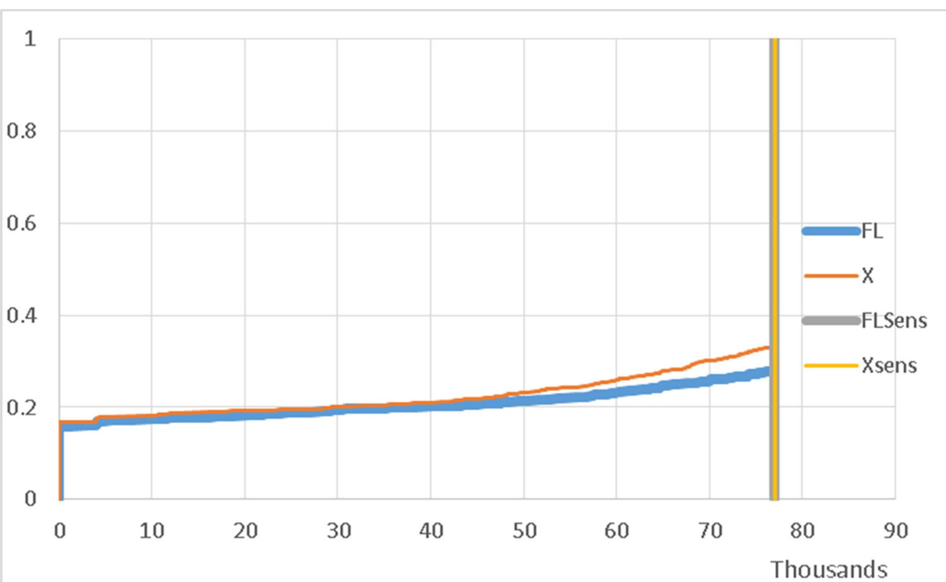

Figure G.64. Cumulative probability of anhydrous ammonia production for 67801 (Dodge City, KS) across scenarios of stochastic future linear (FL), future mixed-integer (X), future linear sensitivity (FLSens) and future mixed-integer sensitivity (Xsens).

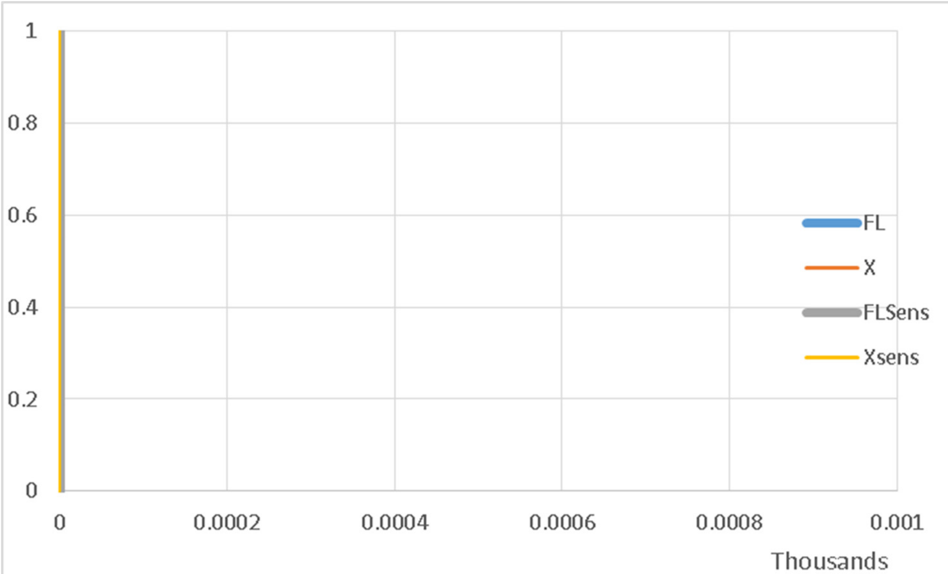

Figure G.65. Cumulative probability of urea production for 67801 (Dodge City, KS) across scenarios of stochastic future linear (FL), future mixed-integer (X), future linear sensitivity (FLSens) and future mixed-integer sensitivity (Xsens).

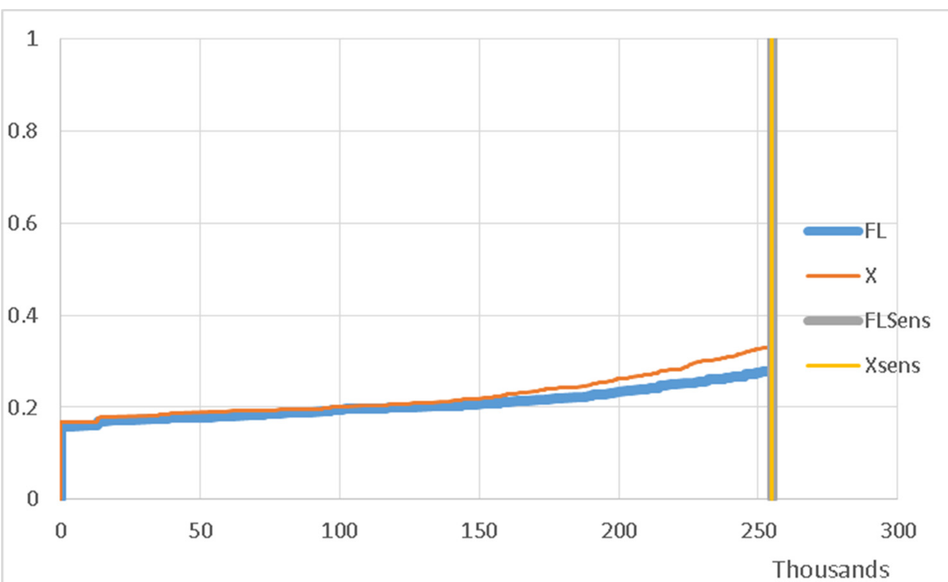

Figure G.66. Cumulative probability of UAN production for 67801 (Dodge City, KS) across scenarios of stochastic future linear (FL), future mixed-integer (X), future linear sensitivity (FLSens) and future mixed-integer sensitivity (Xsens).

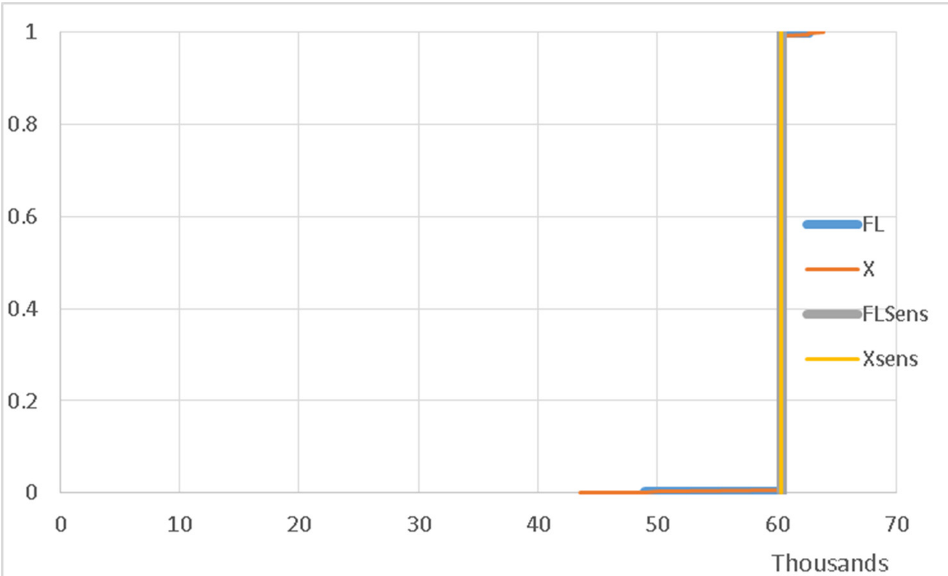

Figure G.67. Cumulative probability of anhydrous ammonia production for 68310 (Beatrice, NE) across scenarios of stochastic future linear (FL), future mixed-integer (X), future linear sensitivity (FLSens) and future mixed-integer sensitivity (Xsens).

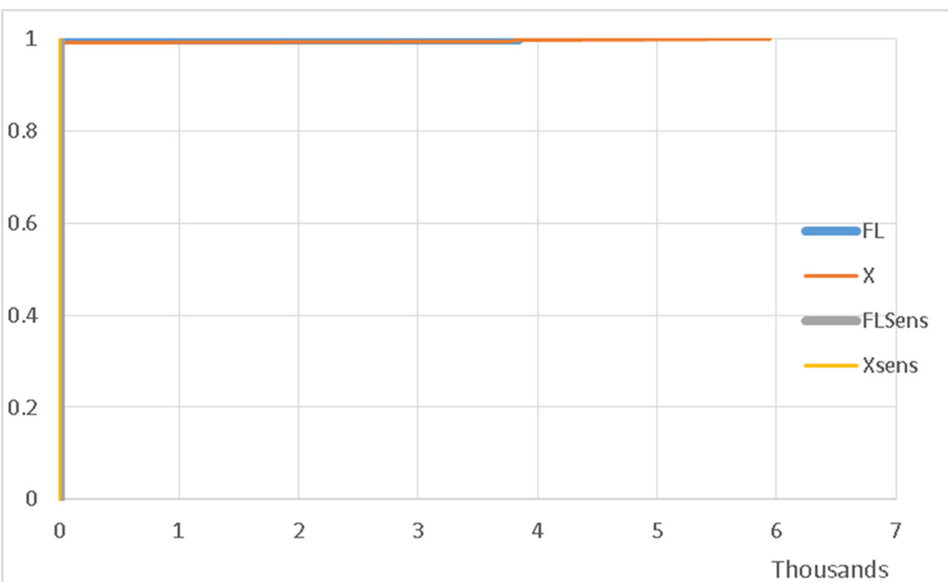

Figure G.68. Cumulative probability of urea production for 68310 (Beatrice, NE) across scenarios of stochastic future linear (FL), future mixed-integer (X), future linear sensitivity (FLSens) and future mixed-integer sensitivity (Xsens).

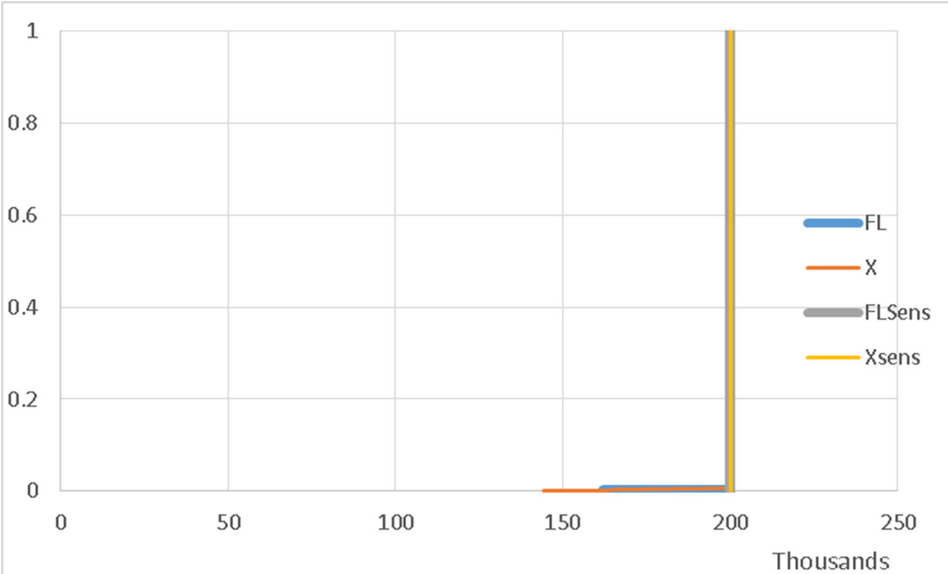

Figure G.69. Cumulative probability of UAN production for 68310 (Beatrice, NE) across scenarios of stochastic future linear (FL), future mixed-integer (X), future linear sensitivity (FLSens) and future mixed-integer sensitivity (Xsens).

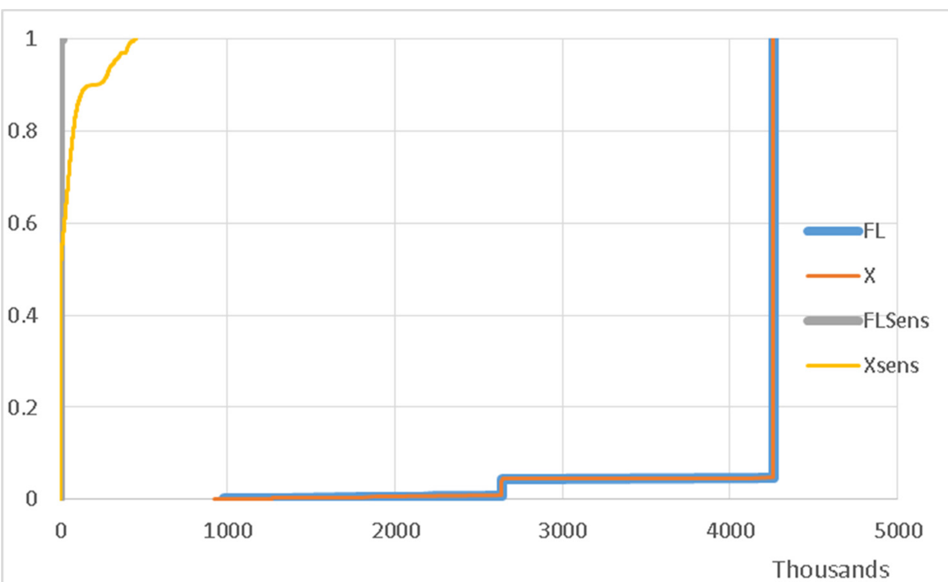

Figure G.70. Cumulative probability of anhydrous ammonia production for 70346 (Donaldsonville, LA) across scenarios of stochastic future linear (FL), future mixed-integer (X), future linear sensitivity (FLSens) and future mixed-integer sensitivity (Xsens).

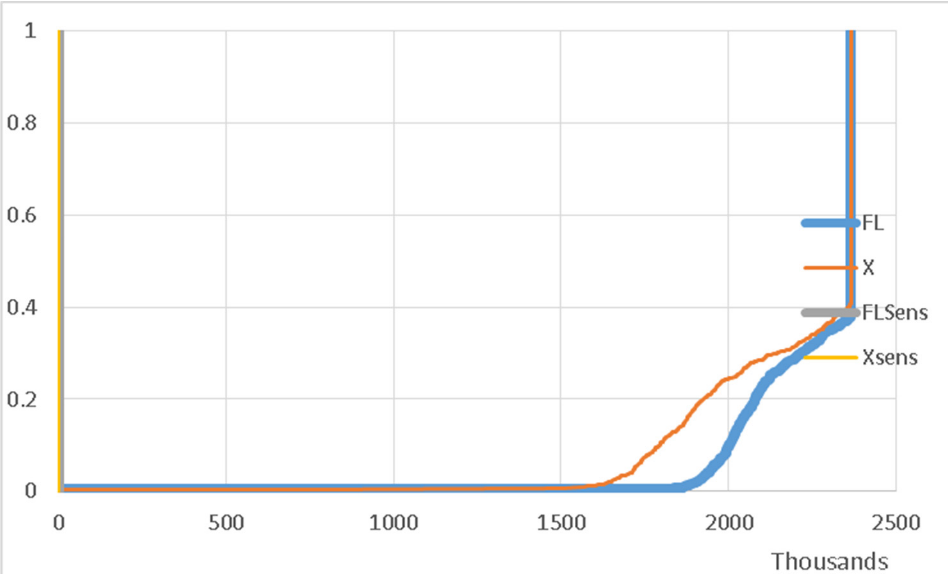

Figure G.71. Cumulative probability of urea production for 70346 (Donaldsonville, LA) across scenarios of stochastic future linear (FL), future mixed-integer (X), future linear sensitivity (FLSens) and future mixed-integer sensitivity (Xsens).

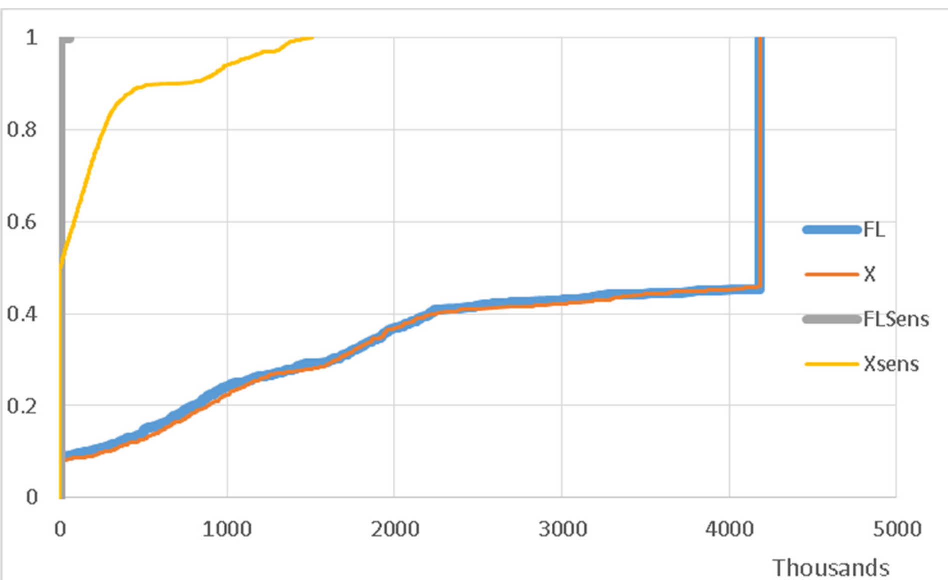

Figure G.72. Cumulative probability of UAN production for 70346 (Donaldsonville, LA) across scenarios of stochastic future linear (FL), future mixed-integer (X), future linear sensitivity (FLSens) and future mixed-integer sensitivity (Xsens).

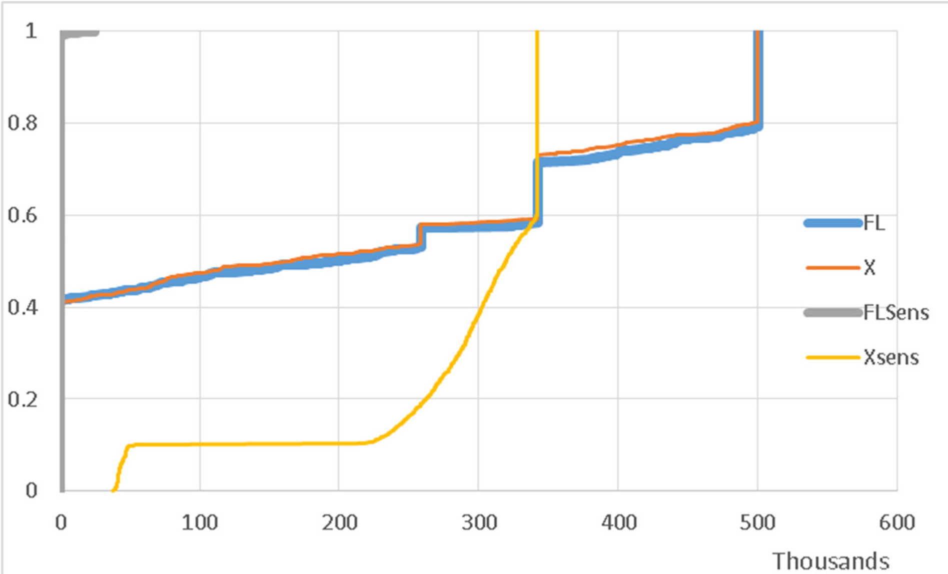

Figure G.73. Cumulative probability of anhydrous ammonia production for 70734 (Geismar, LA) across scenarios of stochastic future linear (FL), future mixed-integer (X), future linear sensitivity (FLSens) and future mixed-integer sensitivity (Xsens).

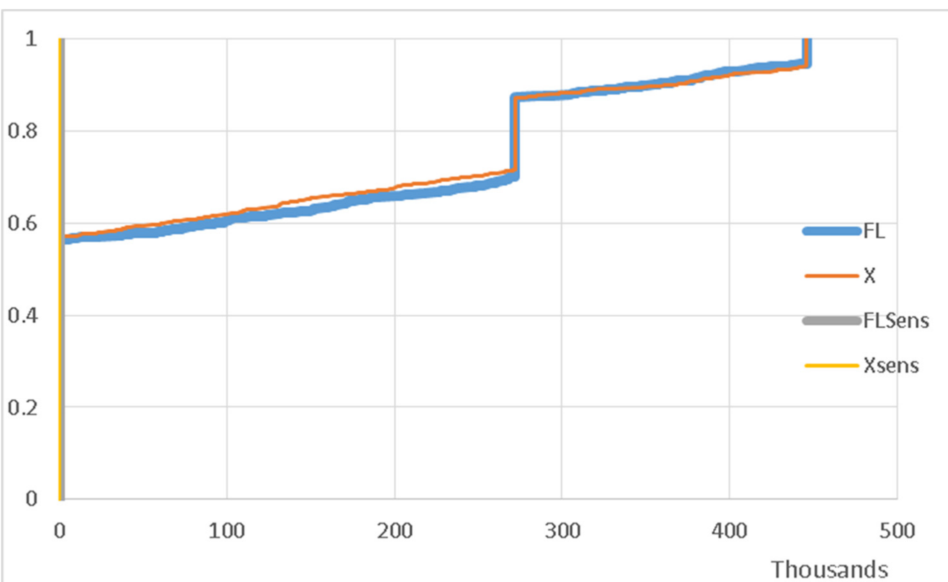

Figure G.74. Cumulative probability of urea production for 70734 (Geismar, LA) across scenarios of stochastic future linear (FL), future mixed-integer (X), future linear sensitivity (FLSens) and future mixed-integer sensitivity (Xsens).

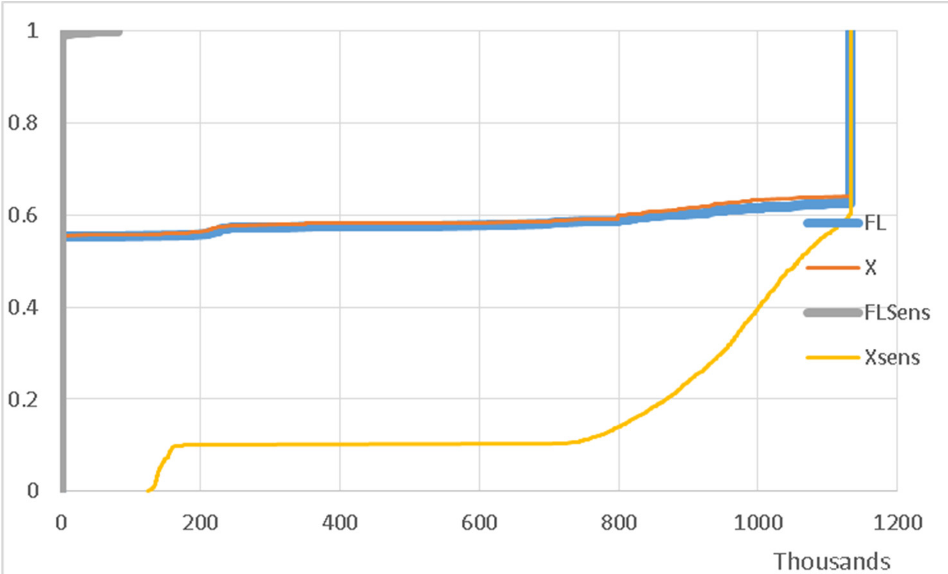

Figure G.75. Cumulative probability of UAN production for 70734 (Geismar, LA) across scenarios of stochastic future linear (FL), future mixed-integer (X), future linear sensitivity (FLSens) and future mixed-integer sensitivity (Xsens).

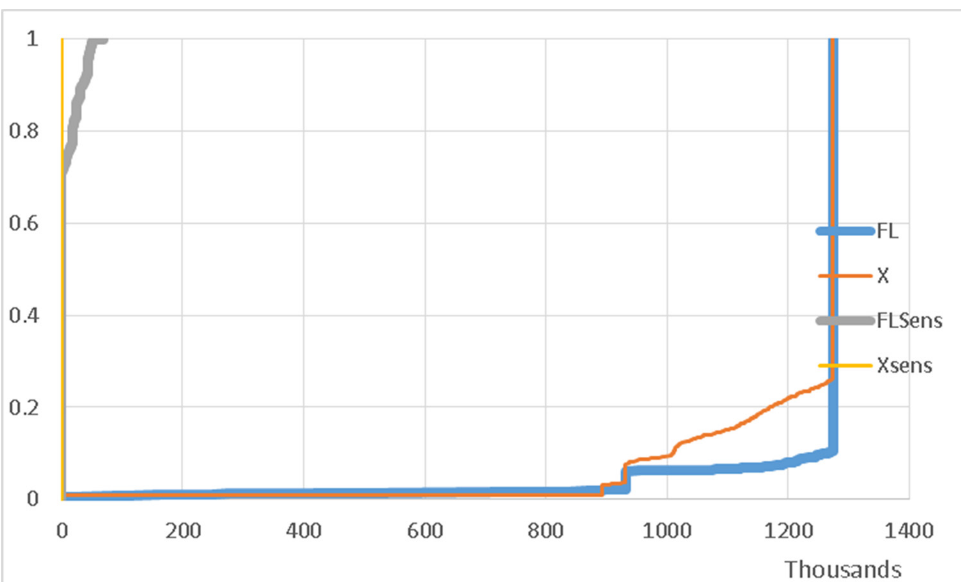

Figure G.76. Cumulative probability of anhydrous ammonia production for 70765 (Iberville, LA) across scenarios of stochastic future linear (FL), future mixed-integer (X), future linear sensitivity (FLSens) and future mixed-integer sensitivity (Xsens).

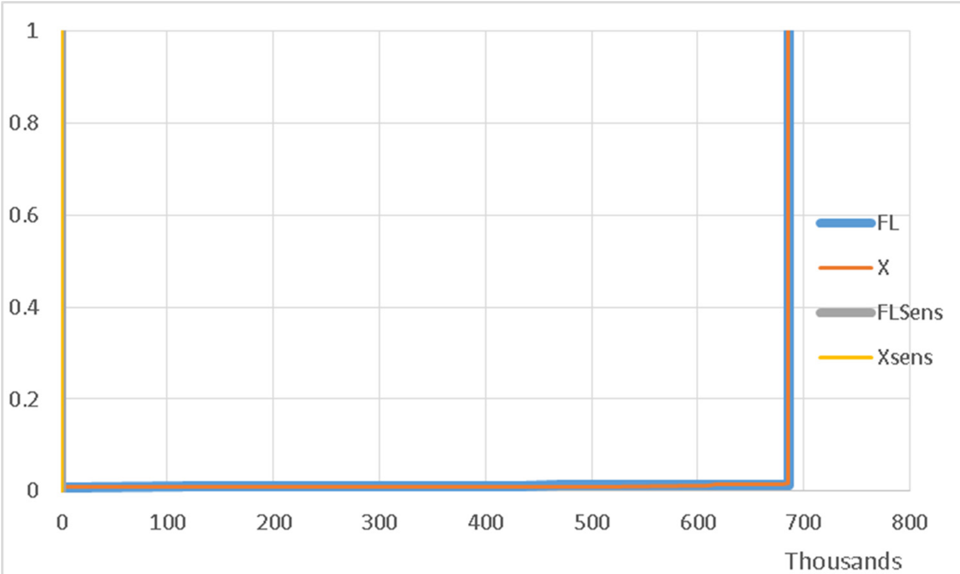

Figure G.77. Cumulative probability of urea production for 70765 (Iberville, LA) across scenarios of stochastic future linear (FL), future mixed-integer (X), future linear sensitivity (FLSens) and future mixed-integer sensitivity (Xsens).

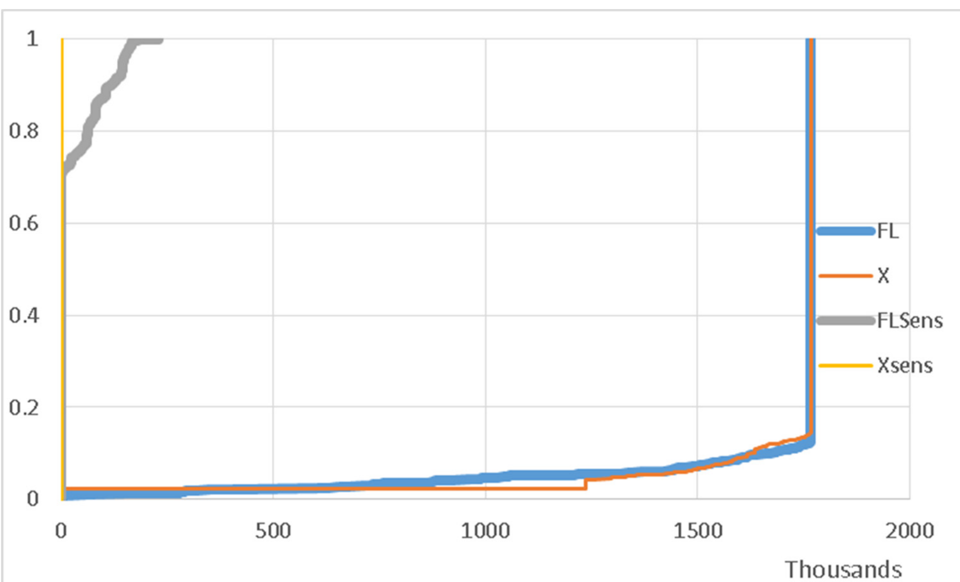

Figure G.78. Cumulative probability of UAN production for 70765 (Iberville, LA) across scenarios of stochastic future linear (FL), future mixed-integer (X), future linear sensitivity (FLSens) and future mixed-integer sensitivity (Xsens).

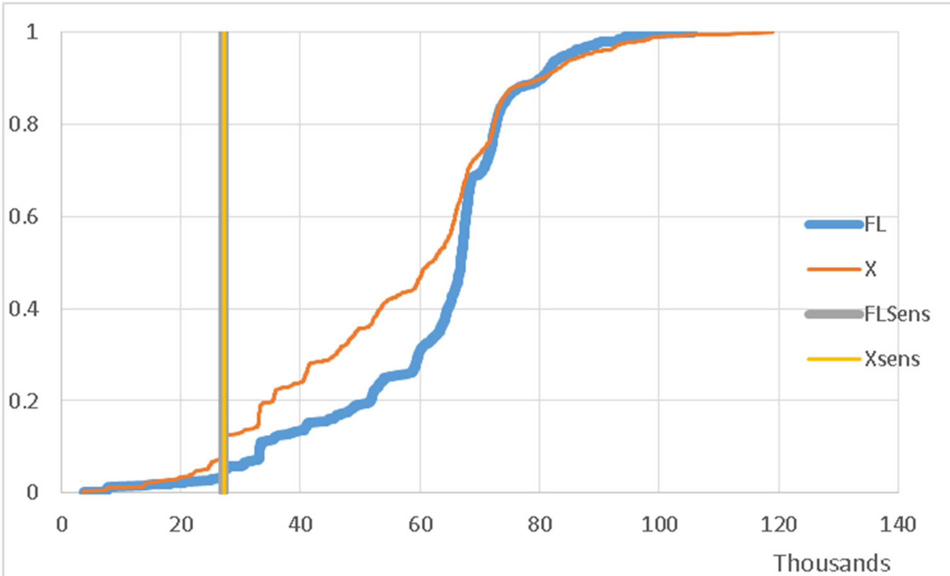

Figure G.79. Cumulative probability of anhydrous ammonia production for 73701 (Enid, OK) across scenarios of stochastic future linear (FL), future mixed-integer (X), future linear sensitivity (FLSens) and future mixed-integer sensitivity (Xsens).

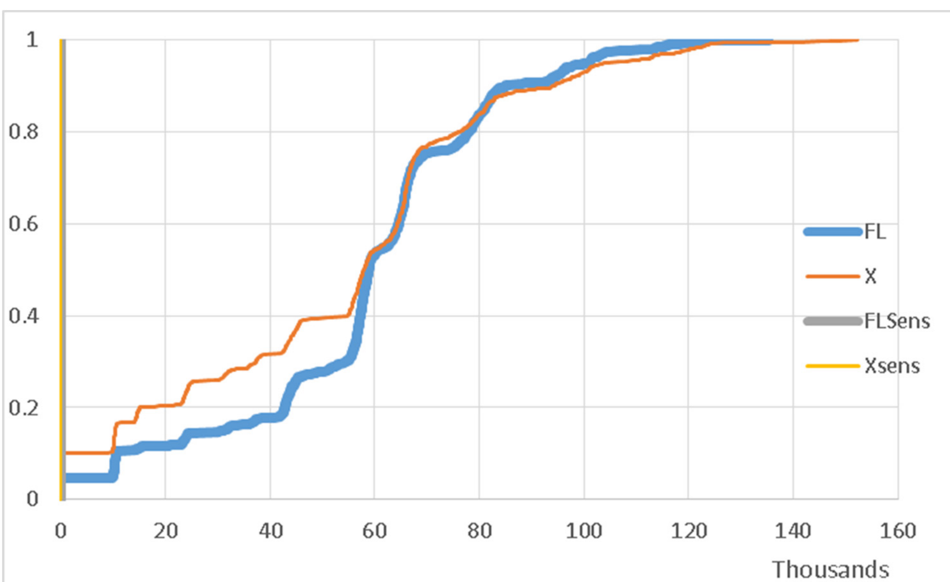

Figure G.80. Cumulative probability of urea production for 73701 (Enid, OK) across scenarios of stochastic future linear (FL), future mixed-integer (X), future linear sensitivity (FLSens) and future mixed-integer sensitivity (Xsens).

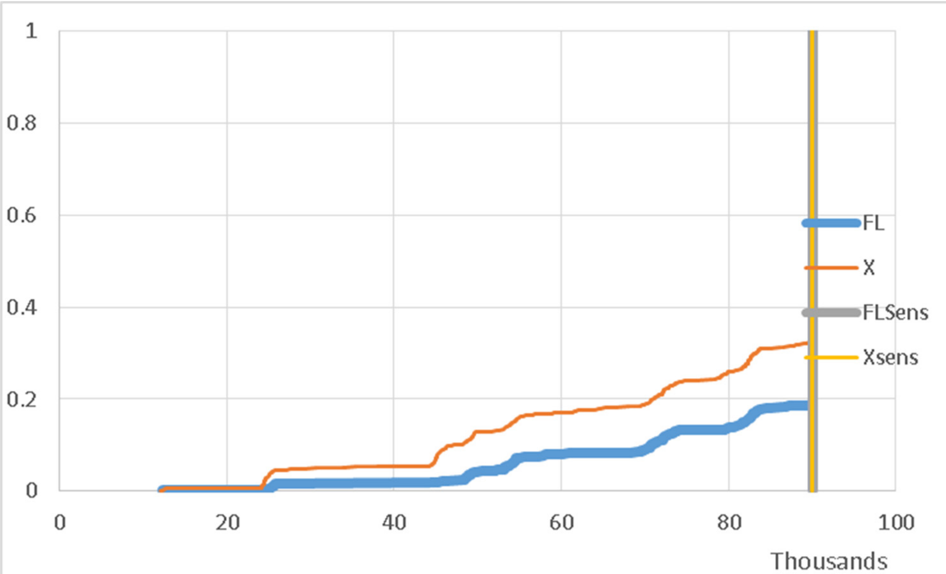

Figure G.81. Cumulative probability of UAN production for 73701 (Enid, OK) across scenarios of stochastic future linear (FL), future mixed-integer (X), future linear sensitivity (FLSens) and future mixed-integer sensitivity (Xsens).

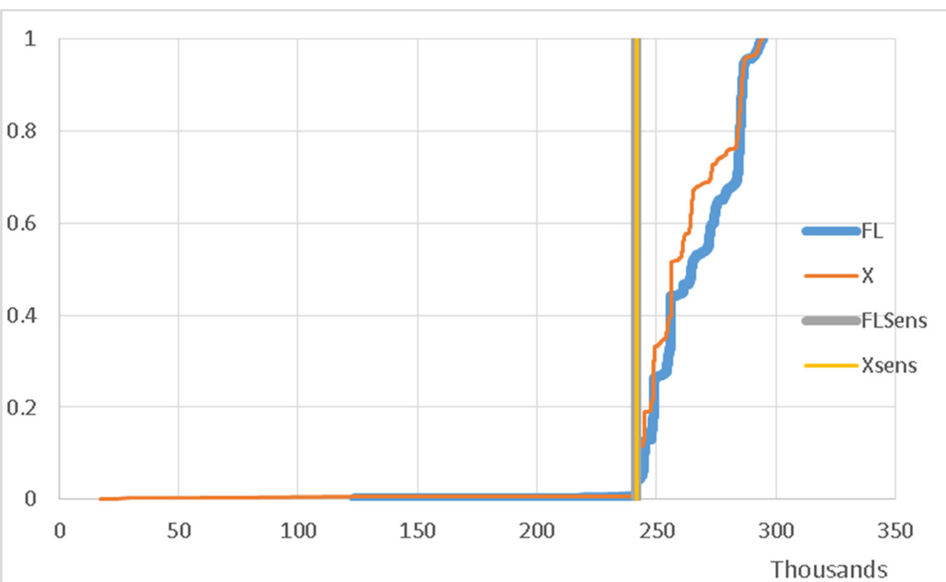

Figure G.82. Cumulative probability of anhydrous ammonia production for 73801 (Woodward, OK) across scenarios of stochastic future linear (FL), future mixed-integer (X), future linear sensitivity (FLSens) and future mixed-integer sensitivity (Xsens).

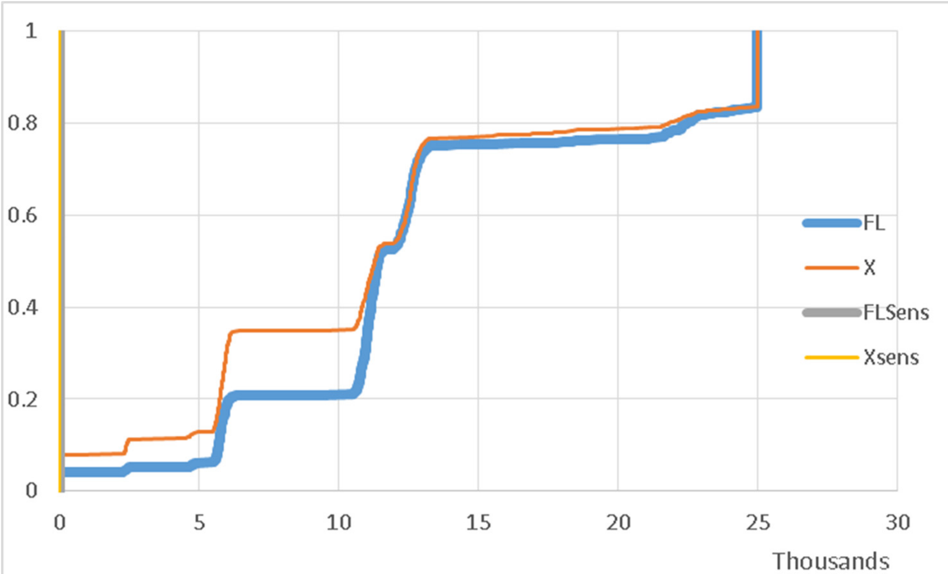

Figure G.83. Cumulative probability of urea production for 73801 (Woodward, OK) across scenarios of stochastic future linear (FL), future mixed-integer (X), future linear sensitivity (FLSens) and future mixed-integer sensitivity (Xsens).

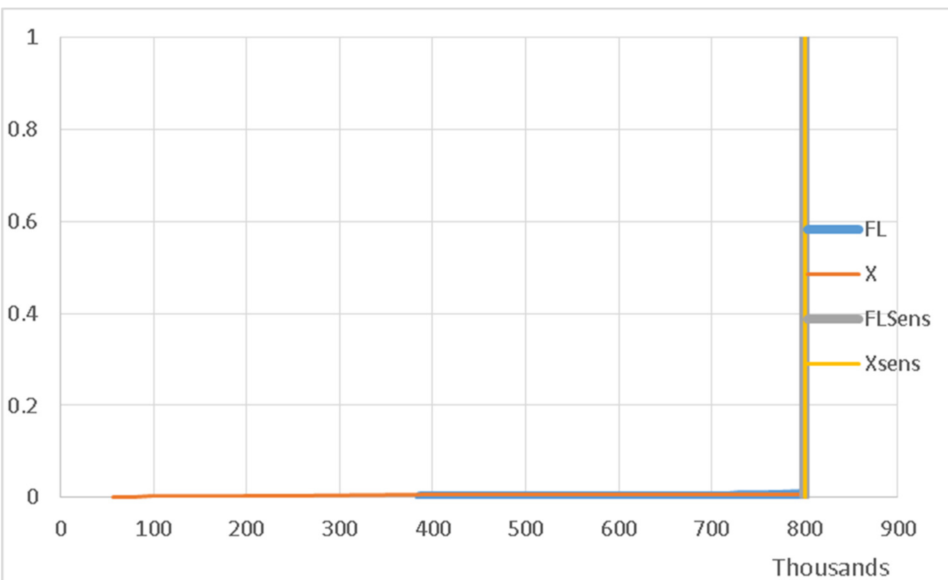

Figure G.84. Cumulative probability of UAN production for 73801 (Woodward, OK) across scenarios of stochastic future linear (FL), future mixed-integer (X), future linear sensitivity (FLSens) and future mixed-integer sensitivity (Xsens).

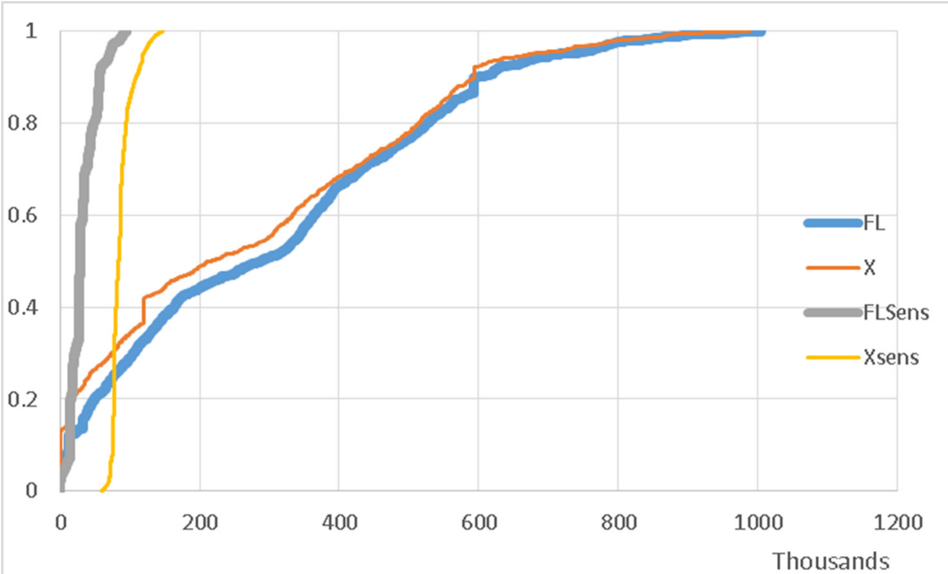

Figure G.85. Cumulative probability of anhydrous ammonia production for 74019 (Verdigris, OK) across scenarios of stochastic future linear (FL), future mixed-integer (X), future linear sensitivity (FLSens) and future mixed-integer sensitivity (Xsens).

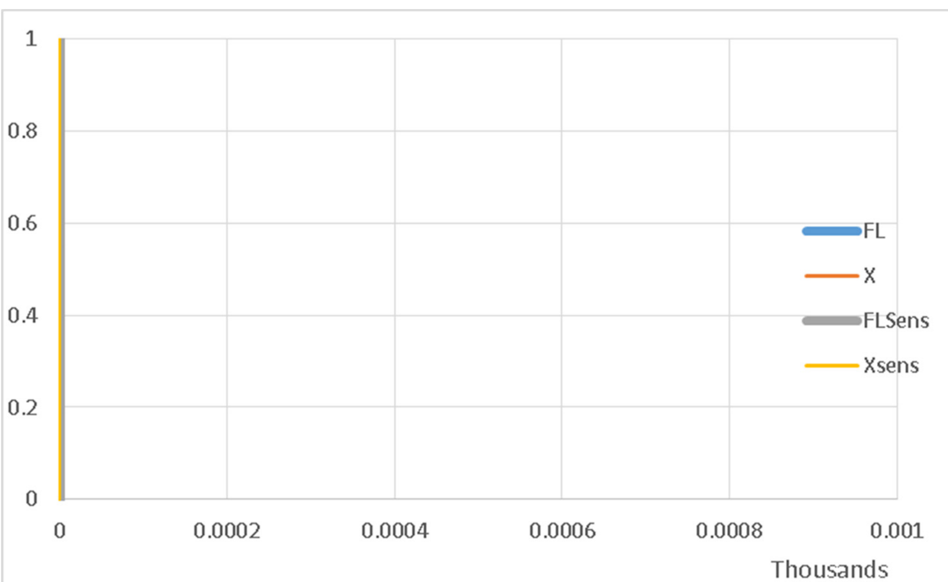

Figure G.86. Cumulative probability of urea production for 74019 (Verdigris, OK) across scenarios of stochastic future linear (FL), future mixed-integer (X), future linear sensitivity (FLSens) and future mixed-integer sensitivity (Xsens).

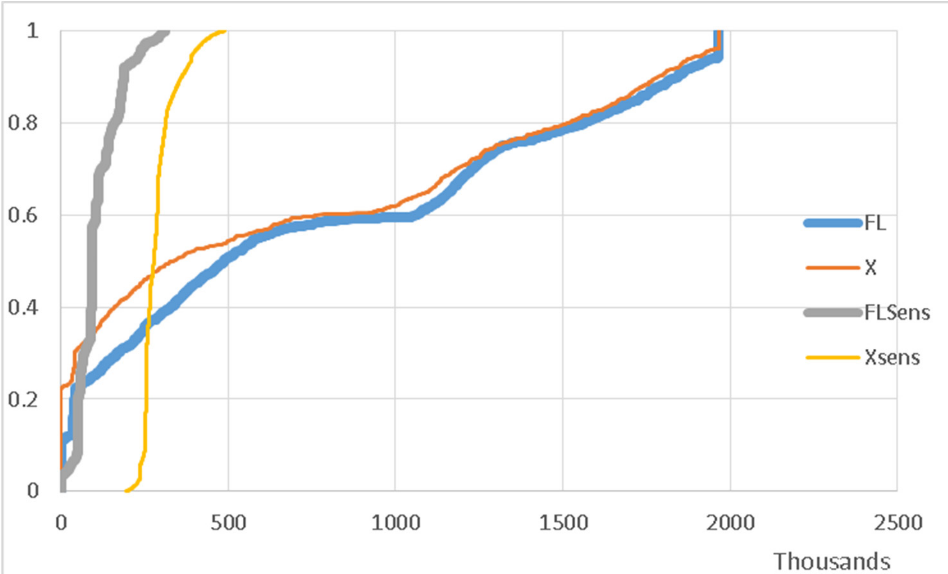

Figure G.87. Cumulative probability of UAN production for 74019 (Verdigris, OK) across scenarios of stochastic future linear (FL), future mixed-integer (X), future linear sensitivity (FLSens) and future mixed-integer sensitivity (Xsens).

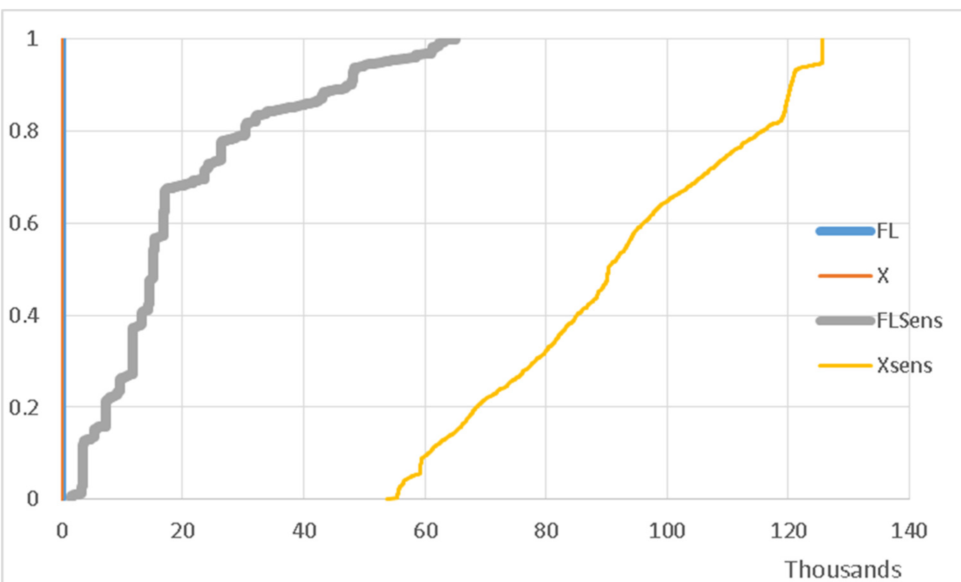

Figure G.88. Cumulative probability of anhydrous ammonia production for 74362 (Pryor OK) across scenarios of stochastic future linear (FL), future mixed-integer (X), future linear sensitivity (FLSens) and future mixed-integer sensitivity (Xsens).

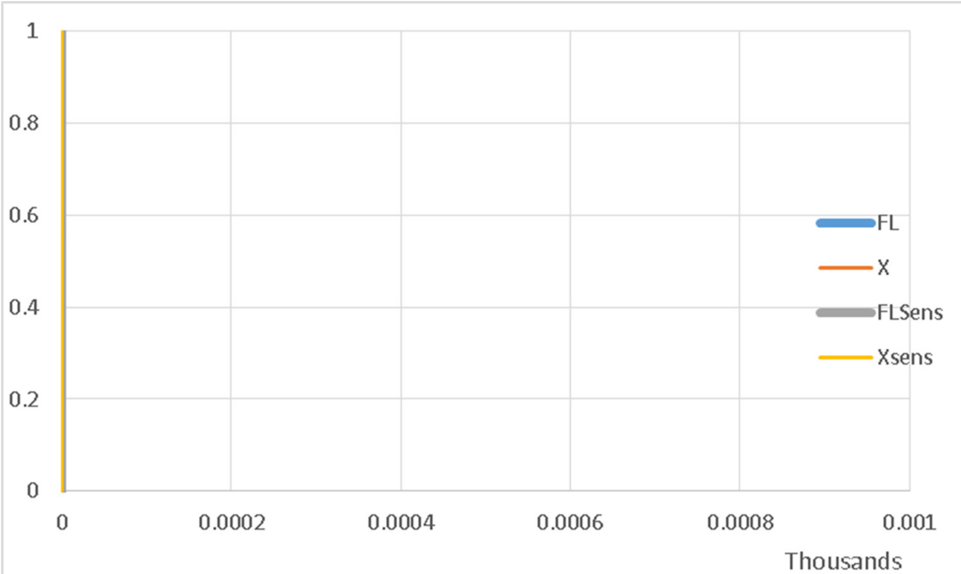

Figure G.89. Cumulative probability of urea production for 74362 (Pryor OK) across scenarios of stochastic future linear (FL), future mixed-integer (X), future linear sensitivity (FLSens) and future mixed-integer sensitivity (Xsens).

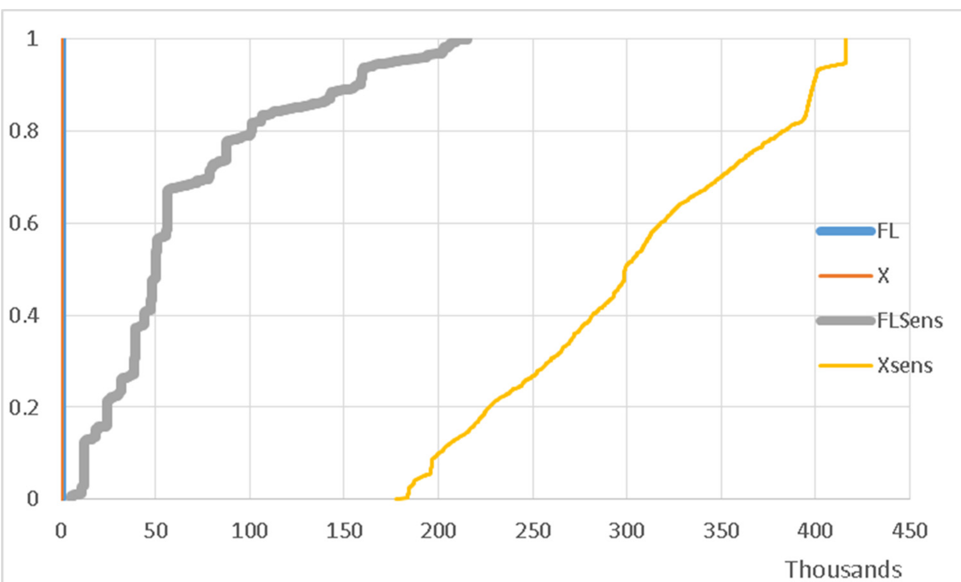

Figure G.90. Cumulative probability of UAN production for 74362 (Pryor OK) across scenarios of stochastic future linear (FL), future mixed-integer (X), future linear sensitivity (FLSens) and future mixed-integer sensitivity (Xsens).

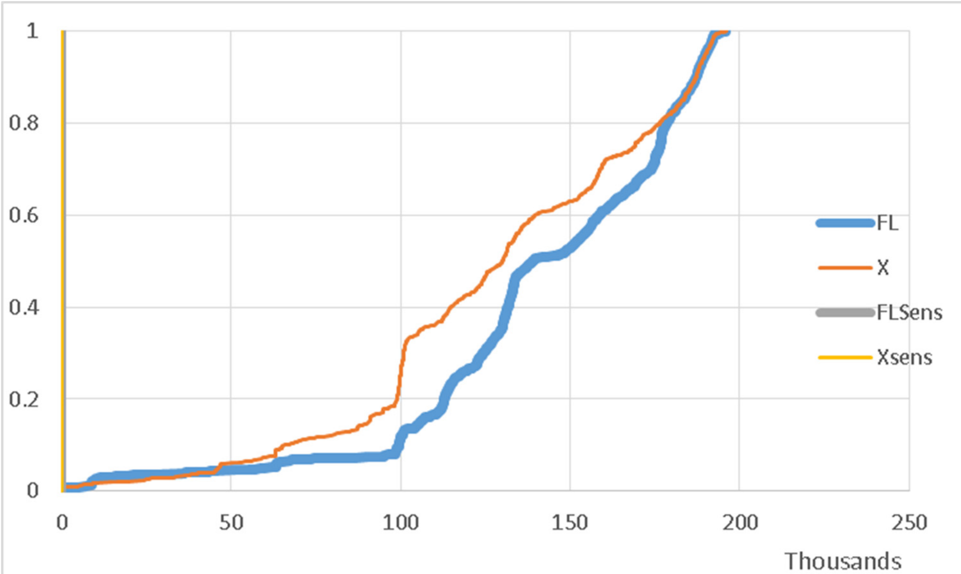

Figure G.91. Cumulative probability of anhydrous ammonia production for 79007 (Borger, TX) across scenarios of stochastic future linear (FL), future mixed-integer (X), future linear sensitivity (FLSens) and future mixed-integer sensitivity (Xsens).

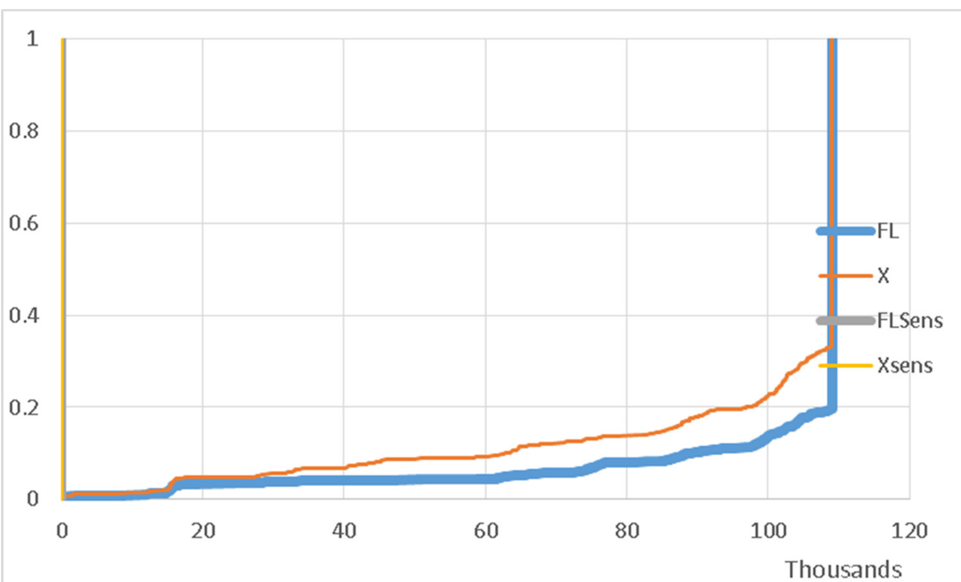

Figure G.92. Cumulative probability of urea production for 79007 (Borger, TX) across scenarios of stochastic future linear (FL), future mixed-integer (X), future linear sensitivity (FLSens) and future mixed-integer sensitivity (Xsens).

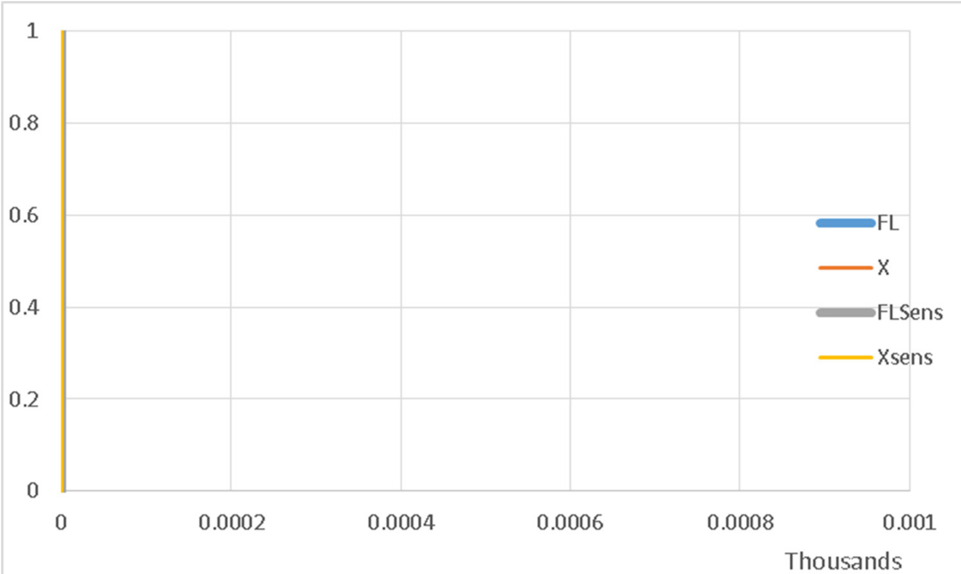

Figure G.93. Cumulative probability of UAN production for 79007 (Borger, TX) across scenarios of stochastic future linear (FL), future mixed-integer (X), future linear sensitivity (FLSens) and future mixed-integer sensitivity (Xsens).

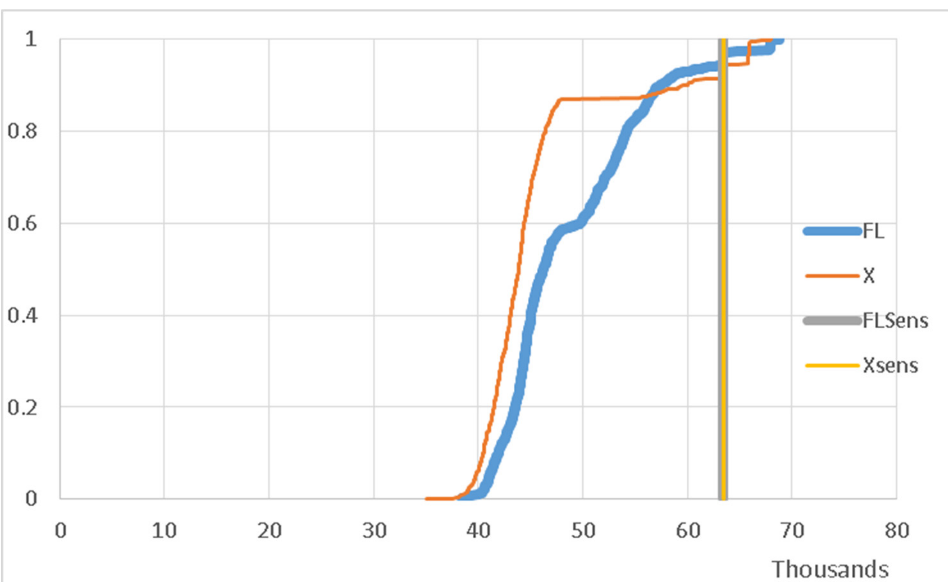

Figure G.94. Cumulative probability of anhydrous ammonia production for 82001 (Cheyenne, WY) across scenarios of stochastic future linear (FL), future mixed-integer (X), future linear sensitivity (FLSens) and future mixed-integer sensitivity (Xsens).

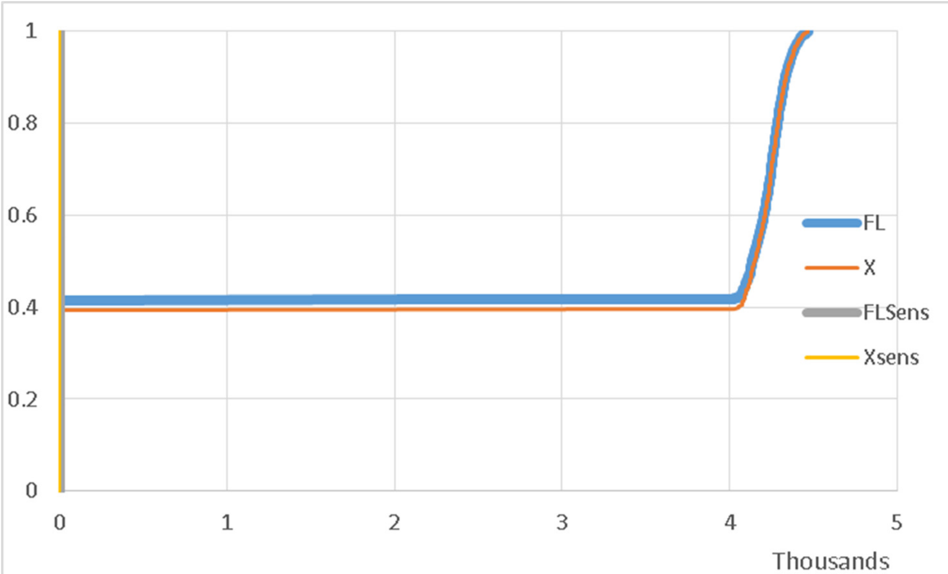

Figure G.95. Cumulative probability of urea production for 82001 (Cheyenne, WY) across scenarios of stochastic future linear (FL), future mixed-integer (X), future linear sensitivity (FLSens) and future mixed-integer sensitivity (Xsens).

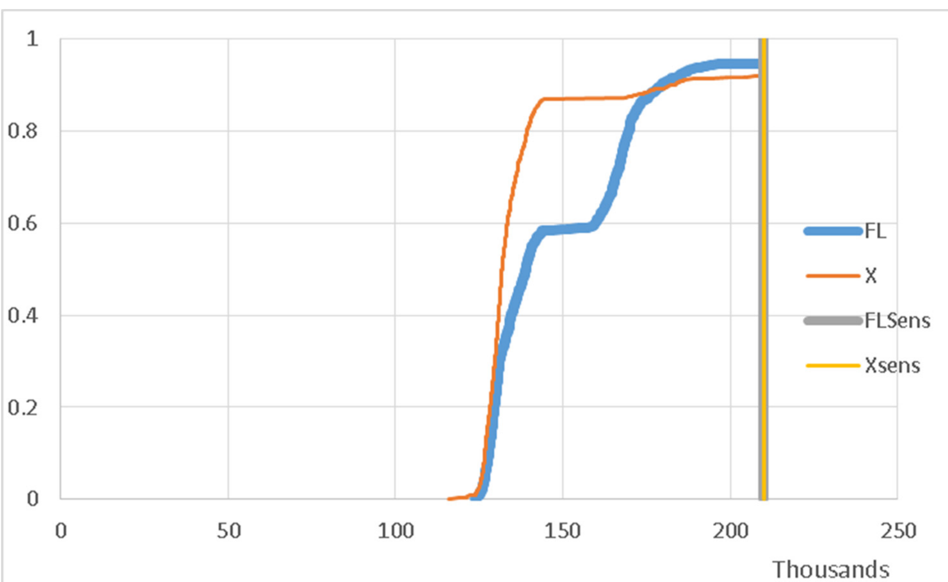

Figure G.96. Cumulative probability of UAN production for 82001 (Cheyenne, WY) across scenarios of stochastic future linear (FL), future mixed-integer (X), future linear sensitivity (FLSens) and future mixed-integer sensitivity (Xsens).

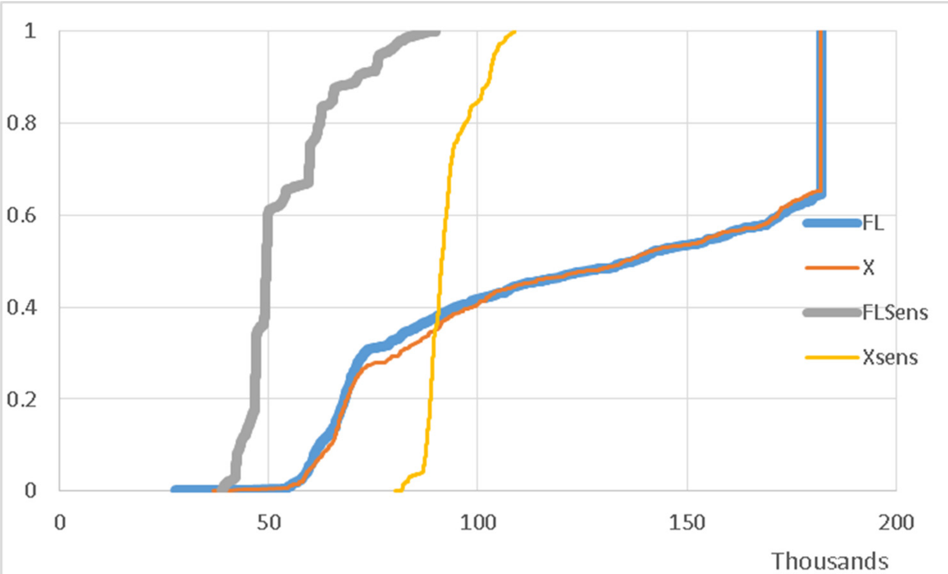

Figure G.97. Cumulative probability of anhydrous ammonia production for 83211 (American Falls, ID) across scenarios of stochastic future linear (FL), future mixed-integer (X), future linear sensitivity (FLSens) and future mixed-integer sensitivity (Xsens).

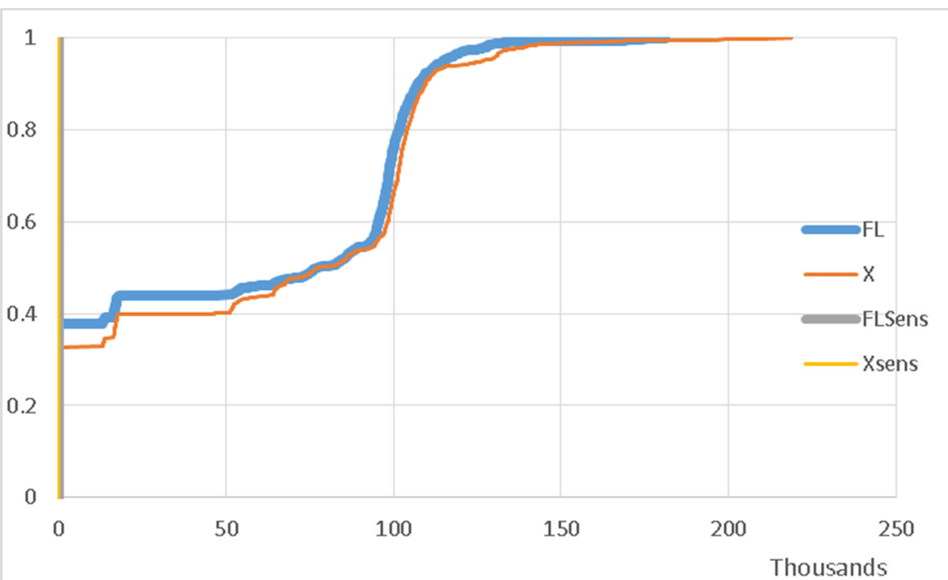

Figure G.98. Cumulative probability of urea production for 83211 (American Falls, ID) across scenarios of stochastic future linear (FL), future mixed-integer (X), future linear sensitivity (FLSens) and future mixed-integer sensitivity (Xsens).

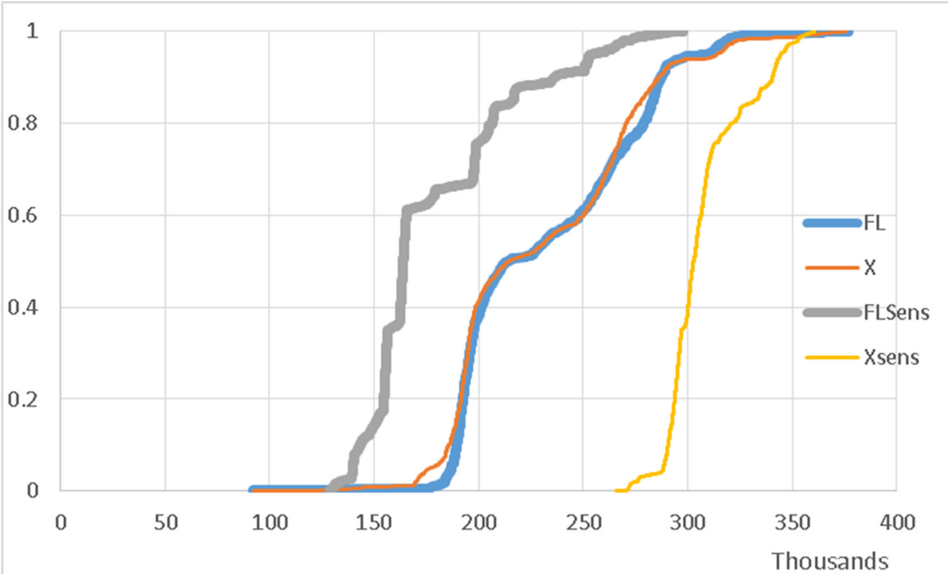

Figure G.99. Cumulative probability of UAN production for 83211 (American Falls, ID) across scenarios of stochastic future linear (FL), future mixed-integer (X), future linear sensitivity (FLSens) and future mixed-integer sensitivity (Xsens).

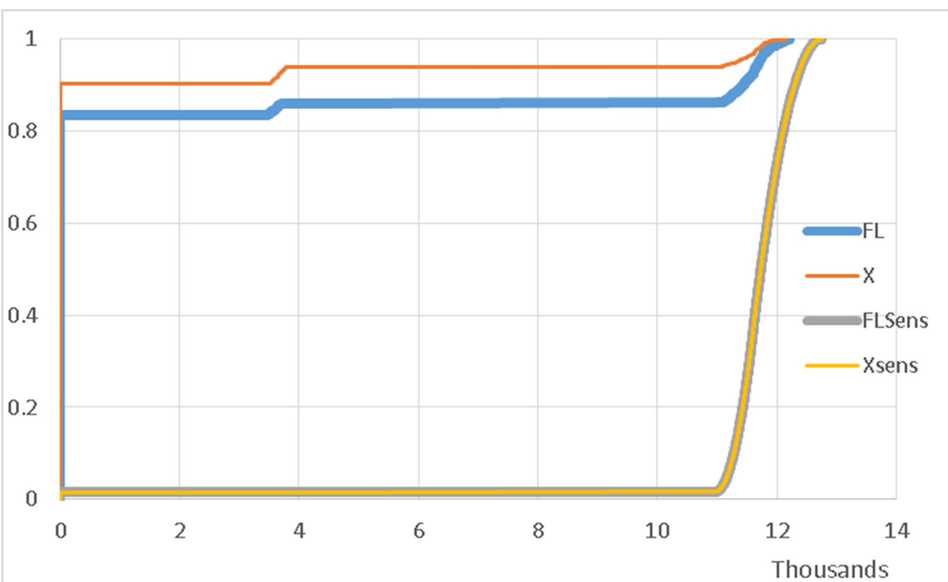

Figure G.100. Cumulative probability of anhydrous ammonia production for 8800451 (POE: Emerson, ND) across scenarios of stochastic future linear (FL), future mixed-integer (X), future linear sensitivity (FLSens) and future mixed-integer sensitivity (Xsens).

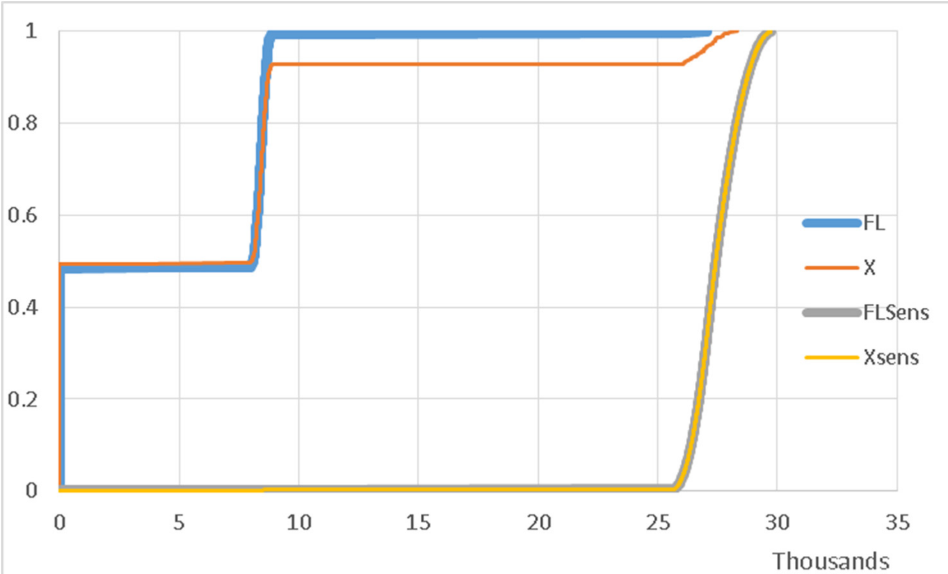

Figure G.101. Cumulative probability of urea production for 8800451 (POE: Emerson, ND) across scenarios of stochastic future linear (FL), future mixed-integer (X), future linear sensitivity (FLSens) and future mixed-integer sensitivity (Xsens).

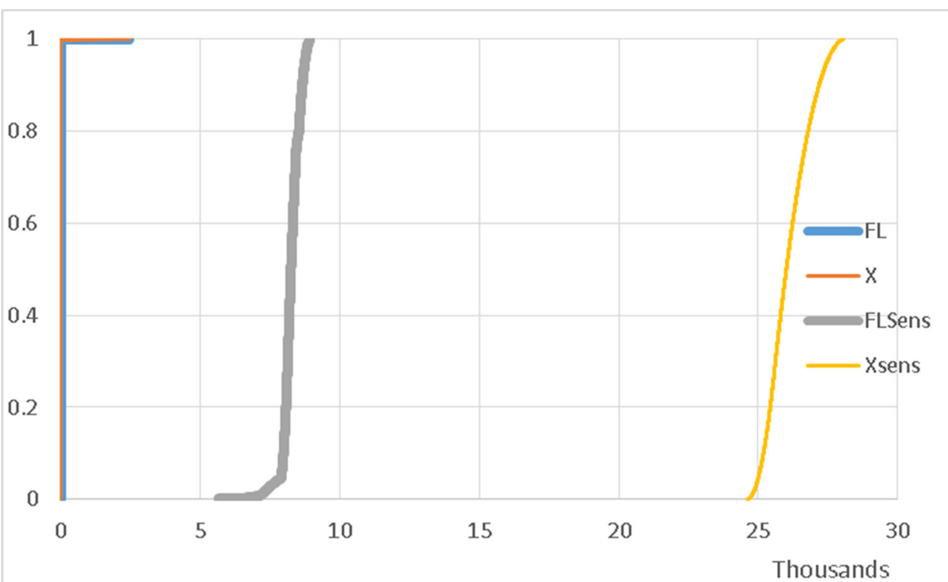

Figure G.102. Cumulative probability of UAN production for 8800451 (POE: Emerson, ND) across scenarios of stochastic future linear (FL), future mixed-integer (X), future linear sensitivity (FLSens) and future mixed-integer sensitivity (Xsens).

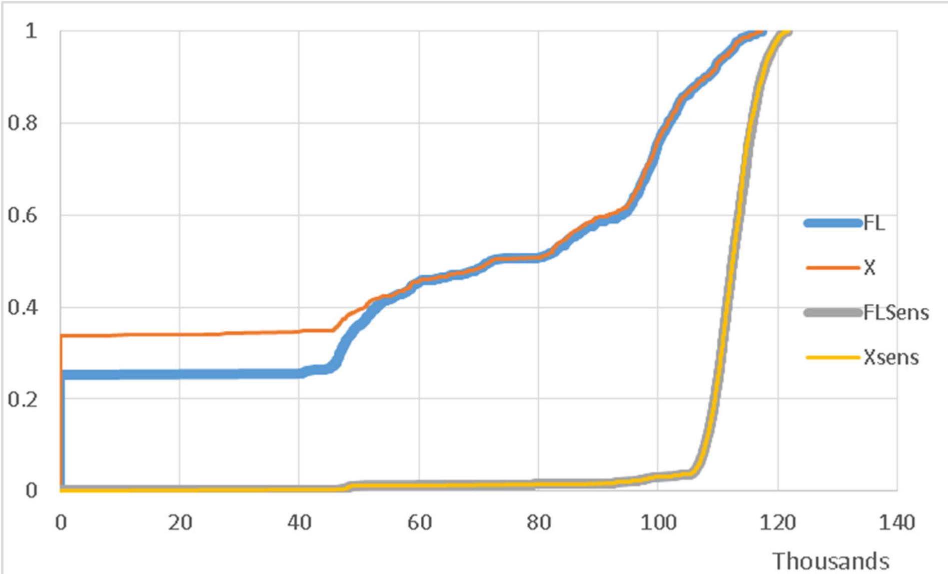

Figure G.103. Cumulative probability of anhydrous ammonia production for 9163 (POE: Kingsgate, ID) across scenarios of stochastic future linear (FL), future mixed-integer (X), future linear sensitivity (FLSens) and future mixed-integer sensitivity (Xsens).

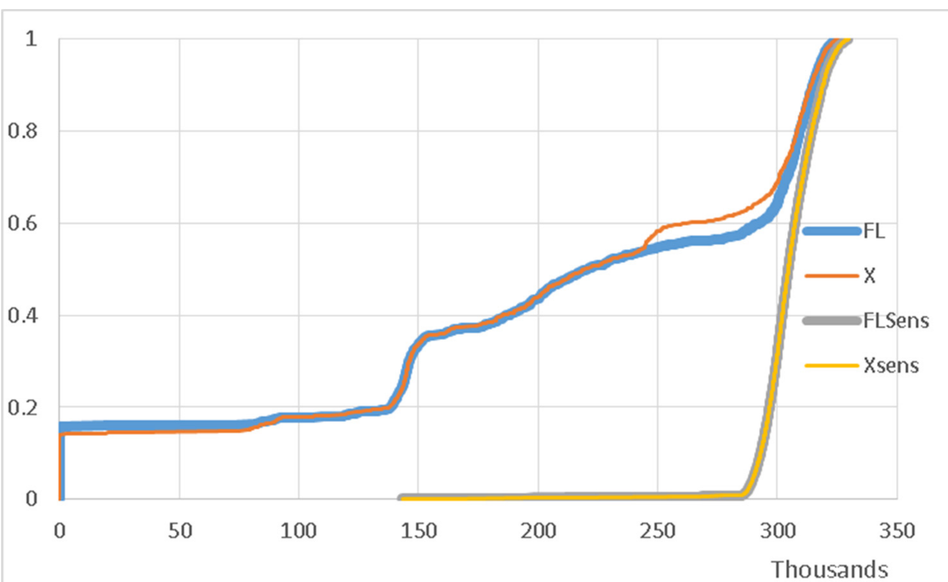

Figure G.104. Cumulative probability of urea production for 9163 (POE: Kingsgate, ID) across scenarios of stochastic future linear (FL), future mixed-integer (X), future linear sensitivity (FLSens) and future mixed-integer sensitivity (Xsens).

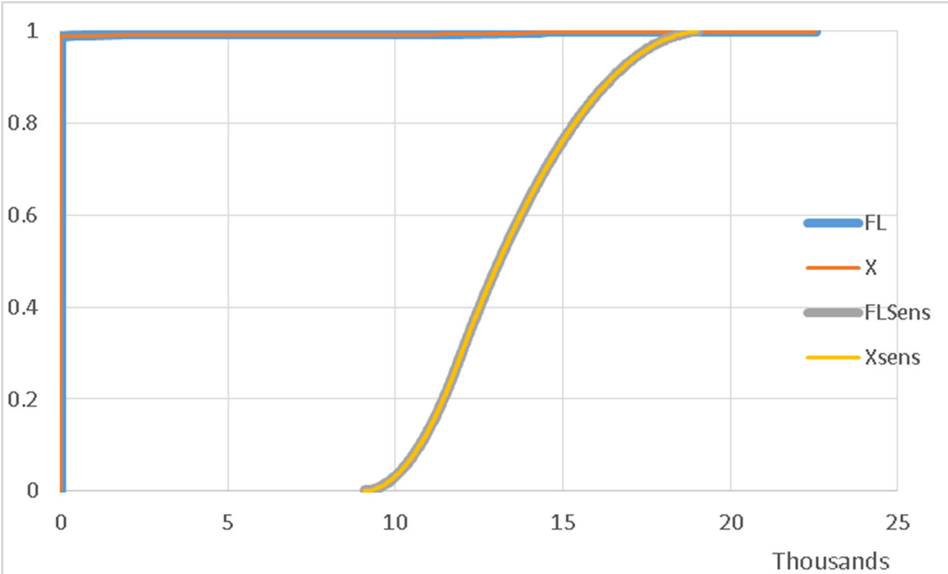

Figure G.105. Cumulative probability of UAN production for 9163 (POE: Kingsgate, ID) across scenarios of stochastic future linear (FL), future mixed-integer (X), future linear sensitivity (FLSens) and future mixed-integer sensitivity (Xsens).

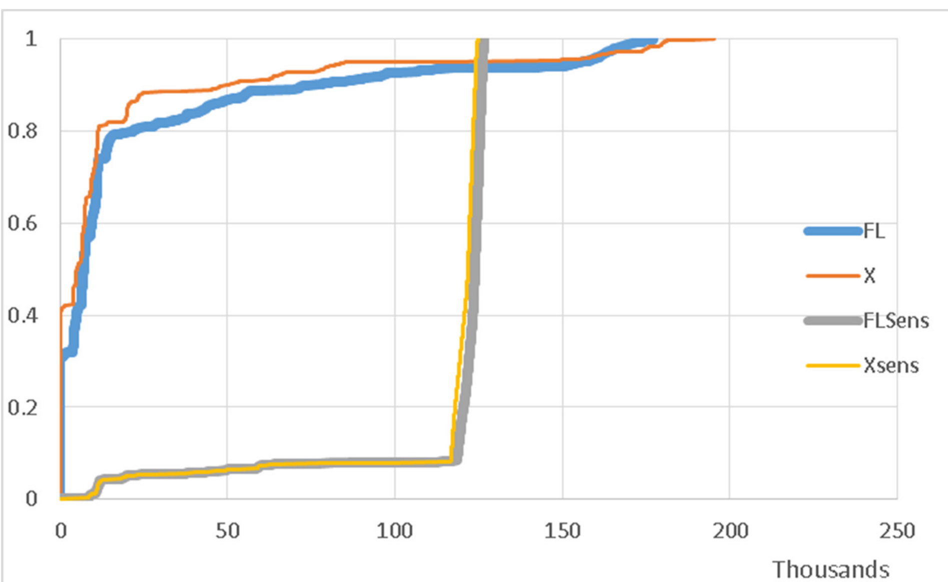

Figure G.106. Cumulative probability of anhydrous ammonia production for 9303 (POE: Coutts, MT) across scenarios of stochastic future linear (FL), future mixed-integer (X), future linear sensitivity (FLSens) and future mixed-integer sensitivity (Xsens).

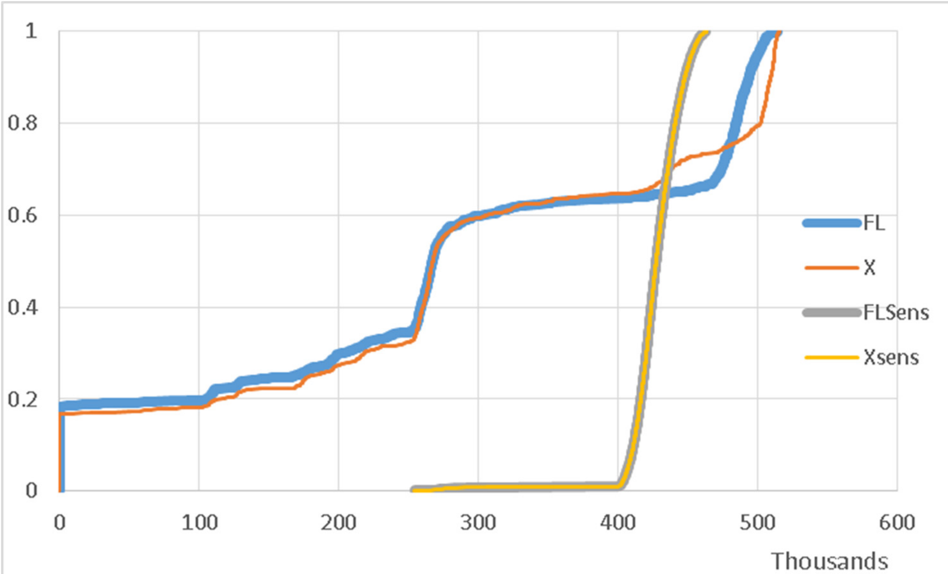

Figure G.107. Cumulative probability of urea production for 9303 (POE: Coutts, MT) across scenarios of stochastic future linear (FL), future mixed-integer (X), future linear sensitivity (FLSens) and future mixed-integer sensitivity (Xsens).

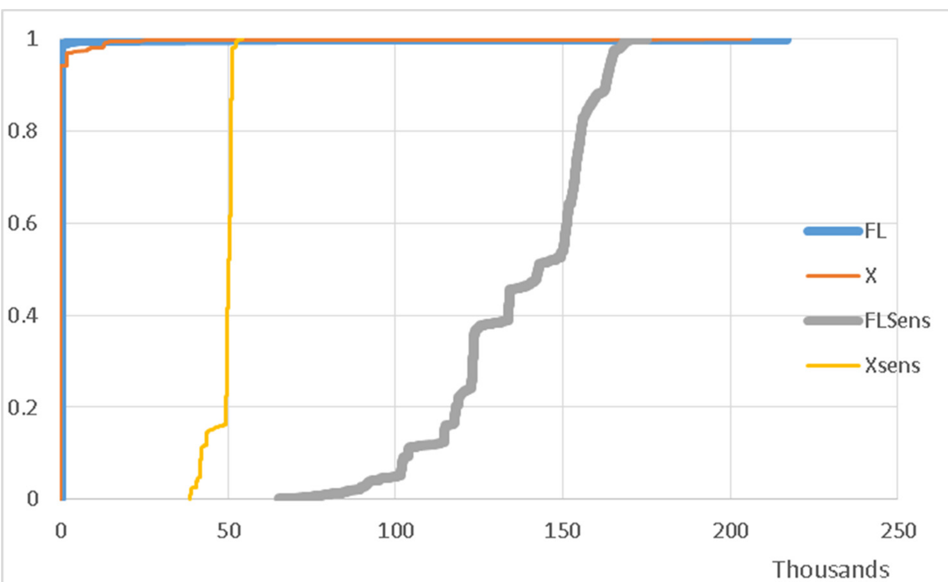

Figure G.108. Cumulative probability of UAN production for 9303 (POE: Coutts, MT) across scenarios of stochastic future linear (FL), future mixed-integer (X), future linear sensitivity (FLSens) and future mixed-integer sensitivity (Xsens).

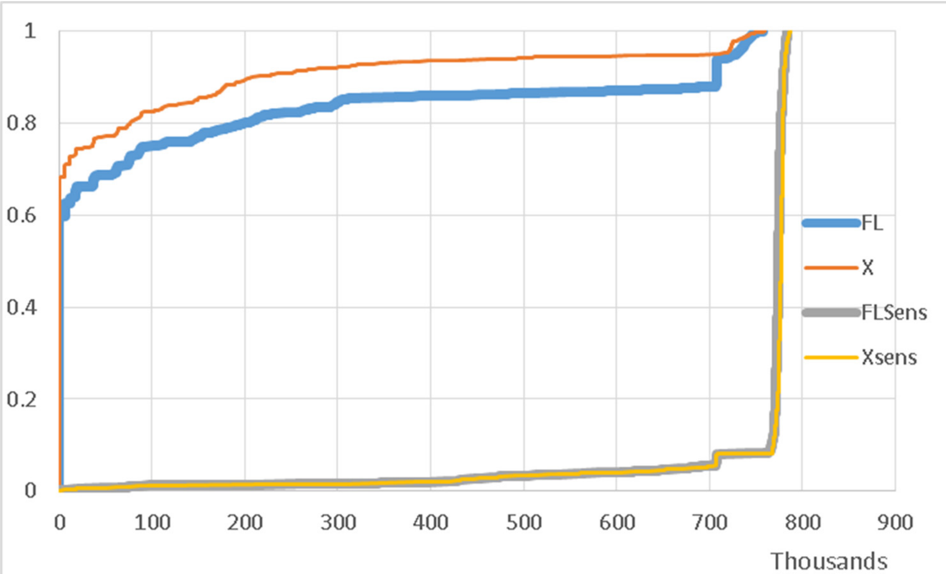

Figure G.109. Cumulative probability of anhydrous ammonia production for 9384 (POE: Portal, ND) across scenarios of stochastic future linear (FL), future mixed-integer (X), future linear sensitivity (FLSens) and future mixed-integer sensitivity (Xsens).

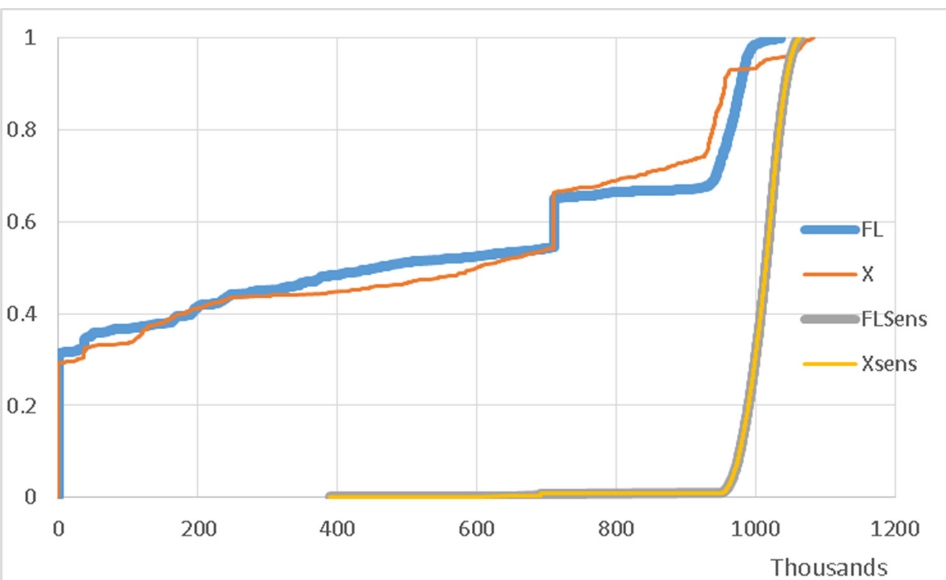

Figure G.110. Cumulative probability of urea production for 9384 (POE: Portal, ND) across scenarios of stochastic future linear (FL), future mixed-integer (X), future linear sensitivity (FLSens) and future mixed-integer sensitivity (Xsens).

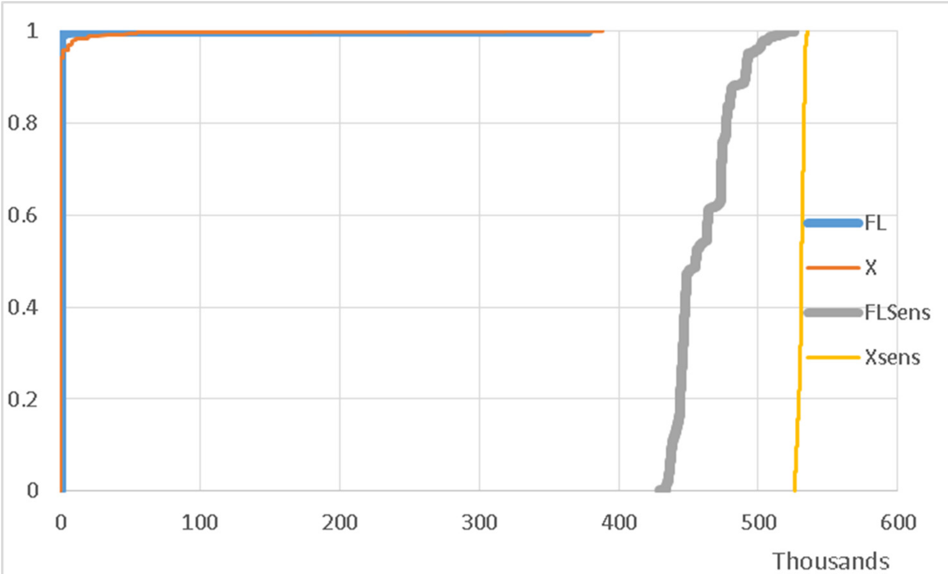

Figure G.111. Cumulative probability of UAN production for 9384 (POE: Portal, ND) across scenarios of stochastic future linear (FL), future mixed-integer (X), future linear sensitivity (FLSens) and future mixed-integer sensitivity (Xsens).

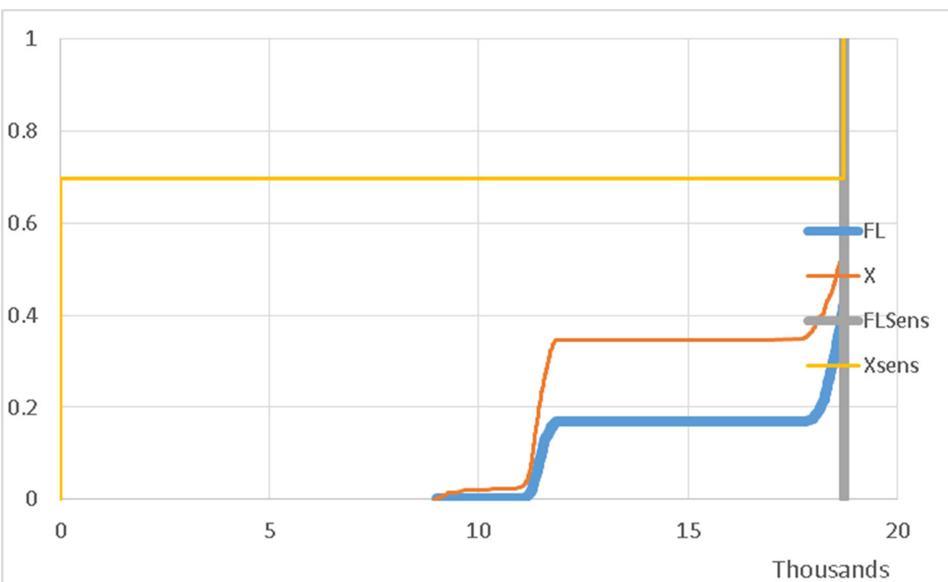

Figure G.112. Cumulative probability of anhydrous ammonia production for 97051 (St. Helens, OR) across scenarios of stochastic future linear (FL), future mixed-integer (X), future linear sensitivity (FLSens) and future mixed-integer sensitivity (Xsens).

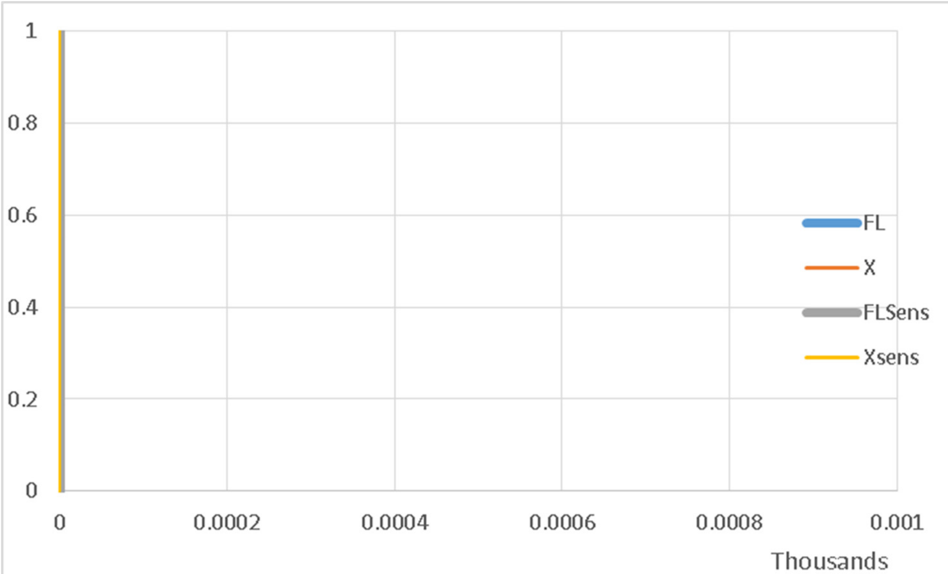

Figure G.113. Cumulative probability of urea production for 97051 (St. Helens, OR) across scenarios of stochastic future linear (FL), future mixed-integer (X), future linear sensitivity (FLSens) and future mixed-integer sensitivity (Xsens).

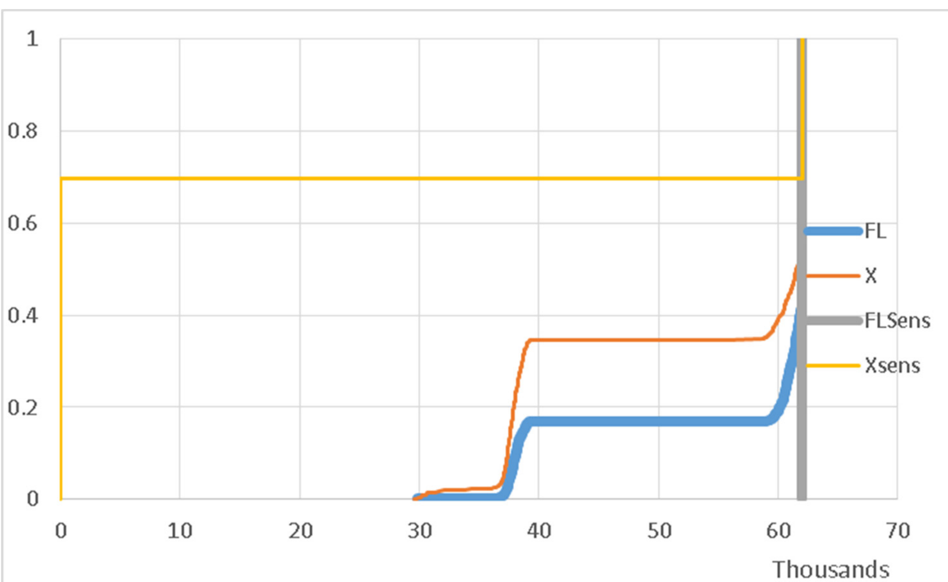

Figure G.114. Cumulative probability of UAN production for 97051 (St. Helens, OR) across scenarios of stochastic future linear (FL), future mixed-integer (X), future linear sensitivity (FLSens) and future mixed-integer sensitivity (Xsens).

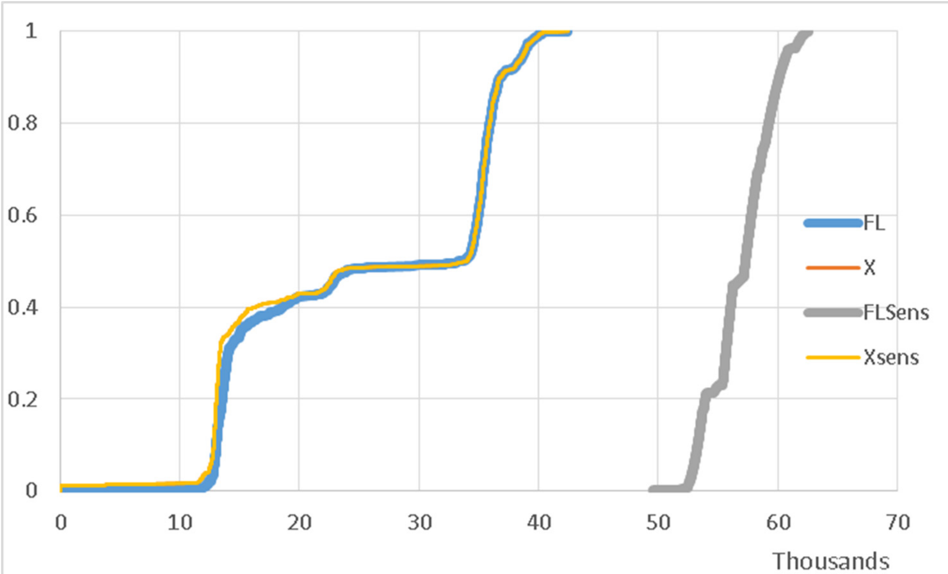

Figure G.115. Cumulative probability of anhydrous ammonia production for 99337 (Kennewick, WA) across scenarios of stochastic future linear (FL), future mixed-integer (X), future linear sensitivity (FLSens) and future mixed-integer sensitivity (Xsens).

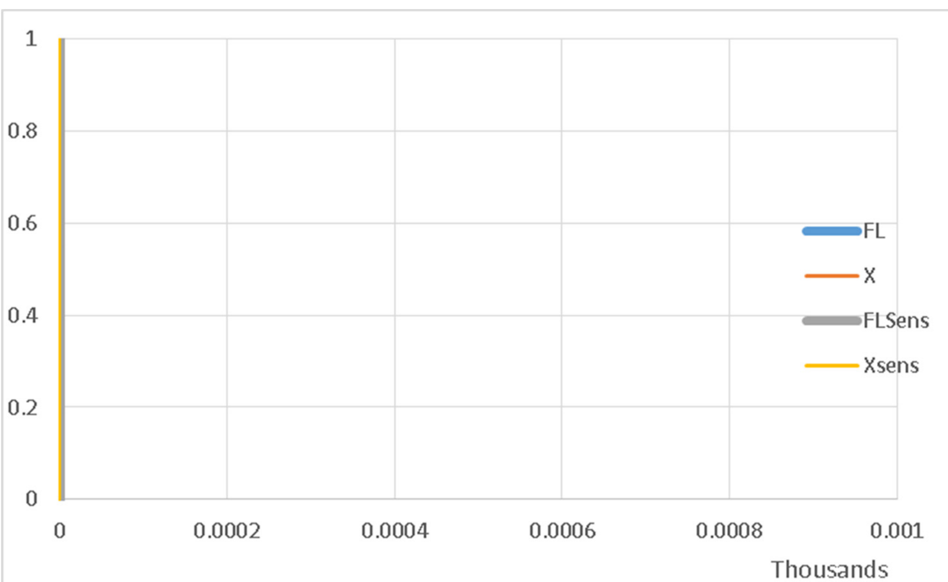

Figure G.116. Cumulative probability of urea production for 99337 (Kennewick, WA) across scenarios of stochastic future linear (FL), future mixed-integer (X), future linear sensitivity (FLSens) and future mixed-integer sensitivity (Xsens).

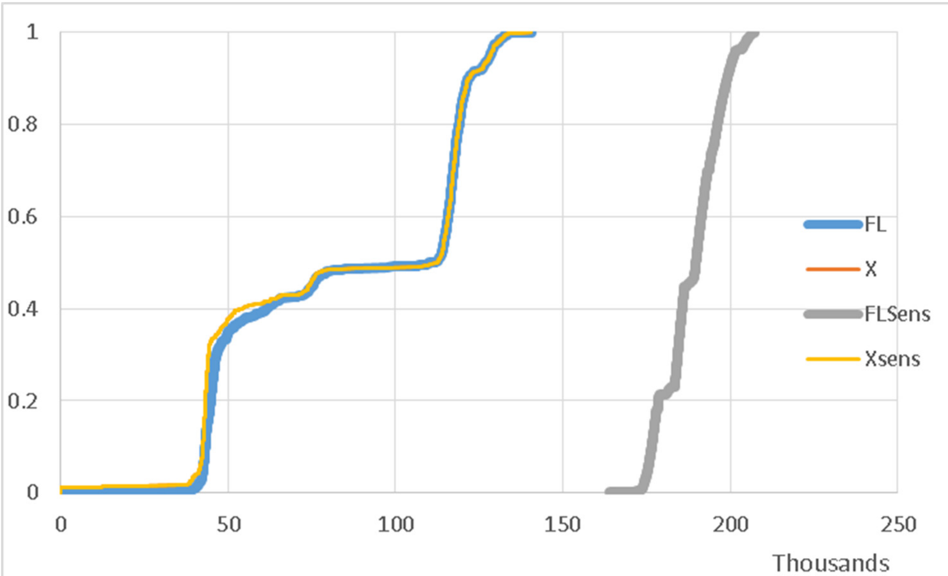

Figure G.117. Cumulative probability of UAN production for 99337 (Kennewick, WA) across scenarios of stochastic future linear (FL), future mixed-integer (X), future linear sensitivity (FLSens) and future mixed-integer sensitivity (Xsens).