The Impact of Increased Automotive Interest on the World Magnesium Market: Dynamic Material Market Simulation

By

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Abstract

In recent years magnesium has emerged as a viable material for lightweight automotive component designs. Magnesium is a good choice for vehicle light-weighting because of its exceptional strength, weight and casting properties. Despite these properties, magnesium is not a widely used automotive material due to its small supply base and high cost.

In the face of these higher costs automakers have slowly introduced magnesium cast components into their designs. The positive results of these initial applications have spurred further automotive interest in magnesium, but automakers remain leery of short supplies and material price volatility. Increasing interest in magnesium has resulted in several proposals for greenfield expansions of the material supply. However, uncertainties surrounding these new supply streams and the sustainability of demand still remain.

To investigate the stability of the world market for magnesium, a systems dynamics model of the market was created. The analysis performed led to two possible strategies for attaining future stability in the market. First, on the supply-side of the market, future capacity expansion was linked directly to model predictions of the emerging automotive demand. Second, a magnesium material market-making mechanism was instituted on the demand-side of the model to purchase low priced material in periods of market oversupply and release when demand strengthened. The first strategy of increased coordination between material supply and automaker demand proved a more viable strategy for promoting more stable market dynamics, which is reflected in current automaker investment in magnesium production ventures. The demand-side market-maker did not reasonably stabilize the most aggressive supply expansion plans, but did show some promise in more moderate scenarios by holding onto reserves on the order of 100 k tons of magnesium. In either case the cooperative and financial efforts necessary to coordinate the strategies would likely be the most difficult aspects of their implementation, but these efforts could prove essential to maintaining stable growth in both magnesium supply and demand.

Thesis Supervisor: Joel P. Clark
Title: Professor of Material Science and Engineering

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1 Overview

For nearly 100 years the automobile has been a central part of the modern world. The automobile is perhaps the most pervasive form of transportation and has provided personal mobility to millions. Popularized during the early 1900s in the United States by industrial pioneers Henry Ford and Alfred Sloan, automobiles quickly became as icons of personal freedom. By the end of the century, however, the automobile came under fire by critics in the environmental and energy fields as creating problems for the future. The sustainability of fuel reserves and the impact of automotive emissions on the global environment may be a threat to personal automotive transportation in the next century, if the fuel efficiency of automobiles is not improved drastically.

In the 1970s the western world was pinched by oil shortages that greatly increased the price of petroleum products. These shortages also caused the cost of energy to rise drastically. As a large consumer of petroleum, the automobile became an easy target for regulators hoping to alleviate some of the pain of the oil shock. In order to reduce consumption of gasoline Congress passed the Energy Policy and Conservation Act of 1975. With this Act, the Congress established nationwide standards for automotive fuel efficiency. This prompted automakers to address fuel economy, formerly a minor factor in automotive design, as a vital engineering requirement. In the years following the introduction of CAFE, the fuel efficiency of vehicles increased to match the standards, due to the threat of federal penalties.

Since the introduction of CAFE, the fuel economy standards for vehicles have been raised several times and auto manufacturers have invested much time and resources to maintain their compliance. During the 1990s, however, fuel economy standards for cars and light trucks were frozen at 27.5 and 20.7 miles per gallon respectively, which has led to stagnation in fuel efficiency gains. Despite the regulatory freeze, several factors have recently combined to pressure automakers to again address aspects of fleet fuel economy.

Relatively low gasoline prices in the early 90s, which led to rising demand for light pick-up trucks and sport-utility-vehicles in the US, made it difficult for the automakers to continue fuel economy gains. These large truck-based vehicles had the tempting attribute of relatively high profit margins, which tended to overshadow their notoriously poor fuel economy. Finding their fuel efficiency efforts being circumvented by a shift in consumer preference toward trucks, environmental groups have begun to pressure legislators to close the truck loophole in the CAFE standard. This threat of regulation coupled with recent trends toward rising oil prices could jeopardize the strong profits linked to light trucks as consumers switch their focus from utility to fuel economy. Again automakers are searching for methods to improve fuel efficiency in order to maintain image, boost consumer demand and head off threats of future regulation.

One of the simpler methods to achieve improved fuel economy is to reduce vehicle mass. However reducing vehicle mass and using lightweight materials, like other fuel efficiency technologies, is not always an easy task. Vehicle light weighting and cost reduction, a constant pressure for auto manufacturers, are two goals that usually run counter to each other. Low density materials are typically much higher in price and more costly to manufacture when compared to steel, the dominant automotive material. Despite costs, the mounting threat of tightening regulations is allowing more exotic materials like aluminum, polymer composite and magnesium to gain an increasing share of automotive component designs.

Magnesium has secured a small, but growing, role in some select automotive applications despite its high cost and limited supply. Magnesium has the lowest density of any major engineering material and is therefore very attractive when designing lightweight automobiles. Magnesium also has excellent manufacturing properties that enable it to be formed into shapes that consolidate many parts into a single component. This not only translates to mass savings, but also decreases assembly time and manufacturing costs. Some applications where cast magnesium has gained a noticeable share of automotive designs include, cross-car instrument panel beams, steering wheels, steering column supports and valve covers. Because of interest in these areas the market for automotive magnesium parts has grown rapidly, nearly 15% per year, during the 1990s and is expected to continue that trend [1].

Despite positive industry trends and vehicle light-weighing initiatives, there is still a great deal of uncertainty about the future of magnesium in automotive applications. Magnesium suffers from the typical cost hurdles when compared to more traditional materials like steel. Magnesium, at a price between $1.40 and $1.80 per pound, is often 4.5 to 5.5 times more expensive than sheet steel on a per mass basis. Despite this price premium the additional benefits of reduced mass, improved manufacturability and other engineering benefits in some cases justify a switch to magnesium design.

Another challenge for the development of magnesium into a large player in the automotive component market is the relative immaturity of the material supply structure. Magnesium supply and manufacturing industries are still in their infancy. More mature material industries, like steel and aluminum, dwarf the output of magnesium industry and produce nearly 1400 and 45 times as much material respectively on a yearly basis. As a result, the market price for the magnesium is prone to swings as demand grows and absorbs a very small global supply.

Many new greenfield magnesium facilities have been proposed in order to sustain recent increases in demand, but it is not certain whether these sites will be enough to stabilize the market price for magnesium. Continued market volatility has a negative impact on the ability of magnesium to enter automotive design consideration. Price pressures and intense competition between the auto manufacturers ensure that any auto designs considered are examined under extreme cost constraints. Recent swings in magnesium price have already been shown to cause automakers to switch magnesium components back to other competitive materials [2]. In this competitive environment, volatility in material price can be enough to disregard and substitute other more certain, stable priced materials.

This thesis will investigate the issues of stability in the world magnesium market in the face of increased automotive demand. A dynamic model of the world market for magnesium was created to simulate the historic trends in the magnesium market and investigate the possible effects of increased automotive interest in the material. The model was based on market modeling techniques used in the Material Systems Laboratory at the Massachusetts Institute of Technology and specifically targeted at emerging engineering materials. This technique employs aspects of econometrics, engineering utility analysis, microeconomics and system dynamics modeling to establish the interactions between demand and supply in the market. Market sectors that use magnesium, from aluminum alloying to die casting, steel desulfurization to cast iron, were considered.   The purpose of the study is to examine the stability of the magnesium market and investigate future scenarios of automotive demand on market supply, industry demand and material pricing. The goal is to gain insight into the dynamics of this material market and the impact of increasing interest in magnesium by the automotive interest. With this insight it should become easier to plan for future supply expansions and coordinate the introduction of innovative magnesium auto designs without jeopardizing the stability of the market.

2 Background: *Oil Crisis in the 1970s Leads to Increased Automotive Magnesium Usage*

In order to investigate the interactions within the magnesium market it is important to understand the motivation leading toward vehicle light-weighting and the reasons that magnesium has been chosen as a material enabler for vehicle light weighting. One of the primary motivations for vehicle light-weighting is the need to reduce consumption of limited supplies of fossil fuels. Improved fuel economy by vehicle light-weighting also reduces the amount of pollution generated by driving, another important concern of automakers and their customers.

The following chapter historically links the increased costs of energy to increased automotive interest in magnesium, by the route of increased government regulation and automotive light-weighting efforts. The first section shows how events in the oil industry and increasing energy costs in the 1970s lead to increased regulatory pressure on automakers to improve the fuel efficiency of their products. The second section of this chapter examines the historic progress of the US fleet fuel efficiency and discusses possible future trends for regulation in the face of growing energy and environmental concerns. Following the discussion of fuel economy regulation is an introduction of vehicle light-weighting as a strategy for improving fuel economy. As vehicle mass is directly related to energy expended to operate the vehicle, it can be seen as a central concern to meeting fuel economy requirements. Also included in this section is an examination of the implementation of light-weight materials in the auto industry following the introduction of fuel economy standards. The final section of this chapter will detail magnesium’s role in reducing vehicle mass, as well as other characteristics, that make it an attractive material for automotive design. This final section completes a historic journey, leading from energy concerns in the 1970s to the increasing attention automakers have given to the magnesium industry.

2.1 US Oil Crisis leads to Fuel Economy Regulations for Auto Industry

During the first half of the 20th century America was introduced to and quickly fell in love with the automobile. Henry Ford made personal transportation affordable with the introduction of the first mass produced automobile, the Model T. With inexpensive production methods, Ford provided a vehicle that was affordable for the masses. Affordable vehicles and cheap fuel enabled the public to expand across the continent and enabled much economic growth in America. Expanding past Ford's idea of affordable transportation, Alfred Sloan of General Motors took the automobile and made it into an expression of style. During their heyday in the 1950s and 60s, cars became big, fast and beautiful, to reflect core American ideals. Big cars with V-8 engines were common, because fuel efficiency was not a concern. Fuel was cheap and plentiful, therefore little engineering effort was dedicated to improving the efficiency of vehicles.

During the 1970s the American oil and energy picture changed drastically. After decades of growing automotive usage, western oil consumption began to have a large impact on the petroleum industry. A large American fleet of heavy, gas-guzzling vehicles began to strip the world's oil reserves. As oil reserves fell, gasoline and energy price began to rapidly increase.

This effect was intensified by the emergence of a strong international oil cartel, the Organization of Petroleum Exporting Countries (OPEC). OPEC, composed mostly of Middle Eastern and South East Asian countries, was founded in 1960 with the purpose of protecting the economies of developing nations where a majority of the world's petroleum was produced [3]. By the early 1970s OPEC had begun to effectively exercise its market power by restricting its output of oil to the western world.

As a result of OPEC's restrictions, oil inventories fell further in the US and Europe fell and gasoline prices skyrocketed, resulting explosive inflation, receding western economies and long lines at gas stations. Public outcry prompted the US Congress to attempt to reduce American dependence on foreign oil. The initial effort of the Congress was to push for federal fuel economy standards, in hopes that a more efficient American automotive fleet would enable the US to live within a reduced petroleum allotment. The United States Congress established corporate Average Fuel Economy (CAFE) standards in 1975 with the enactment of the Energy

Policy and Conservation Act [4]. A fuel efficiency standard of 18 miles per gallon for cars was introduced in 1978, the first year of CAFE enforcement. Light trucks were added at roughly the same level in the following year. Following introduction the standards were rapidly increased on a yearly basis, until 1989 when the requirements were frozen at 27.5 miles per gallon for cars and 20.7 miles per gallon for light trucks.

Following the enactment of CAFE, the threat of Federal penalties and public scorn encouraged American auto manufactures to pursue the standards into the late 1970s and early 80s despite its great cost. Since the introduction of CAFE, fuel economy standards have been included as engineering targets on each vehicle designed in the US. Enacting regulations, however is never a guarantee of compliance, the next section will chronicle the history of CAFE and the trends expected in its future.

2.2 The History of CAFE Compliance and Possible Future Trends

The enactment of CAFE in 1975, re-introduced the public and the automakers to the importance of fuel economy. Automakers could no longer only produce large, heavy vehicles that guzzled fuel. Automakers began to develop smaller cars, lower displacement engines and light-weight alternatives to steel construction in their pursuit of CAFE compliance. Figure 1, below, shows a history of how the automakers attempted keep up with rising federal standards [5].

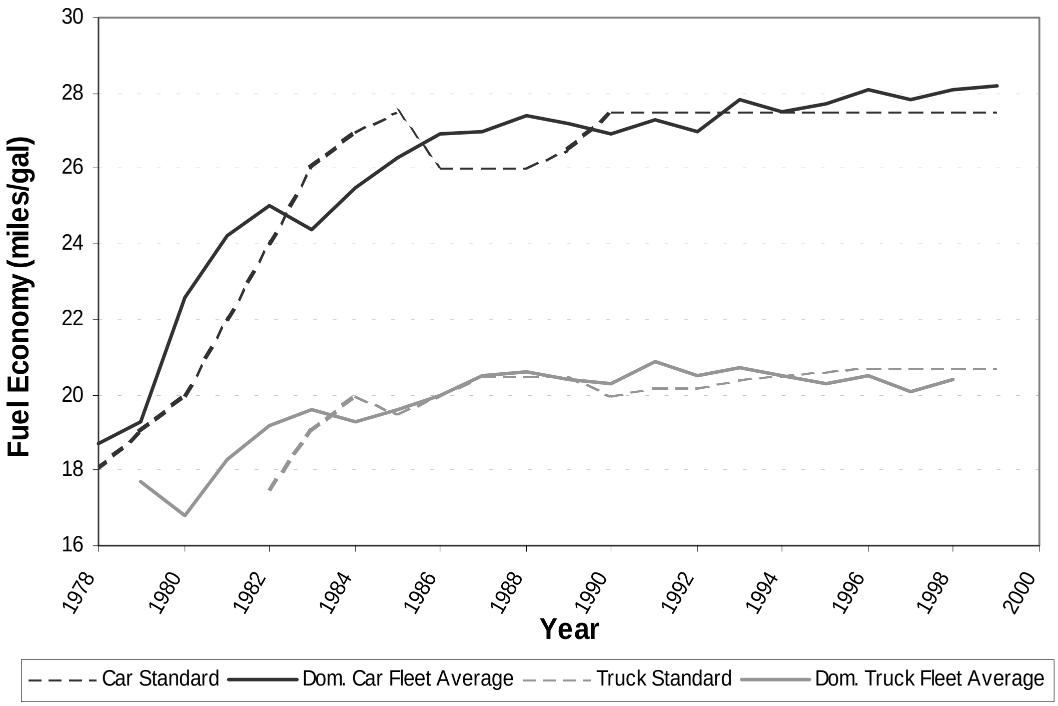

Figure 1: Historic Corporate Average Fuel Economy (CAFE) Standards and Average Domestic Fleet Fuel Economy Performance

After the oil shocks in the 1970s, the US congress aggressively increased efficiency standards hoping to wean America from its dependence on foreign oil. Despite the efforts at the federal level, the American automakers fought the regulatory pressure. The collective pressure of the automakers and their lobbyists enabled carmakers to create some soft spots in the regulations. As a result the advancement of CAFE was slowed in some years, as seen between 1984 and 1988. Elaborate regulatory loopholes were also introduced that allowed automakers to store credit for years when their fuel economy exceeded requirements for possible application to past or future regulatory shortfalls. Light-trucks were also allowed to have a much lower fuel efficiency standard. Constant resistance from domestic automakers, coupled with stabilization in oil prices, resulted in a stagnation of CAFE standards by the end of the 1980s. With increased automotive efficiencies and no further signs of problems in the oil supply, attention to fuel economy waned.

The current standards, frozen since 1989, have required that the fleet average of cars sold by each manufacturer attain a level of 27.5 miles per gallon, while light truck fleets must reach an average of 20.7 miles per gallon. Mirroring the stagnation of the regulation the efficiency of American automotive fleet leveled off during the 1990s. Oil prices actually fell for most of the 1990s primarily due to added petroleum supply and a weakening in the cohesion of OPEC's member countries. Concerns about foreign oil dependence were quieted, so any proposals for additional regulations were dropped. With a reduced threat of rising standards and little public demand for fuel-efficient vehicles, automakers made few strides to further improve the fuel economy of their vehicles during the last decade.

Reduced oil prices in the 1990s actually increased American demand for light trucks, sport-utility-vehicles and vans, as utility and size began to overshadow consumers concern for the cost of operating their vehicles. Automakers were happy to provide consumers with these large vehicles, as trucks and SUVs carried much higher profit margins compared with smaller cars. The big, fast and beautiful vehicles of the past emerged in a new guise, this time sporting four-wheel drive.

Despite the trends of the past decade, several indicators are hinting that changes in regulatory focus and public opinion on fuel economy may be on the horizon. Recent trends in fuel prices and shifts in environmental attitudes are creating new pressures on automakers to improve vehicle fuel efficiency.

In the year 2000 gasoline prices in the US increased over forty percent due to low reserves and reduced oil output by a seemingly more unified OPEC. Rising oil consumption from a US fleet increasingly dominated by light trucks and SUVs was again stripping away fuel supplies. Figure 2 below shows the trend in oil and gasoline prices in the year 2000 [6].

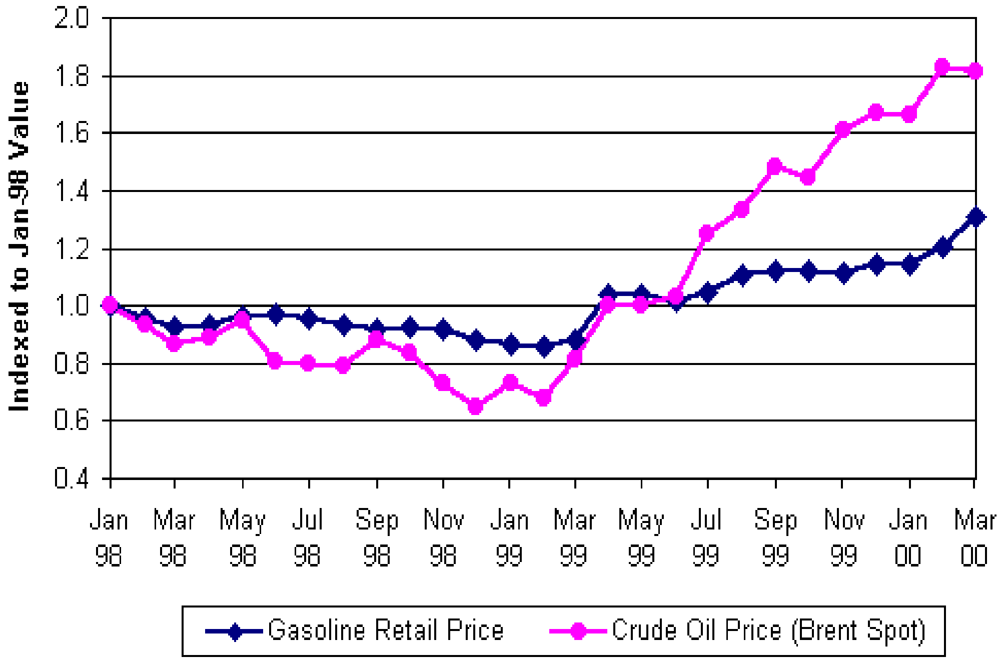

Figure 2: Recent US Crude Oil and Gasoline Pricing Trends (indexed to Jan 98): January 1998 to March 2000

Public outcry against rising fuel prices was substantial. Neglect of fuel economy during the 1990s appeared to be coming back to haunt automakers and consumers alike. Many consumers were stung by fill-ups of $50 or more on their full-size sport utility vehicles.

While gas stations have yet to run out of fuel, consumers and legislators have some painful memories of the energy crisis of the 70s. With the potential problems that could be created by another oil crisis, legislators could again be stimulated to increase CAFE requirements in hopes of heading off potential oil supply problems before they get out of control. Automakers are beginning to worry that CAFE targets may again be raised. One of the largest potential regulatory targets being discussed in political circles is the truck loophole. Pundits often discuss the likelihood that the truck standard will be raised up to the same level as cars. With light-trucks generating a large portion of corporate profits, this CAFE increase could be a serious regulatory and technological threat for automakers.

A rise in the public's environmental awareness is also seen as a possible motivator for increasing fuel economy standards. Concerns about the negative effects of global warming are gaining weight in the public's eye. The global warming effect, hypothesized by Svante Arrhenius at the beginning of the 20th century, is caused when the emission of greenhouse gases, primarily carbon dioxide from burning fossil fuels, in the atmosphere trap more of sun's energy. Evidence of the gradual warming of the Earth's atmosphere and its link to fossil fuels has been accumulating since the 1950s. As evidence of global warming built up, so have media coverage, public attention and regulatory concern. Several United Nations conferences were held on the problem of global warming during the 1990s, the last of which culminated in the inception of the Kyoto Protocol. The Kyoto agreement pledges over 160 countries to substantial reductions in their carbon dioxide emissions [7].

As automobiles contribute nearly 20% of yearly carbon dioxide emissions in the US, any federal efforts made to comply with the Kyoto Protocol would likely involve regulations to encourage a drastic drop in automotive gasoline consumption [8]. CAFE increases are likely to be used to achieve reduced fuel consumption and greenhouse emissions.

The treat of regulatory action is not the only source of pressure automakers are feeling related to fleet fuel economy. Internal pressures at the automakers themselves are also on the rise. Environmental stewardship and fuel economy are increasingly being touted by automakers in hopes that "green" practices will result in a positive public image. Multiple "green" initiatives have recently been introduced by automakers including electric vehicles and improved catalytic converters. These efforts have been marketed to consumers in efforts to improve corporate image and, hopefully, increase auto sales. If these trends continue the environmental arena could quickly become a competitive selling point, much like horsepower, stylish design, and safety.

Due to several changes in regulatory, public and corporate attitudes discussed previously, automotive manufacturers have become increasingly sensitive to the possibility that fuel economy of their fleet will need to increase drastically. Whether by Congressional action on CAFE standards or competitive pressure, fuel economy is once again becoming an important engineering challenge. In fact, the challenge of improving efficiency may prove to be the biggest problem for the automotive industry in the next decades if regulations are raised or fuel supplies drop. Many technology options, from improved aerodynamics to hybrid powertrains, fuel cells to light-weighting, are being investigated in the research and development centers of the automakers in hopes that they might offer hedges against possible regulations and swings in public opinion on fuel efficiency.

2.3 Automotive Light-weighting and its Impact on Fuel Economy

Increasing the fuel efficiencies of the automobile may prove to be one of the greatest technical challenges facing the automotive industry in the near term. There are many possible technical solutions to this problem, many of which are very expensive. Large amounts of money are spent each year researching alternate powertrains, performing aerodynamic tests and developing exotic materials for automotive use. The solution or combination of solutions that delivers the most effective use of investment for improved efficiency, however, has not been found.

Using lightweight materials is one of the most conceptually simple ways to reduce fuel consumption during the operation of a vehicle. Lighter vehicles require less fuel to operate due to the application of the first principles of physics. The first principle states that the required force is equal to mass of an object multiplied by its acceleration. Other factors like aerodynamics, internal frictional forces and engine specifications also contribute to fuel efficiency in different ways, but due to fundamental physics, the impact of vehicle mass is unavoidable.

The relationship between mass and fuel efficiency have been traditionally lumped into an accepted industry rule-of- thumb called the 10 -5 rule. In general it is observed that a ten percent reduction in the mass of a vehicle results in a five percent improvement in fuel efficiency. Auto light-weighting has also been shown to have large impacts on total vehicle mass reduction through secondary weight savings. This secondary effect refers to a relaxation engineering requirements that reduced weight auto bodies can capitalize on. Lower weight vehicles are able to maintain acceptable levels of performance with less weighty non-body components. For example, low mass auto bodies require less massive suspension systems to deliver a constant level of ride and handling. Reducing the unsprung mass of a vehicle has in some cases been estimated to net up to an additional 100% in additional mass savings related to other systems [9].

Due to the intimate relationship between vehicle mass and fuel efficiency, automakers have recently been spurred to investigate low mass alternatives to the traditional steel that has dominated automotive design for the last century. Polymers, aluminum and magnesium have increased their automotive applications in the last decade partly due their lower densities compared to steel. Replacing steel assemblies with components in these light-weight materials helped the automakers to achieve the federal fuel economy targets. The table below shows how the material content of the average American automobile has changed over the last decades [10]. All of the light-weight materials have all increased their presence in automotive designs, polymers increasing 50%, aluminum increasing over 150% and magnesium increasing 800% since 1977.

Table 1: Material Content of the Typical Family Automobile [10]

	Mass of Material (lb) in Year X					
Material	*1977*	*1985*	*1992*	*1998*	*1999*	*2000*
Ferrous (steels and iron)	2,742	2,250.5	2,141	2,174	2,161	2,140
Plastics / Composites	168	221.5	243	243.5	245	248.5
Aluminum	97	138	173.5	224	235	245.5
Magnesium	1	2.5	3.5	6.5	7	8
Other	657.5	575	574.5	613.5	626	644
Total	3,665.5	3,187.5	3,135.5	3,261.5	3,274	3,286

From the table it is evident that while steel has maintained its competitive dominance of automotive materials, light-weight materials are becoming increasingly more important. Light-weight metals, like aluminum and magnesium have made the large gains going from minor contributors to preferred materials in specific applications.

Despite its very low density, magnesium continues to play only a small role in the automotive arena. Magnesium's rapid growth in the past decade, however, has shown that the automakers are acknowledging its potential for mass reduction. If the growth trends in automotive magnesium usage continue, it could play a major role in the near future. Usage could also accelerate if fuel economy improvements become a vital concern.

2.4 Magnesium and its Application to Automotive Design

Magnesium is the lightest of the common engineering materials, with a density roughly two thirds that of aluminum and a quarter that of iron and steels [11]. The low density of magnesium makes it an attractive material for automotive design as light-weight vehicles consume less fuel. Despite this mass advantage, the acceptance of magnesium in the automotive industry has been a relatively cautious process. Magnesium has traditionally been viewed as an expensive, exotic material with poor corrosion properties. This perception has made it difficult for magnesium to compete with more traditional automotive materials like steel, aluminum and polymers. As fuel economy concerns rose during the end of the 20th century, magnesium emerged as new material for some applications of lightweight auto design. This section follows the evolution magnesium auto design from early applications, to current design successes and engineering benefits and possible future applications.

Volkswagen, in the two decades following World War II, pioneered the earliest applications of automotive magnesium design. Each VW Beetle model produced during that period contained 20 kg of magnesium in the gearbox and crankcase [12]. However, due to its high price, magnesium had trouble gaining much acceptance in the automotive world until the oil crisis of the mid 1970s. Automakers were content to design cars in steel because of its low cost, ease in manufacture and familiarity.

As fuel economy concerns surfaced during the 1970s, investigations into lightweight materials were initiated by automakers. Reducing vehicle mass became a vital part of the strategy to meet federal fuel economy goals. Following introduction of CAFE requirements, automotive designs showed rapid increases in the application of lightweight materials like aluminum, polymer and magnesium. Magnesium usage remained relatively low compared to other lightweight materials, as its high price and susceptibility to corrosion kept it from consideration.

Magnesium did not find much application in the automotive sector until the 1990s, when engineers became aware of several additional properties, other than low density, that made magnesium attractive in select automotive applications. Development of high purity alloys, the AZ and AM series, during this period greatly improved the corrosion resistance of die-cast parts, one of the biggest problems with adopting magnesium auto designs. Reducing concerns about corrosion opened the door to many possible auto applications for magnesium. Other characteristics like thin wall casting, long tool life and part consolidation potential strengthened the potential of magnesium. The following table lists these properties of magnesium and their benefit to automotive design.

Table 2: Properties of Magnesium that are Attractive to Automotive Applications [13]

Property	Engineering Benefit
Low Density	- 2/3 density of Aluminum, 1/4 density of Steel; enables lower vehicle mass and improved fuel economy
Part Consolidation	- Near net shape cast parts can replace designs of multiple steel stampings with a single piece; reduces assembly and quality problems at component interfaces
Low Reactivity with Tool Steel	- Extended tooling life compared to casting aluminum alloys
Improved Corrosion Resistance	- Development of high purity alloys yield corrosion resistance on par with cast aluminum
Good Damping Properties	- Control NVH in body, steering and suspension applications

Following these technical advancements in magnesium technology, the applications of magnesium in the automobile grew rapidly. The initial applications of magnesium design in the 1990s were limited to small components, such as brake pedal brackets and steering wheels. These bracket applications capitalized on the low density of magnesium and some part consolidation. They also allowed auto engineers to become familiar with the material and provided a technical basis for future magnesium applications [14].

As internal pressures to reduce vehicle mass increased and experience in using the material grew, engineers began to be more ambitious in magnesium component design. During 1990s Ford Motor Company had dominated auto industry use of magnesium by employing the material in many brackets, steering wheels, seats and transfer cases [15]. In mid 1990s, however, General Motors took the lead in automotive magnesium by debuting the first single piece magnesium instrument panel (IP) beam in an American automobile [16]. This application delivered on the part consolidation potential of magnesium design by eliminating dozens of brackets, beams and supports in the instrument panel of the 1997 Buick Park Avenue. This system had several additional benefits including improved body rigidity, lower mass and faster assembly time. GM quickly applied the magnesium IP design to many of its large cars and trucks, including the Chevy Express full size van, which boasts the world's largest automotive magnesium casting, weighing 15 kg [17]. Other magnesium designs at GM and the other American automakers followed up on the success of the IP application. Growth in instrument panel beams, engine valve covers and four-wheel-drive transfer cases has generated an explosive growth rate in automotive castings in the late 1990s, ranging from 10 to 20% per year [18].

Future applications of magnesium are projected to continue to capitalize on the mass reduction and part consolidation attributes that were pioneered in the designs of the 1990s. Magnesium suppliers and die-casters are taking an active role in promoting the use of their material. These magnesium advocates are developing and researching several innovative applications of magnesium. The list below shows the current accepted automotive applications of magnesium and possible next generation applications.

Table 3: Current and Next Generation Magnesium Automotive Applications

Current Generation Auto Applications	Next Generation Auto Applications
Various Brackets	Door / Closure Inner Panels
Steering Column Supports	Cross Car Structural Members
Steering Wheels	Body Pillars
Seat Frames	Auto / Manual Transmissions
Instrument Panel Supports	Road Wheels
Transfer Cases	Engine Blocks
Engine Valve / Cam Covers	Engine Cradles

These future applications could increase the already rapid growth in automotive magnesium usage. The world magnesium industry will benefit from this additional interest in their material, but it will also face some difficult challenges. Magnesium supply is not nearly as mature as their major material competitors in the steel, aluminum and polymer industries. The growing interest in magnesium automotive components could add huge volumes in demand to an extremely small market. This added demand could be enough to cause drastic movements in material price, material supply and market demand. The remainder of this study will address the market issues surrounding the rapid growth in automotive magnesium demand and how it could affect the dynamics of the maturing magnesium market. The next chapter will start off this effort by describing the magnesium market, including both suppliers and consumers.

3 The World Magnesium Market: *Material Supply and Demand*

In order to understand how increased automotive interest will affect the dynamics of the world magnesium market it is very important to understand the separate players in the world magnesium market and their motivations. The following chapter introduces these actors on both the supply and demand sides of the market. The first section focuses on the magnesium suppliers, including their technical aspects producing their product and the history of their industry. The second section focuses on the demand side of the market and gives short summaries all of the primary magnesium consuming industries and looks at the trends for magnesium demand in their sectors.

3.1 Magnesium Supply

Magnesium is a relatively abundant material, listed as the eighth most common element on the earth and third most abundant element dissolved in seawater [19]. Despite its abundance magnesium has a relatively small supply base. A study by Solomon Smith Barney investigating the extent of world magnesium supply says that the total world capacity for producing the material is roughly 500,000 metric tons per annum (tpa) in 1998 [20]. When compared to its closest material competitor, the aluminum industry producing 22.3 million tpa of material in 1998, the magnesium industry is dwarfed. The following sections will provide background as to the immature nature of the magnesium industry. The first section focuses on the technical features and challenges of producing magnesium. The second section provides a historic perspective of the magnesium supply industry and its evolution over the years. Both technical and historical information will provide some reasons behind the relative immaturity of the industry.

3.1.1 Magnesium Sources and Production Techniques

Magnesium is produced from a variety of different source materials, including mineral ores like dolomite, carnallite and magnesite as well as from high salinity seawater brines. There are also supply sources being planned that will use the tailings from asbestos mines as a source of magnesium. The following table shows the relative magnesium content of these magnesium sources [21].

Table 4: Description of Common Sources of Magnesium

Magnesium Source	*Description*	*% Mg*	*Comments*
Brines	Generally Chloride Salts	Varies	From seawater, or salt lakes
Carnallite	Double salt of magnesium and potassium chloride hydrate, $Mg\ Cl_2.KCl.6H_2O$	8.75	Natural mineral
Dolomite	Carbonate rock, with similar proportions of magnesium and calcium, $MgCO_2.CaCO_2$	21.7 max	Isomorphous carbonate rock
Magnesite	Magnesium carbonate, $MgCO_2$	26-28 max	Rarely found pure, some iron and calcium
Serpentinite	Magnesium silicate, $3MgO.2SiO_2.2\ H_2O$	26.3	Found in asbestos tailings

There are several processing techniques that can be used to isolate the magnesium alloy. The most common method for refining magnesium is an electrolytic process that is employed for processing from any of the magnesium sources. The process has five steps, listed below [22].

1) Leach the raw material with hydrochloric acid to create magnesium chloride.

2) Purify the magnesium chloride solution into a concentrated liquor by precipitating out impurities

3) Dehydrate the liquor to produce anhydrous magnesium chloride for feedstock to electrolytic cells

4) Apply an electric current to feedstock in electric cell to drive off molten magnesium while producing a byproduct, chlorine gas.

5) Cast the molten magnesium into ingots

Dow Chemical Company perfected the electrolytic method for producing magnesium from seawater at its Freeport, Texas facility over many years. Many other facilities have attempted to duplicate the Dow process making it the most popular method of refining magnesium.

The electrolytic pathway has many technical and economic challenges. Electrolytic plants have great constraints on their processes, often requiring high purity inputs and very expensive capital equipment. Due to the expensive capital equipment electrolytic facilities are typically limited in size. Small plants are then further challenged by limited scale economies. The Dow facility was possibly the only exception. The Freeport plant could process a fairly low purity source, seawater, and ran with relatively low costs. Because they used old, simple equipment the Dow site had virtually no capital costs [23].

The energy content required to purify and electrolyze the feedstock is also fairly high, up to 50% higher than for aluminum. A majority of this energy is used to dehydrate the magnesium chloride feed before the electrolysis step. Due to this huge energy expense, electrolytic magnesium facilities are typically found in areas with cheap electricity, like hydroelectric plants. A similar co-location phenomenon is witnessed in the aluminum industry, which also utilizes an electrolytic pathway [24].

Another challenge for magnesium producers using the electrolytic pathway is dealing with the environmental implications of their chlorine byproducts. Chlorine gas, a potent greenhouse gas, is produced in the electrolytic cells during electrolysis step. Emission of chlorine gas byproducts has made MagCorp, an electrolytic magnesium producer in Utah, one of the nations worst polluters [25]. Not all electrolytic magnesium producers, however, are large polluters. By employing strict, albeit expensive emission controls, Norsk Hydro has reduced its chlorine emissions to 5 kg/ton Mg [26].

The electrolytic pathway, however, is not the only method of refining magnesium. Other popular magnesium refining methods use metallothermic processes. Magnesium producers in China commonly utilize this technique. These processes utilize small boilers in batch operations that use reducing agents, like calcium carbide, calcium silicate, but most commonly ferrosilicon, to isolate magnesium. The batch reactors heat the ores and reductants at high temperatures that remove the oxygen portions of the ore. The batch is operated under a vacuum, which draws off vaporized magnesium from the melt. Condensation processes then collect the magnesium vapors [27].

Collecting the magnesium vapor can be a very dirty operation, which often yields highly contaminated magnesium. Because of this lack in purity, metallothermic magnesium is often not an acceptable feedstock for use in structural applications, like die-cast parts. However, in other industries where magnesium purity is not an issue, like desulfurization of steel, metallothermic magnesium is acceptable, and often preferred due to its reduced cost.

Despite its relatively simple technology, the ferrosilicon method of magnesium refinement is challenged by more difficult scale problems. Facilities that use this methodology produce microbatches of material in quantities much lower than the electrolytic pathway [28]. For small Chinese operations this scale issue is a minor concern, but it is unlikely that these suppliers will be primary providers for large increases in magnesium demand.

An alternative experimental metallothermic method for producing magnesium is currently under investigation in Australia. This method, called the Heggie Process, shows some additional cost benefits unattainable by the traditional batch thermal processes. The Heggie Process, which is similar to other metallothermic processes, uses aluminum to reduce the magnesium ores, rather than ferrosilicon, in an electric arc furnace. The magnesium vapor is drawn off with a vacuum as in the previous ferrosilicon pathway. A developmental production process utilizing scrap aluminum as a feed is underway in Batchelor, Australia. Due to the availability of low cost of aluminum scrap and developments to continuously cast the magnesium vapor, this project may be very cost competitive [29].

Despite their different pathways, all magnesium production techniques have a common environmental challenge. Each process generates molten magnesium metal, which is extremely combustible in the ambient atmosphere. To combat the explosive behavior of the raw magnesium, smelters have employed a cover gas method, using small amounts of the gas, sulfur hexaflouride (SF_6). While the use of the gas is small, sulfur hexaflouride users have come under increasing environmental pressure since SF_6 is a potent greenhouse gas. The release of one kilogram of sulfur hexaflouride is equivalent to a carbon dioxide emission of 23.9 tons. Magnesium producers have spent a large amount of time and effort to minimize the release of the cover gas. Some producers have reduced emissions of sulfur hexaflouride to as little as 0.5 kilograms per ton of material produced [30]. Development efforts are underway to find technical replacements for sulfur hexaflouride like, sulfur dioxide (SO_2). However, sulfur dioxide has its own technical challenges due to its corrosive properties and toxicity.

There are many technical, environmental and economic challenges of producing magnesium in large quantities. The magnesium supply base, however, has only recently begun to seriously address these challenges. Recent spikes in magnesium demand, primarily in the automotive sector, are making refinement and enlargement of the supply base vital to market stability. The next section gives a short history of evolving magnesium supply industry, its current trends and its future plans for meeting increasing demand.

3.1.2 A Historic View of the World Market Supply of Magnesium

For much of the century magnesium remained a small immature material industry. Few facilities supplied it and few industries needed it, therefore it remained a rather exotic material with a relatively expensive price. By the end of the century, however, several major events caused rapid changes in the makeup of the magnesium supply industry.

For much of the 20th century magnesium production was dominated by a single supply source, Dow Chemical Company. Utilizing an old and inefficient, but cheap electrolytic process, Dow dominated the market in a virtual cartel position up until the end of the 1980s. By using old equipment with nearly no capital cost, Dow exercised incredible pricing power. If threatened by a competing source Dow could offer material at a price of roughly $1 per pound, essentially its operating cost. This market power established Dow's dominance in the market and kept new suppliers from entering up until the end of the 1980s [31].

There were several other major players in the magnesium market at this time, as well. They included, MagCorp, which operated a large facility that derived magnesium from the waters of the Great Salt Lake in Utah, Northwest Alloys, a subsidiary of Alcoa, devoted to supplying magnesium for aluminum alloying, and Norsk Hydro, with large facilities in Norway and Canada. However, these other players had relatively little power in the market, due to Dow's low operating costs. The rest of the magnesium supply base consisted of small facilities scattered around the globe in Europe, South America, and Canada.

In the early 1990s several factors led to a dramatic increase in the supply base for magnesium. First, the fall of Soviet Communism allowed magnesium producers in Russia and Eastern Europe to enter into the world magnesium market. Russian producers, strapped for cash, were willing to sell magnesium material at or even below operating cost. These supplies of magnesium were entering the market with large volumes and low pricing, which put them on par with Dow Freeport [32].

A second challenge to the traditional market structure for magnesium came from the Far East. Starting in 1990, the People's Republic of China brought online large numbers of small metallothermic facilities utilizing vast deposits of high purity dolomite. These facilities consisted of simple boilers and relied heavily on low cost manual labor. The metallothermic process was a dirty way of producing magnesium, but it was acceptable to some industries. Cheap labor and simple technology allowed these facilities to sell material at prices below $1 per pound, which was very attractive to consumers [33]. Steel producers in the west quickly snapped up Chinese magnesium for desulfurization, which does not require high purity magnesium. . Increased demand for low cost, low quality, magnesium enabled China to become the world's largest supplier of magnesium in less than ten years. Again, low operating costs and large volumes were threatening Dow and the other large American magnesium producers.

In response to import pricing pressures, American magnesium producers effectively lobbied the US Congress for trade restrictions on magnesium imports from Russia and China. By mid 1994 anti-dumping duties of nearly 100% were approved for all magnesium imports from the two nations. These tariffs essentially cut off all magnesium imports from Russia and China into the US. However, without these sources domestic supply of magnesium could not keep up with the domestic demand. As a result magnesium inventories fell dramatically and prices skyrocketed to over $2 per pound in 1995. This price peak proved unsustainable, as a resounding outcry from magnesium consuming industries forced the US government to effectively eliminate the tariff on Russian magnesium in 1996 (as long as it came from approved import channels). The flood of Russian magnesium back into the market allowed prices to resume levels similar to those observed prior to the anti-dumping action [34]. Despite loosening restrictions on Russian imports, tariffs on Chinese sources remained intact. Magnesium consuming industries would like tariffs on Chinese magnesium to be lowered in hopes that its low cost would induce more negative pricing pressure. However, the threat of low cost Chinese magnesium to western material producers makes it unlikely that restrictions will be eliminated in the near term.

The third major market event that influenced the magnesium market in the 1990s was caused by a hurricane. In November 1998 Dow's Freeport, Texas facility closed down its production completely due to flood and lightning damage inflicted by strong storms. After years of dominating the market, Dow removed itself from the fray [35].

With Dow, and its pricing power out of the picture, many more magnesium sources were proposed and even more are being planned for the future. Much of these new sources are needed in order to maintain magnesium's recent growth trends, especially in the automotive area. In order to secure stable sources of material, auto manufacturers are playing a powerful role in these new ventures. Dead Sea Magnesium, a joint venture sponsored partly by Volkswagen, recently finished ramping-up production at its 24,000 ton facility harnessing magnesium from the brines in Israel. Due to initial technical success and rising demand, an expansion of the Dead Sea facility is already in the planning stages. Ford Motor Company has likewise signed on to support a 90,000 ton magnesium plant in Queensland, Australia slated to start production in 2001. Other magnesium sources are being proposed in Australia (Mt. Grace), Canada (Noranda) and the Congo [36]. Table 5 shows a list of proposed greenfield magnesium sources and the comparative size of the expansions to the current industry capacity for primary material.

Table 5: Proposed Near-Term Greenfield Magnesium Projects [36]

Magnesium Project	*Magnesium Source*	*Proposed Capacity of Project*	*Current Status*	*Proposed Start-Up Date*
Noranda, Quebec	Asbestos Tailings	58,000 tpa	Ramp-Up	2000
Mt. Grace, NT, Australia	Magnesite	50,000 tpa	Pilot testing	2003
Queensland Mag. Co., Queensland, Australia	Magnesite	90,000 tpa	Pilot testing	2004
Magnesium Alloy Corp., Congo	Carnalite	50,000 tpa	Pre-Feasibility	2004
Current Industry Material Capacity	**Various Sources**	**~550,000 tpa**	**In operation**	**-**

Despite rosy forecasts in expanding supply, the success of each of these ventures and the stability of the market is not certain. The business proposals of each of the new greenfield production sites hinges on a virtual market paradox. Areas of large magnesium growth potential, like automotive design, require large availability of low cost magnesium alloys. However, the viability of the proposed sources, that will eventually provide the material for this growing usage, is intimately linked to a relatively high and stable price for magnesium.

The expansions in supply will likely be necessary to maintain the stability of the magnesium market if current demand trends continue. These demand trends, however, present their own challenges as well. Magnesium material is used by many different types of industries, all of which will be competing for the relatively small amount of magnesium production each year. With rapid growth in sectors like, automotive die-casting, there is a potential problem that total demand in all sectors will outstrip supply, even with the added planned supply expansions. The next section will provide general descriptions of all of the magnesium consuming industry as background into the demand side of the magnesium market. This section will provide a context into the size, scope and motivations of each magnesium consuming industry.

3.2 Magnesium Demand

Magnesium is a material used by different types of industries and applications. Some use magnesium for its chemical properties, others for its alloying properties and still others for its structural attributes. Despite their different motivations, these industries compete for a rather small supply of material. With rising demand the interactions between these competing magnesium demand sectors could cause instability in the market. Similar to the supply side, the demand sectors must also be investigated in order to understand the dynamics of the market completely. Table 6 below shows how the world consumption of magnesium was divided among the major industrial demand sectors in 1998.

Table 6: World Demand for Magnesium By Industrial Sector, 1998

Industrial Sector	Description	Tons of Mg Used	% of Yearly Demand
Aluminum Alloying	Mg is a vital alloying agent in the production of sheet Al	154,400	42.6%
Die Casting	Production of die cast parts, mostly for automotive sector	110,100	30.4%
Steel Desulfurization	Mg used to remove impurities from steel in smelting	48,200	13.3%
Nodular Iron	Mg used as a carbon nodularizing agent in cast iron	11,300	3.1%
Electro Chemical	Mg for sacrificial anodes and battery production	10,000	2.8%
Other	Secondary shipments and some shipments to China and Russia	9,300	2.6%
Chemical	Mg as a Grignard reagent and pyrotechnic applications	6,800	1.9%
Metal Reduction	Mg as a reducing agent for producing Titanium, Beryllium, Zirconium and Uranium	4,900	1.4%
Wrought	Mg for extrusion, sheet and plate	4,500	1.2%
Gravity Casting	Mg for sand and permanent molding	2,600	0.7%

The following sections will discuss these demand sectors briefly to provide insight into their motivations for magnesium demand. The section will conclude with a general discussion of the future of magnesium demand trends.

3.2.1 Magnesium in Aluminum Alloying

Magnesium is one of the most common metals introduced into aluminum for alloying where it is used as agent for improving metal ductility. Magnesium content is highest in aluminum used in sheet used for can stock. The tops and bottom of aluminum cans contain up to 4.5% magnesium [37]. Currently, the aluminum industry is the largest consumer of magnesium worldwide accounting for nearly 43% of magnesium demand in 1998 [38]. The market for aluminum cans is relatively mature due to deep penetration of aluminum in beverage can applications. Other applications of aluminum sheet for packaging have remained at relatively low levels of penetration due to stiff competition from other materials, like paper and polymers [39].

3.2.2 Magnesium for Die Casting

High-pressure die-casting (HPDC) is a process where molten metal is injected into a mold with a desired shape at high pressures. The liquid is then cooled and the part is removed from the die in a near net shape [40]. This process can make complex shapes in single pieces if the proper die design is implemented. Magnesium and aluminum are the primary alloys cast in the HPDC process. Magnesium die-casting is the second largest consumer of magnesium following aluminum alloying and accounted for roughly 30% of world demand in 1998 [41].

Aluminum die-casting is a fairly well known manufacturing process in western countries, while magnesium die-casting is still a relatively immature industry. The largest magnesium die caster is Meridian Technologies, with manufacturing facilities in Michigan, Ontario and Italy. Meridian is a joint venture between Norsk Hydro, the world's largest magnesium company, and Teksid, an Italian foundry [42].

The primary consumer of magnesium die-castings is the automotive industry, which accounts for nearly 80% of die cast demand. Other applications of magnesium die-castings include power tools, cellular phones and computer housings. North American industries also dominate the demand for magnesium castings, creating nearly two thirds of demand. Western Europe accounts for another quarter of world demand for magnesium die-castings, while Asia comprises less than 5% of world demand in this sector [43]. Growth in the automotive sectors has fueled large growth rates in the last decade of over 10 % per annum. Future growth rates, further motivated by automotive interest in light weighting, are projected to remain high, between 10-20% [44]. With continued double-digit growth magnesium die-casting could easily surpass aluminum alloying as the world's largest magnesium consuming industry.

3.2.3 Magnesium for Steel Desulfurization

Magnesium is also used in the production of steel as a desulfurizing agent. Removal of sulfur impurities is vital to maintain steel quality. Magnesium combines with sulfur in the steel melt to create stable magnesium sulfides. Magnesium also has the added benefit of assisting with deoxidizing the steel melt [45]. Magnesium emerged in the 1980s as a replacement for calcium carbide and soda ash reagents and found quick acceptance. Steel desulfurization is the third largest magnesium consuming activity, accounting for 13% of worldwide demand in 1998 [46].

3.2.4 Magnesium in Nodular Iron Production

Magnesium is used in the production of cast or nodular iron. Magnesium is used as an alloying element to promote the formation of spheres, or nodules, of carbon in the cast products and prevent the formation of graphite sheets. Nodular carbon maintains the strength of cast irons. Magnesium in quantities as low as 0.05% are shown to increase nodularization and strength of cast irons considerably [47]. Desired levels of magnesium content are between 0.02-0.06% [48]. Cast Iron is used primarily in auto applications, especially engine blocks for automotive and industrial vehicles. Production of nodular iron is the fourth largest industrial consumer of magnesium accounting for roughly 3% of world demand [49].

3.2.5 Other Chemical Uses of Magnesium

There are several other industrial uses for magnesium that utilize its unique chemical properties. These sectors are relatively small and constitute less than 3% of total yearly magnesium demand. The remaining magnesium chemical applications are employed in chemical, electrochemical and metal reduction activities.

In electrochemical applications, magnesium is used as a sacrificial anode to protect large steel structures from corrosion. Other electrochemical applications of magnesium also include the manufacture of anodes for long life batteries. Both applications are linked to public sector works, as sacrificial anodes used in large public building projects and magnesium long-life batteries are primarily sourced for the military. Electrochemical uses account for a very small amount of yearly magnesium consumption, less than 3% of world demand in 1998 [50].

Magnesium is also used as a reducing agent for the isolation of other metal materials. Use of magnesium in this application is usually reserved for refining exotic materials like titanium, beryllium and uranium. Similar to chemical uses, these more exotic metals are often dominated by government-controlled activities in military or aerospace applications. Metallic reduction activities accounts for only a small fraction of magnesium consumption, less than 1.5% of world demand [51].

Magnesium is also used as reagent in chemical processes. Magnesium is a vital component for many organic chemical processes. The Grignard Reaction that is used to create synthetic carbon-carbon bonds relies on magnesium to complete the reaction [52]. The production of fireworks also capitalizes on the chemical properties of magnesium to produce impressive pyrotechnic effects. These two primary chemical applications of magnesium also account for a very small fraction of magnesium consumption, roughly 2% of yearly demand [53].

3.2.6 Other Physical Uses of Magnesium

There are also several other physical applications of alloyed magnesium, beyond die-casting. Similar to the above section, these demand sectors are very minor, constituting less than 2% of annual magnesium demand. The two other forms of physical magnesium products include wrought (extruded magnesium or plate) and gravity cast.

Wrought magnesium is extruded or formed into plates for load bearing applications. The shapes these products can take are more limited than die-cast parts, but can be useful for some lightweight structural uses, like construction or aerospace applications. Military and public works applications dominate the wrought magnesium market, using it for light-weight aerospace and load bearing applications. Wrought magnesium industries consume a very small fraction of world demand, roughly 1% in 1998 [54].

Gravity casting produces parts in steel molds in a method similar to the HPDC process. Rather than injecting metal at high pressures into the die, in gravity casting the molten alloy is poured downward into a vertical cavity. After cooling the tool is opened and the part is removed. Due to the lack of high injection pressure the products that can be produced in gravity casting are not as high quality as in the HPDC process. Wall thicknesses cannot be as thin, because gravitational forces cannot deliver metal into small crevices without solidifying. Without high injection pressures, gravity casting parts cannot form as densely compacted parts. Gas bubbles can form in the cast part and limit their strength. In cases where lower quality and strength are acceptable, gravity casting may be a more cost-effective forming alternative. Drawbacks of the process and the poor quality, however, have limited the popularity of gravity casting method. Gravity casting activity accounted for less than 1% of magnesium demand in 1998 [55].

3.2.7 Magnesium Demand Trends

While global demand for magnesium in general has been increasing for the last decade, the separate sectors have exhibited different demand trends. The entire spectrum of demand trends has been observed in separate sectors, from explosive growth, to stagnant demand, from slow growth, to decline.

Magnesium die-cast parts have shown rapid growth due to the interest generated by the automotive sector. Sectors, like aluminum alloying, have shown slower steady growth, roughly in pace with economic expansion. Some sectors like, chemical and nodular iron, have remained at relatively stagnant levels of demand. Still other sectors, like metal reduction and wrought applications, have shown decline as the military and public works drivers that feed these industries have also declined. Figures 3 and 4 show examples of recent trends in magnesium demand [56].

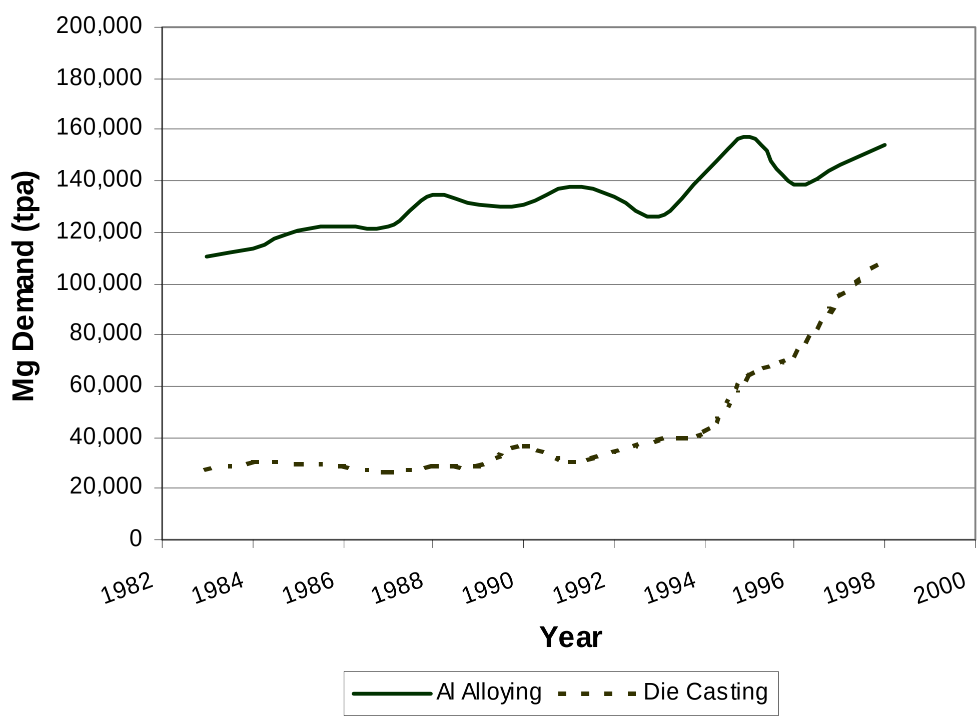

Figure 3: World Magnesium Demand Trends for Aluminum Alloying and Die Casting, 1983-1998 [56]

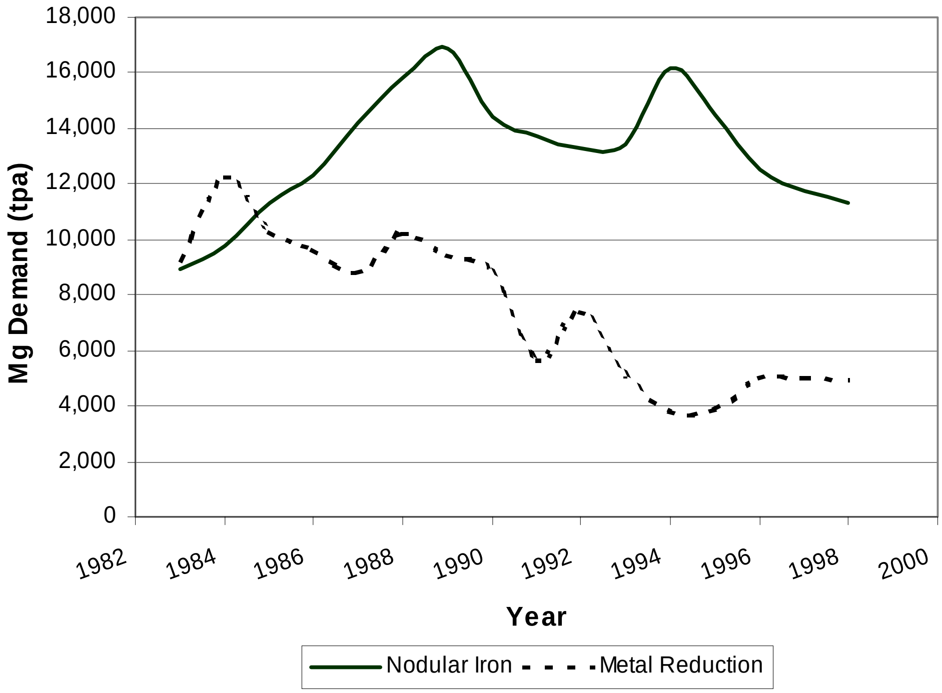

Figure 4: World Magnesium Demand Trends for Nodular Iron and Metal Reduction, 1983-1998 [56]

These separate trends in demand can create interesting dynamics in the market and possible challenges to maintaining market stability. These trends, coupled with the rapid changes in the supply side of the market previously discussed in this chapter, have the potential for creating unstable dynamics. Will rapid increases in automotive demand outstrip future magnesium supplies leading to exploding prices? Will other demand sectors be overwhelmed by automotive demand? Is there a way to balance the increasing demand across sectors and coordinate supply expansions to promote markets stability? These types of questions are the focus of this study. The next chapter will discuss the question of stability in the magnesium market and by building upon on the background information in the preceding chapters.

4 Research Question

This thesis will investigate the impact of rising automotive demand on the relatively small and immature world magnesium market. The previous sections of background information were intended to create a context for this problem by describing some of the historic factors that have led to rising magnesium demand and introducing positions of actors participating in the market.

This chapter will focus on the challenges that face the actors in the magnesium industry from a market perspective, highlighting those encountered and created by rapidly increasing magnesium demand in the automotive sector. These challenges will be summarized into a research question that will be the focus of the following market analysis and modeling.

The world magnesium market is a wildly dynamic and changing environment with many competing actors and concerns. Many industries are vying for the availability of a scarce resource, while at the same time trying to limit their costs. Magnesium suppliers, on the other hand, are attempting to secure steady customers and ensure profits with high, stable pricing. Introduced into this competitive environment is a new and rapidly expanding magnesium consumer, the automotive industry, which exhibits unique cost constraints and motivations. The interaction of all of these players has the potential to create a chaotic and unstable dynamic that is difficult to understand, much less predict. Wildly fluctuating prices in the magnesium market would be undesirable, however, because it discourages demand and negatively impacts the financial viability of suppliers. Pricing swings and the resulting volatility in demand will work against all players by limiting chances for stable growth and maturation of the market. Creating strategies that limit these market swings in pricing and demand, lumped together as the term "market instability", will be the main focus of this study.

The primary source of growth in magnesium usage stems from automotive industry. During the 1990s the automakers increased their interest in magnesium due to energy and fuel economy concerns. Magnesium suppliers are currently attempting to continue this trend by creating innovative applications for their material. Unstable pricing, however, remains a concern for automakers considering increasing their magnesium usage. Rapid magnesium demand expansion, intense supply competition and trade regulations, have introduced price volatility into the market in the past, which has then shown automakers that choosing magnesium is potentially hazardous. In the 1990's a large price spike had wide negative impacts across the world magnesium market as the result of high demand and US tariffs on Russian and Chinese magnesium imports. Figure 5 shows the price history of magnesium, including the price spike in 1995.

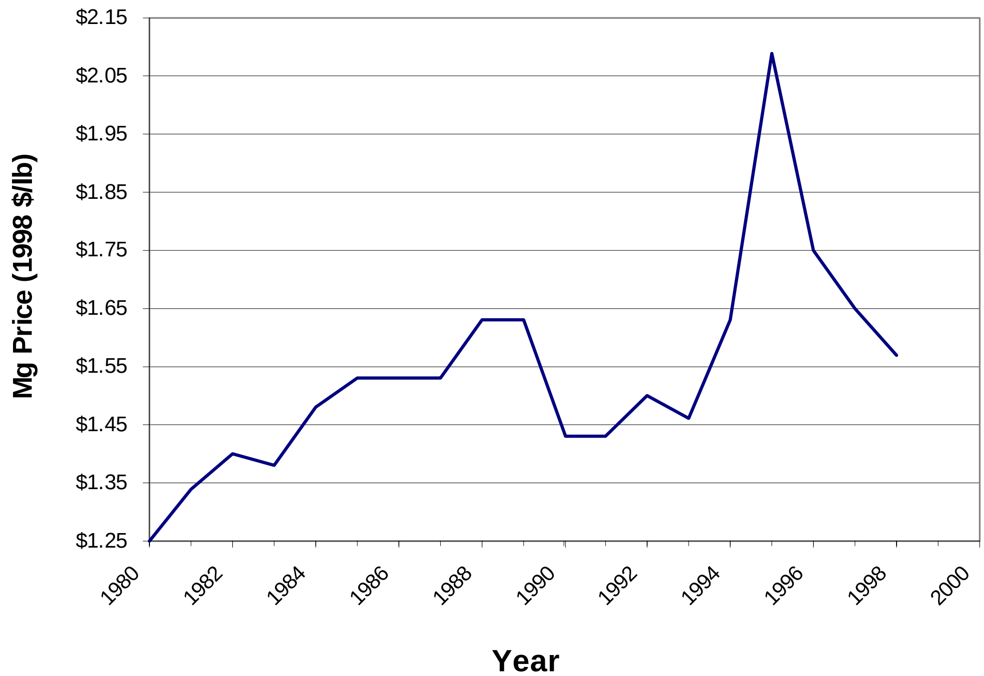

Figure 5: Recent Magnesium Market Pricing, including price spike following US trade sanctions against Russia and China in 1994 [57]

Recent history demonstrates the negative impact magnesium price volatility can have on automotive design consideration. Following the magnesium price spike in 1995 Ford Motor Company quickly switched four-wheel drive transfer cases from magnesium to aluminum on its full size pickup trucks. This price instability slowed Ford's implementation of several other light-weight magnesium component designs. Only recent downward trends in magnesium price and Ford's investment in Australian magnesium projects have rekindled their former interest. As a result, the magnesium transfer case is planned for re-introduction in Ford full-size trucks in the 2002 model year [58].

As is evident in this example, securing large quantities of magnesium at stable prices is essential to the success of magnesium automotive design. Without stable, relatively low prices, other traditional automotive materials will be chosen over magnesium. With the immature state of the magnesium industry, it is fair to question whether the supply structure will capable of such stability in instances of rapidly expanding demand.

Many other industries, beyond automotive, also rely on magnesium as a valuable raw material. Any price volatility will likewise have a negative impact on the demand for magnesium in the aluminum, steel and chemical sectors. Additionally, the interactions of these players with the magnesium market will constitute a large part of the future market behavior. Magnesium is a vital component of these industries, which will need to compete for the same resources targeted by the automotive firms. These consumers, large and small, will vie for supplies of material in a dynamic world magnesium market that is struggling to gain the maturity and stability on par with other accepted engineering materials.

Suppliers of magnesium material, like the industries that utilize the material, have their own challenges. Since the closure of Dow Freeport the competition between magnesium suppliers has intensified. All magnesium producers wish to supply their material in large quantities and substantial margins in order to secure their financial success. The emergence of Russian, Chinese and Israeli magnesium suppliers, however, has added additional competitive pressure and forced prices down as producers jockey for supply contracts.

Negative price pressures have contributed to the increased interest in magnesium in all consuming industries, to the benefit of many magnesium suppliers. Larger volumes of material (especially for the automotive industry), however, will be required to fulfill future demand. New greenfield facilities are in the planning stages, but there is no way to know if these plans will be enough to sustain the growth in demand across all sectors. Magnesium suppliers may soon find themselves in a situation where demand outstrips supply. Such a situation would surely result in price spikes and intensified market volatility. In the face of such volatility it is unlikely that magnesium could retain recent market successes.

Given these challenges confronting the world magnesium market, the following set of research questions were formulated:

1) What influence do economic factors and material price have on current magnesium consuming activities?

> By analyzing trends in magnesium demand it will be possible to characterize the possible future for the market. Magnesium demand would be expected to be positively correlated to improvements in the regional economy and specific industrial sectors. Demand would likely also show a negative correlation to rising material prices

2) Do rapidly emerging magnesium consuming activities, specifically automotive applications, display a specific demand pattern based on the price of material?

> Rapidly evolving demand sectors, like automotive, would not be expected to show similar trends as in the past. The future of these demand trends will need to be investigated in a more detailed manner rather than looking solely at economic and material price correlations.

3) Can understandings about magnesium demand in the past and future trends be used to simulate past dynamics of the magnesium market?

> If market demand can be characterized and combined with information about the magnesium supply structure it should be possible to simulate past market behavior in supply, demand and material price. If successful this simulation could then prove useful for thinking about the future of the market.

4) If the past dynamics of the market can be simulated with relative accuracy, what can we learn about the impact of magnesium demand on the future stability of the magnesium market?

> A successful market simulation can be used as a guide for future market dynamics. The purpose of this study is to investigate sources of possible market instability. Instabilities should be limited so that price swings do not jeopardize the financial positions of magnesium consumers and suppliers alike.

5) How can supply and demand interactions be coordinated to promote future market stability?

> Adding various feedback mechanisms to the model representing the intelligent coordination of magnesium suppliers and consumers could provide the necessary stability that the market needs. These mechanisms need to be technically effective and realistic in their operation as to provide proper guidance and strategic insight to the players in the market.

The above research questions will be used as a framework for the remainder of this investigation. The next chapter will examine research techniques that can be used to gain insight into each of the above questions. These methods will be combined to create a dynamic simulation model of the world magnesium market. The model will then be used to address the main focus of this study, summarized in the final question about strategies to promote stability in the magnesium market. The goal is to identify strategies on both the demand and supply side of the market that can be employed to promote stable growth in the industry.

5 Research Methods

To address the questions stated in the previous section a discrete set of research methodologies were selected for the analysis. These methods include econometrics, utility analysis/engineering interviews, supply curve construction and system dynamics modeling. The sections will introduce the technical ideas behind the methods, the strengths of the methods that were exploited by this study and the specific tools that were used in the analysis.

Each of the tools was used to contribute a specific part to the overall goal of understanding the dynamics of the magnesium market. Econometrics was employed to understand the demand trends within the magnesium industry. Engineering interviews were used to understand the emerging demand patterns in the automotive sector and gain insight into the utility tradeoffs automotive engineers must perform when considering magnesium for design.   A standard micro economic approximation technique was used to build a rough supply curve from operating cost data of world magnesium producers. System dynamics was used to integrate the supply and demand interactions investigated using the previous techniques into a single simulation model for the world magnesium market. This model incorporates the interactions of all of the players and includes complex feedback behaviors.

5.1 Econometrics

Microeconomic theory is often used as a guide in the forecasting of demand for products and services. In its most general form demand is negatively correlated to the price paid for a product or service. Much of microeconomic research is concerned with uncovering the mathematic interpretations for demand trends based on pricing and other economic factors. Econometrics is the field of economic study that employs standard statistical tools in estimate future demand trends.

In a standard econometric problem, economic factors, like industrial indices, productivity statistics and/or material prices are related to empirical demand data using a regression curve fit.

A regression curve fit attempts to infer a functional relationship between the empirical demand data and the economic factors. If the relationships are valid, an equation will approximate historically observed demand, based only on knowledge of economic conditions and product pricing. The hope is to gain a good curve fit, which can then be used to extrapolate to future values of demand.

In the case of this magnesium market study, magnesium demand data from the International Magnesium Association (IMA) was used. The IMA maintains a list of annual magnesium shipments to all industries from aluminum alloying, to gravity casting. This data is also aggregated by global region, including the areas of most interest in this study, North America, Europe and Asia. For this analysis IMA statistics on magnesium shipments were used as a representation of regional and industrial sector demand for magnesium [59].

In order to investigate econometric demand trends in the magnesium demand data, a general mathematical representation of demand was formed. Linear relationships between magnesium demand and both economic conditions and magnesium price were assumed. For example, magnesium demand for a region and industry was assumed to have a positive relationship to industrial indicators for their respective industrial sector and global region. As economic conditions in an industry and region improved, the demand for magnesium by that industry and region was expected to increase. Conversely, magnesium demand was assumed to have a negative linear relationship with the historic trends in the price of the material. As the prices for magnesium observed by the industry increased, the demand for magnesium in industry sectors and regions would be expected to decrease. Likewise, if magnesium prices fell, demand was expected to increase. It was also reasoned that historic prices for magnesium up to five years before consumption could have an effect on demand. This is justified because design decisions in industries with long lead times, like automotive or military, will have chosen materials years before material is actually delivered. The following generalized equation summarizes the linear model used in the econometric regression fits of this study.

$$MD^{ij}_{\ t} = A^{ij} + B^{ij}(IA^{ij}_t) + C^{ij}(MP_{t-x})$$

where: $MD^{ij}_{\ t}$ = Magnesium demand in industry i and region j during period t

A^{ij} = Linear additive constant for demand in industry i and region j

B^{ij} = Linear multiplicative constant for industrial activity in industry i and region j

C^{ij} = Linear multiplicative constant for historic Mg pricing in industry i and region j

IA^{ij}_t = Industrial activity for industry i and region j in period t

MP_{t-x} = Historic magnesium pricing for a period t-x

Several different statistics software packages are capable of performing the necessary curve fits, from spreadsheets to specific statistics programs. For this investigation the statistics program SPSS 6.0 for Windows was used to determine the specifics of the linear relationships that fit observed magnesium demand. SPSS proved very useful in determining the regression coefficients associated with the linear demand model and also provided a set of standard indicators of regression fit like, coefficient of determination (R^2) and T-statistics. Additional attention was paid to metrics of co-linearity to ensure the independence of the regression variables and thus the validity of the statistical relationship.

Curve fits of regional industrial activity and historic magnesium pricing were found to fit very well with this linear model. Results of the econometric trending will be discussed further in Section 6.3.1, on Evolutionary Demand Models, and Appendix A: Econometric Curve-Fits For Magnesium Demand Sectors.

Econometric methods were useful for creating demand trends for magnesium demand in mature and evolutionary industries like steel, aluminum and chemical applications. In these industries magnesium plays a supporting role and demand should be expected to exhibit behavior similar to that observed in the past. In order to address trends in this area, the automakers themselves were asked about the future of magnesium demand in their industry.

5.2 Utility Analysis / Engineering Interviews

Applying statistical methods to a newly developing demand sectors, like automotive applications, is not a good choice. The rapidly changing priorities of automakers seeking magnesium as a light-weight solution to their fuel economy problems will not likely exhibit similar behavior as observed over the past decade. To get a clearer picture of these trends, one-on-one interviews were initiated with materials engineers at the world's two largest automakers, General Motors and Ford Motor Company. The goal was to understand the trade-offs made when selecting between magnesium and other automotive materials and quantify how these trade-offs change with respect to price the automakers pay for magnesium.

The benefits and costs of utilizing magnesium in automotive designs are not easy to understand, and even harder to quantify. Materials competing for applications in engineering design must meet minimum requirements for performance, but many performance requirements are not hard specifications. Soft constraints, cost limitations and the many physical requirements combine in a variety of ways to yield unique performance characteristics for different designs and materials. Despite the challenge of understanding the complicated combination of interconnected engineering characteristics, product designers must assign preferences and make decisions based on the summed properties of many materials and designs. The sum of characteristics and performance that can be used to assign a design preference is called utility.

Utility analysis is the field of study where researchers attempt to assign mathematical relationships between multiple performance variables to gauge a decision-maker's preferences. There are multiple methods for assessing the utility functions of individuals who make design decisions in engineering fields. Most applications involve interviewing decision-makers about their preferences between different values, costs, or physical attributes. After the interviews the response data is analyzed and fit to a variety of possible mathematical models of preference. Further information on utility analysis can be found in <u>Applied Systems Analysis: Engineering Planning and Technology Management</u> by Richard de Neufville [60].

In the case of magnesium automotive design, automotive design engineers were interviewed to understand the design trade-offs between magnesium and several other competing materials (steel, aluminum and polymers) in specific auto components. Magnesium offers several benefits including low density, improved specific strength, part consolidation opportunities, extended tool life, vibration damping and reduced machining costs. However, magnesium designs also have some less desirable attributes including corrosion susceptibility, lower ultimate strength and higher material cost. For the purpose of this investigation, the research focus was most concerned with the cost and material price preferences of the design engineers at the automakers. Designers at the automakers were asked specifically about their changes in preference in material as the price of magnesium changed. While material prices are not the only constraints, the interviewees were asked to us magnesium price to highlight the technical challenges in employing magnesium design.

Automotive designers and materials engineers at General Motors and Ford Corporations were interviewed on a set of auto components that have shown magnesium replacement potential. This list was created after reviewing automotive literature and discussing magnesium usage with automotive experts. One of the most extensive lists of magnesium targeted auto parts is included in The Potential for Vehicle Weight Reduction Using Magnesium: *SAE Technical Paper #910551*, by James Davis of Norsk Hydro [61]. This report includes an exhaustive list of magnesium-targeted components aggregated by five vehicle types, small car, medium car, large car, sporty car, and luxury car. The component list used for the interview process was aggregated along similar vehicle lines and also included, small, medium and large trucks. Also included in the SAE report were estimated magnesium part masses for the target components and their current non-magnesium competitors. These part mass figures were also reviewed and adjusted during the interview process to reflect actual automotive designs and concept parts being produced in the automotive industry.

During the interviews, the engineers were asked to review the target part list and were asked several questions. They were asked to cite a price for magnesium (in $/lb material) at which their preference would switch from a design using the current competing material (steel, aluminum, or polymer) to a magnesium design. The interviewees were also asked to reveal at which magnesium price a magnesium part in the specific application would revert back to its competing material. These introduction and removal trigger prices were a crucial piece in the effort to predict future demand in automotive arena. The data sheets on trigger prices for magnesium design introduction and removal are listed in Appendix B: Revolutionary Magnesium Demand / Automotive Demand Triggers.

During the interviews the engineers were also asked about, and often supplied, additional insight into the technical and financial trade-offs that would be necessary to consider components for magnesium design. The feedback indicated several trends in the magnesium design process.

The first engineering trend offered insight into the application of magnesium across car lines. The engineers revealed that larger vehicles would likely have higher trigger prices than small vehicles. This suggests that large vehicles would be more likely to implement magnesium before medium and small vehicles. The engineers attributed this trend to the fact that larger vehicles have poorer fuel economy and were more likely to pay a price premium for light-weight materials. Along the same line of reasoning, trucks of a designated size had higher trigger prices for magnesium design than an equivalent car. Another reason for the difference was attributed to consumer pricing power. Larger vehicles traditionally command higher prices; therefore their programs could better afford to pass on the costs of magnesium design to customers. Smaller vehicle customers, being more price sensitive, were considered less likely to pay for light-weight design. As are result of this price sensitivity, small cars had lower magnesium trigger prices.

Another insight revealed by the interviews showed that several technical challenges could severely limit the application of magnesium in automotive design. These challenges to magnesium implementation included strength concerns for suspension applications, corrosion concerns for exterior body applications and creep concerns for powertrain applications. Along with part cost, technical problems were often cited as the major reasons preventing the application of magnesium to next generation of auto components. Despite the fact that these issues were primarily technical in nature, the engineers were often able to translate the challenges into lower price triggers at which the technical challenges would be overshadowed by the other attractive properties provided by a magnesium part. The design engineers assigned low trigger prices to the components with the toughest magnesium implementation problems, like powertrain components, road wheels and suspensions. Components with minor cost or implementation issues, like structural cross vehicle beams and seats, were viewed to have trigger prices only slightly lower than current material prices. Current applications of magnesium components, like brackets, steering wheels and IP beams, were assigned trigger prices near or even above current material prices. An example magnesium component deployment schedule is shown below in Figure 6, for North American large cars.

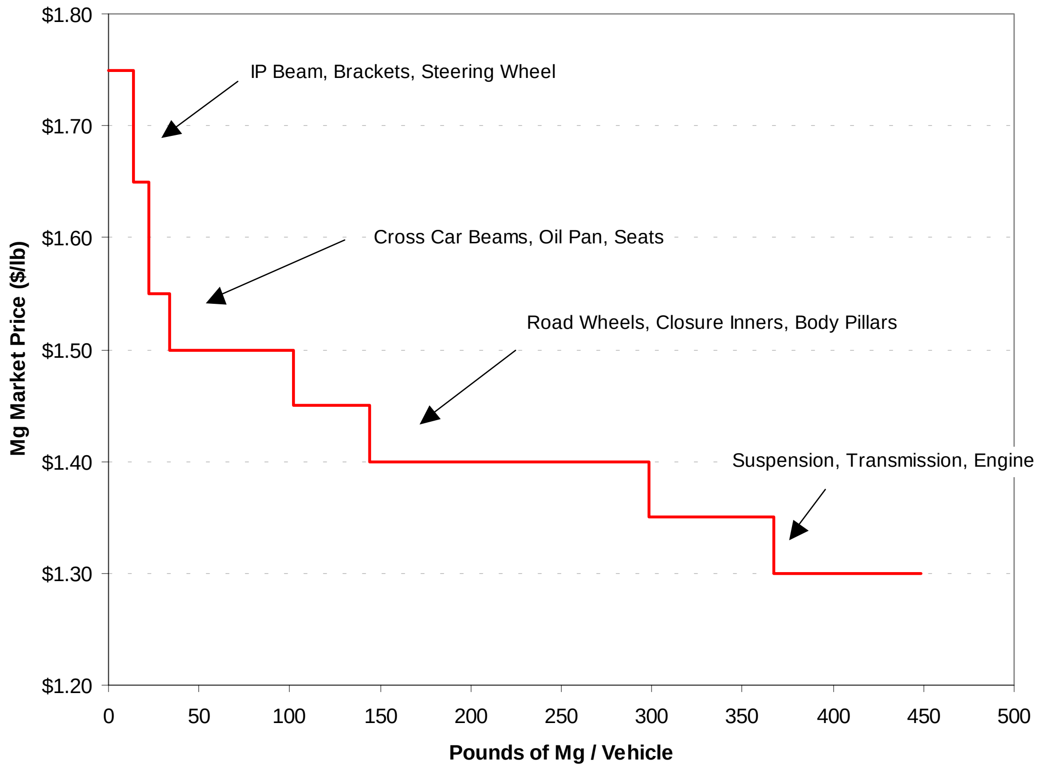

Figure 6: Magnesium Automotive Design Deployment Price Sensitivity, e.g. North American Large Car

The engineering interviews were very useful for understanding the dynamic of future applications of magnesium in the automotive industry. With the econometric demand trends and the magnesium trigger data from the automaker interviews, it was possible to create an approximation of the world demand function for magnesium, including the standard evolving sectors, like aluminum alloying and desulfurization, and the rapidly changing revolutionary sectors, automotive die-casting. The two methodologies adequately address the issues of demand, but this is only half of the market dynamic. The next section examines how standard microeconomic theory helped in creating an approximation of the world magnesium supply curve.

5.3 Microeconomic Supply Curve Construction

To fully understand the future magnesium market dynamics, the past and future trends in the supply of the material must be addressed. For the purpose, an evolving, dynamic approximation of the supply curve was constructed. This curve was created using a standard microeconomic methodology described in many standard introductory economic courses [62].

The microeconomic method involves building up individual supply curves that incorporate the marginal costs of producing material at all of the world's production sites. The individual supply curve for a site can be approximated by the marginal cost of producing the material at that site. The marginal cost of a production site includes the cost of mining mineral ore, plant labor, and electricity for the refining processes. Because the costs of these inputs vary from site to site, the marginal cost supply approximations will also vary between locations. The individual supply curves, however, are only valid over a range of production equal to a particular site's production capacity.

The supply curve is built by adding these curves end to end starting with the lowest marginal cost producer and following in order of increasing operating costs. Figure 7 below gives a generic example of this supply curve build-up process.

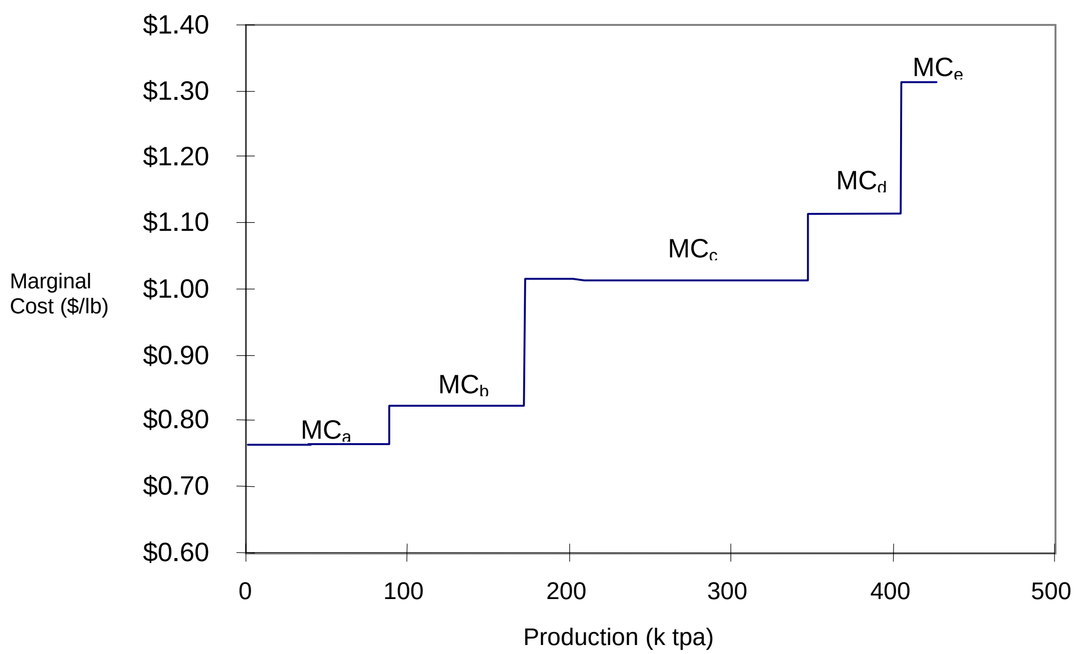

Figure 7: Example of Marginal Cost Approximation of Supply Curve

To make the supply curve dynamic, the individual segments were allowed to change with time. Greenfield construction, brownfield expansions and plant closings will add new steps to the curve, expand segments or remove steps from the total supply curve. Figure 8 shows how the dynamic supply curve has and will change over the time period between the early 1990s until the middle of the current decade. During this period the magnesium supply industry expands from a capacity of 300 k tpa to a projected size of 800 k tpa. The figure shows two general market effects of the maturation of the supply base. First, the new suppliers in the expanding market aim to enter as low cost producers. They need to enter on the low end of the curve to penetrate the market and obtain share from the established, but more expensive, suppliers. These new suppliers extend the current base and flatten out the supply curve. The extended, flatter supply curve leads to the second major market maturation effect, negative pricing pressure. Newer suppliers push the costlier suppliers out of competition, so in the near term at a relatively constant level of production prices begin to fall. In the long term demand may strengthen and restore strong pricing, but the negative pricing pressure caused by new entrants is routinely observed in expanding markets.

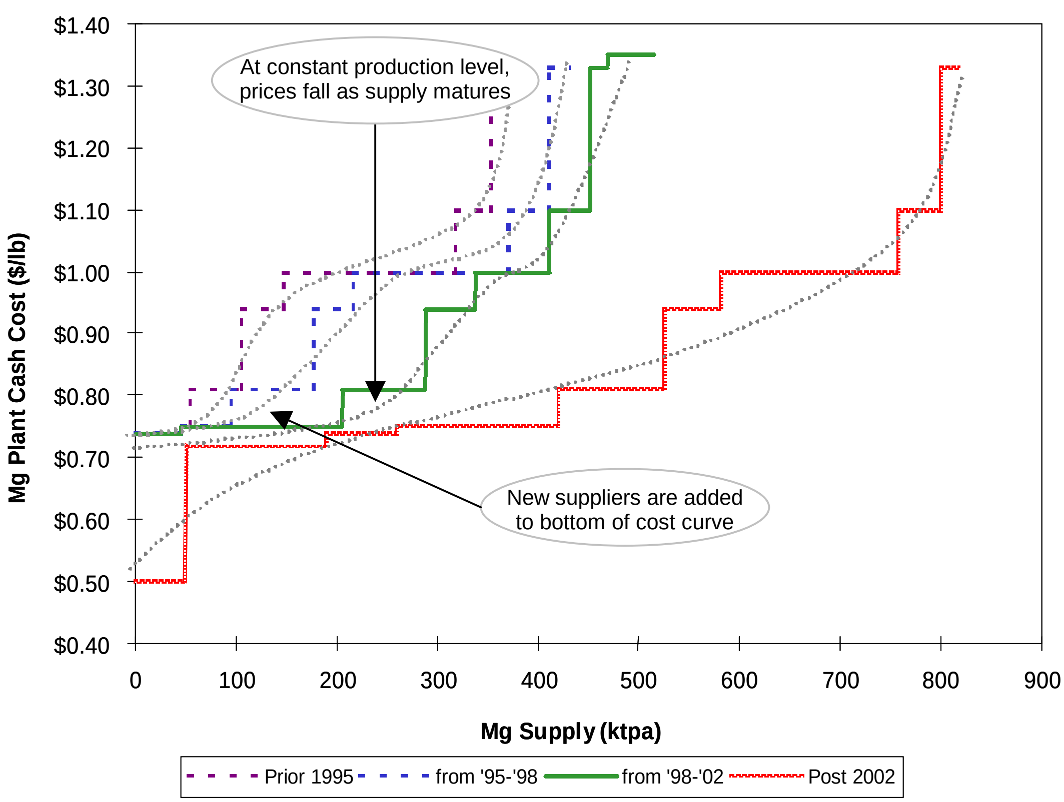

Figure 8: Maturation of Magnesium Supply Curve and Negative Pricing Pressure

The data used for the supply curve approximation in this study was obtained from many sources. Solomon Smith Barney (SSB) published an equity research report on the future of magnesium industry in Australia, a nation actively pursuing several magnesium production projects, in October 1999. Besides an exhaustive look at the many proposed magnesium plants in Australia, SSB provided statistics on the cash operating costs of the world's major magnesium producers, their production capacities, as well as similar numbers for many of the near term magnesium projects in and outside Australia. The United States Geologic Survey (USGS) publishes magnesium mineral yearbook reports and magnesium industry surveys which also verified much of the production capacity and cash cost data from the SSB report and also gave more accurate updated plans for future greenfield and brownfield supply expansions.

Completing the microeconomic approximation of the expanding world magnesium supply curve completes the final part of the demand/supply equation. With both magnesium demand and supply simulated in a satisfactory manner, the tools were in place to complete the market simulation. The interactions of supply and demand create the market dynamic. The demand of customers determines how much suppliers produce, the level of production will determine the price the customers pay, and the price will determine how much customers will demand. The market behavior caused by these interactions is the focus of this study.

5.4 System Dynamics Modeling

A material market is composed of complex interactions of material price, consumer demand and producer supply. Consumers examine market prices and determine the amount of material they will purchase, suppliers produce that material in accordance to their own marginal costs, these costs determine the price at which the material can be sold, which feeds back into the market to affect consumer demand. Complicating the matter is the fact that material demand decisions are often made well in advance of material production and delivery. Specific material selection decisions are likely acted upon after a considerable design and implementation delay. Looping feedback, decision delays and managing production of material and product are very difficult to conceptualize and predict, but modern modeling methods and software can assist with these complex interactions. System dynamics was a field created to address many of these complexities in complex systems. As these issues are also present in the simulation of the magnesium market, especially non-linear feedbacks, information and decision delays and managing inventories, System Dynamics was deemed an ideal technique for analyzing the world magnesium market.

Professor Jay Forrester at the Massachusetts Institute of Technology's (MIT) Sloan School of Business developed system dynamics as a method of analyzing, understanding and controlling complex systems in business and management. Prof. Forrester was hired by the Sloan School to apply a more 'scientific' method for handling the complexities of business systems. Forrester applied his background in electrical engineering to the creation simple feedback models of manufacturing facilities [63]. His first studies explained how seemingly simple interactions between product orders, inventories, and production rates could actually create complex behavior. The following sub-sections will describe some of the several strengths of system dynamics that are applicable to the market dynamic problem.

5.4.1 Non-linear Feedback in Dynamic Systems and its Application to Market Dynamics

One of the strengths of the system dynamics method is its emphasis on non-linear feedback dynamics. Feedback systems that exhibit dynamic patterns over time are common in both the natural and man-made world. From population dynamics, to control loops to market behavior, non-linear feedback systems are pervasive. However, analyzing these non-linear feedback effects often became so complex in large systems that they were deemed too difficult to quantify.

System dynamics addresses the difficulty of non-linearity and feedback by breaking the problem of modeling a complex system into smaller parts. These simple parts, however, maintain the non-linearity of real-world dynamics. Rather than relying on linear approximations of these non-linear behaviors, system dynamics relies on two simple types of feedback relationships to describe observed non-linear behaviors in complex systems. The two building blocks were called positive feedback loops, which display exponential growth/decay patterns, and negative feedback loops, which exhibit goal-seeking behavior. However complex a large system becomes, in system dynamics its components remain as simple as the two types of loops, positive and negative feedback.

The two types of feedback loops are relatively easy to understand despite their non-linearity. Positive feedback behaviors, commonly called exponential behavior, rapidly grow or decay in a non-linear method. In positive feedback loops, increases in a system variable loop back and lead to additional increases in that variable. This is effect called exponential growth. Likewise decreases in system variables will feedback through the system and lead to relative decreases in that variable. A simple example of a system that exhibits positive feedback is a population of animals, like birds. In a flock of birds, pairs of birds will breed and lay a number of eggs. These eggs will hatch into more birds, which breed and lay more eggs. If left unrestricted the population of birds and eggs will grow geometrically. Likewise limiting any of the populations of birds or eggs will slow this growth.

Negative feedback loops counteract these positive loops by introducing balancing or goal seeking behaviors to the system. In negative loops, increases in one quantity will feedback and eventually lead to a counteracting reduction in its level. As a result system variables often train toward an equilibrium or goal state. In the previous example, introducing a limitation to the exponentially growing population of birds, by tracking their supply of food, will balance the population with a negative feedback dynamic. Increasing bird populations will reduce availability of food, which can eventually limit the health of the flock and lead to fewer numbers of birds. Likewise, increases in food supply will increase the health and size of a population, which will consume more food and lead to an eventual reduction in food supply, due to negative feedback. As a result the population will tend to stabilize at a set level of birds and food, which in populations is called the carrying capacity of the environment. Deviations from target system states will tend to be restored by the balancing dynamics in complex systems.

Market dynamics exhibit many of these looping non-linear behaviors that are investigated via system dynamics. Positive loops are very prevalent in industry. A common corporate positive feedback loop is displayed by an industrial company that sells products to generate profits and then invests a portion of this profit into the development of additional products that can generate more revenues. Cycling this simple corporate model will generate higher profits, more products and greater corporate success.

Negative feedback loops are also prevalent in markets. One of the simplest negative feedback loops present in industry and markets is the interaction of supply, demand and price. If the market begins with a rising market price for a commodity product, a balancing dynamic will often result. In response to increased prices, demand for the product will likely decrease in the long term as consuming industries reduce orders and switch to alternate products. As demand for the product decreases, inventories at supplier warehouses will increase. In efforts to clear out ballooning inventories, suppliers will likely drop their sale prices for their commodity product and force the market price of the commodity down. As a result, a simple balancing trend often results in a general trend toward maintaining stable market prices.

Non-linear feedbacks are present in all markets, including the magnesium market. The interactions of many loops is often much more complex than the simple non-linear exponential and goal-seeking. Despite the over-arching complexity involved in explaining and modeling a market, many of the complexities can be built up from constructing simple relationships, linking them together into simple feedback loops and linking together the simple structures into a complex whole.

5.4.2 The Impact of Delay on System Dynamics: Using Stocks and Flows

Another feature of the system dynamic technique is the impact of delays on the overall behavior of a complex system. Delays in a dynamic system could be caused by a wide variety of phenomena. Changes to system variables rarely react instantaneously, because changes to both physical and observed variables take time. In real world systems, handling or producing physical objects can cause delays. In the population dynamics example, time is required to breed and bear offspring or adjust populations to limited food resources. In manufacturing systems, time is required to ramp up or down production levels in response to changes in orders. Adjusting an inventory or completing deliveries also takes time. Even non-physical variables experience delays. In a dynamic system, information flow, much like the flow of physical objects, experiences delays. In the market dynamic example, market demand will only impact market prices for material after some observation delay, as the suppliers of material adjust to changes in consumer orders. Likewise, consumer demand will take time to digest any changes in observed market prices. Decisions, information processing and the physical limitations of managing material resources all present a certain amount of reaction delay to a feedback system. These delays create additional challenges to understanding and controlling complex systems.

To deal with the additional effects of delay, system dynamic uses conceptual tools called stocks and flows. Stocks and flows can be thought of in physical terms as bathtubs and spouts respectively. System variables that experience delays can be represented as stocks, which cannot react instantly to changes in their environment. These variables will only change as the flow into and out of them varies. Linking variables to time dependent flows of material or information creates a first order time delay in the system. Delays of this nature could be caused by physical limitations of managing materials or be used to represent non-physical delays linked to observation, information processing, forecasting and/or decision-making. Regardless of the reason behind the delays, the levels in the stock, like a bathtub, are incapable of instant response or reaction.

There are many problems that can be associated with the introduction of delay into a dynamic system. Information delays in production decisions, as well as use of large material inventories, can create an oscillating production and inventory schedule in a generic manufacturing system. In his first studies using the system dynamics method, Forester showed that oscillations in dynamic systems are often associated with a balancing loop being affected by substantial delays [64]. He explored these trends with a simple example of management a manufacturing system. In this case the balancing loop consisted of a production/ inventory maintenance system, working in the presence of production decision and ramp-up delays. In this system model, increases in orders drain off a large chunk of inventory, production is scheduled to replenish this inventory, but the decision and ramp-up of production takes a substantial time during which inventories continue to be stripped. As a result, production must be ramped much higher than the order rate to rebuild stocks, but quickly overshoots the desired inventory. The resulting production cut-backs again experience decision and ramp-down delay and continue to overshoot order rate. Eventually, production is ramped so far down that orders again strip inventory and the oscillatory cycle begins anew. The amplitude and severity of the oscillations of this cycle will vary depending on the size of the inventory, the length of decision delays and responsiveness of production, but this instability can create large inefficiencies. Damping the swings in production and inventory to create a more efficient production schedule is one of the ongoing challenges of managing a manufacturing system.

Commodity markets, like magnesium, were previously shown to exhibit a classic balancing feedback dynamic [65]. In these markets rising market prices lead to lower demand, lower orders then lead to sales pressure at the suppliers, and finally sales pressure leads to lower market prices in hopes of stimulating demand. As a result commodity markets can often be wracked by the oscillations of a boom-bust cycle. The magnesium market, like most other markets, is subject to the typical material and information delays that can create volatile oscillatory behavior.

Production of magnesium products also must deal with the classic material delay problems of inventory management. Manufacturers of magnesium products can only manufacture and ship product based upon the available inventories of raw material and finished products. If demand shifts rapidly these producers may encounter backlogged orders or inflating inventories. As a result, managing a product through its life-cycle chain, from raw material, to finished product, to delivery, through its useful life and finally to retirement and possible recycling is fraught with many possible time lags. By using the stock and flow method for these materials, products and backlog orders over time, all the constituents of the dynamic system can be more easily monitored. Introducing real world limitations of material delays also allows the market to be modeled more realistically.

A material market, like magnesium, will also display information delay problems. Market prices cannot react instantly to demand changes, as suppliers will need to have time to adjust their production levels and inventories and then pass these costs on to their customers. Conversely demand cannot rapidly change with respect to material pricing because demand for materials is often inflexible in the short term. In fact the material order decision is often locked-in well in advance of the actual delivery of material. This is especially true in the case of long lead-time manufacturers, like manufacturers in the automotive or military sectors. Their products, cars or military products, require a long period of design time, therefore the decision to implement a material is made well in advance (2-5 years) of actual delivery. As a result the commodity price that influenced a "buy decision" is a historic artifact when viewed from demand and order delivery. A product design life will also have a large impact on demand. Because military and automotive products remain in production for periods of four or more years, a choice to select a material will likely bolster commodity demand for substantial lengths of time. This locks in demand until, in the case of high material prices, a replacement material can be selected at the next redesign.

The stock and flow methodology was a very convenient way to implement the two types of delays observed in the magnesium material market. Stocks could be used to represent magnesium material in raw material inventories, backlogged product orders, material in finished product inventories and retired material available to be recycled into new products. Flows into and out of these stocks could be used to represent raw material deliveries, production rates, finished good delivery rates and recycling rates. Stocks and flows were also used to represent the information delays present in the magnesium market. Stocks were used to smooth volatile market price changes and were also used to store the price history used for future demand decisions. Design decisions, magnesium concept parts in design and supply expansion decisions were similarly stored in a system dynamics stock format. All of these non-physical variables experiences information delays that have as much, if not more, impact on the dynamics of the magnesium market than the physical limits of managing physical materials.

5.4.3 System Dynamics Modeling Software: ithink® from High Performance Systems Inc. By decomposing the complicated world of non-linear feedback dynamics into simplified loops, the system dynamics method can adequately address complex systems. Despite this simplification, keeping track of the large numbers of interrelated mathematic relationships created in an accurate, nested model of a real system is still one of major drawbacks of the methodology. Several user-friendly software packages emerged in the 1990s to bring the power of system dynamics into the hands of researchers and common computer users alike.   This section will describe one such software tool, ithink® from High Performance Systems Incorporated.

ithink® is a software tool created to provide users to with a simple computer environment to create system dynamics models easily and efficiently. The program incorporates all of the traditional building blocks required to create a visual representation of the feedback loops associated with the system dynamics techniques. System variables are created as nodes in the graphic user interface. These nodes can then be linked together in loops using connection tools. After the connections are created the user must then define the mathematic relationships between the interconnected nodes. Once a single loop is defined, additional loops and relationships can be added to and branched out from the original relationships. The program also provides a hierarchical modeling environment where sub-sections of modeling loops and sub-models may be organized in a manner that keeps the nested loops of a complex system neat and orderly.

ithink® also provides a set of modeling tools that allows for the introduction of material and information delays in the system model. The stock and flow modeling tools allow users to represent and track materials and information over time. Several different varieties of stocks are available when modeling variables. Traditional bathtub type stocks can be used to represent material inventories or damped variables, like material pricing. Conveyor type stocks can be used for tracking discrete variable histories over time, like in the case of pricing history or design decisions. Other types of stocks like ovens, that fill up and then hold a level for a set time period, and queues that line up inputs flows, are also available in ithink®, but were not used in this study.

Other aspects of the ithink® modeling environment were also very useful, including built in functions, arraying, and graphical variables. Built-in functions were very useful in defining some of the more complex interactions between variables in the models. These functions included operations as simple as trigonometric functions up to complex if-then logic statements. The ability to use nested if-then logic was very important to modeling some of the more complex interactions in the model of the magnesium market. ithink® also allowed for the introduction of arrayed variables. Arrays useful when a particular sub-model is repeated several times over a set of independent variables. In the case of the market model, this was especially useful when tracking the design decisions and implementation of the many targeted magnesium parts. Each of the parts had unique design triggers, part masses and production volumes, however the same types of mathematical operation were performed with these variables. Implementing an arrayed sub-model was very useful in consolidating these operations into a manageable package.

The format of output from ithink® was also very useful in completing the simulations and analyses of the magnesium market study. Separate graphs and tables corresponding to any node variable, stock or flow in the simulation could be created to track their its progress temporally. The data from the various tables was easily imported to spreadsheets for further analysis.

These attributes discussed above are the main reasons that the ithink® was selected, mainly its applicability to the systems dynamic method, its built in capabilities for handling complex mathematic relationships and its easy to monitor and utilize outputs. Other systems dynamics software packages, like Vensim® from Ventana Systems, Inc. [66] and PowerSim® from PowerSim, Inc. [67] are also available, but were not used in this study.

6 Model Description: Simulation Model of The World Magnesium Market

A detailed examination of the dynamics of the world magnesium market required a detailed examination of the material supply and demand as well as the complex interactions among these and many other variables. Accordingly a system dynamics approach was selected to model the market interactions, while a variety of other methods, econometrics, utility-decision analysis and microeconomic theory were applied to address material supply and demand trends. The following chapter will detail model structure that was built for these parts to create a world magnesium market simulator.

6.1 Magnesium Market Model Overview

The magnesium market was aggregated into five separate sub-sectors that represent the main modules of the simulation model. Figure 9 shows a simple schematic of the market model. The ovals represent the five model sub-sectors, while the boxes represent specific data points used or derived by the model sectors. The five sectors are, the Supply Side Model, the Evolutionary Demand Model, the Revolutionary Demand Model (automotive), the Production Model and the Price-Clearing Model.

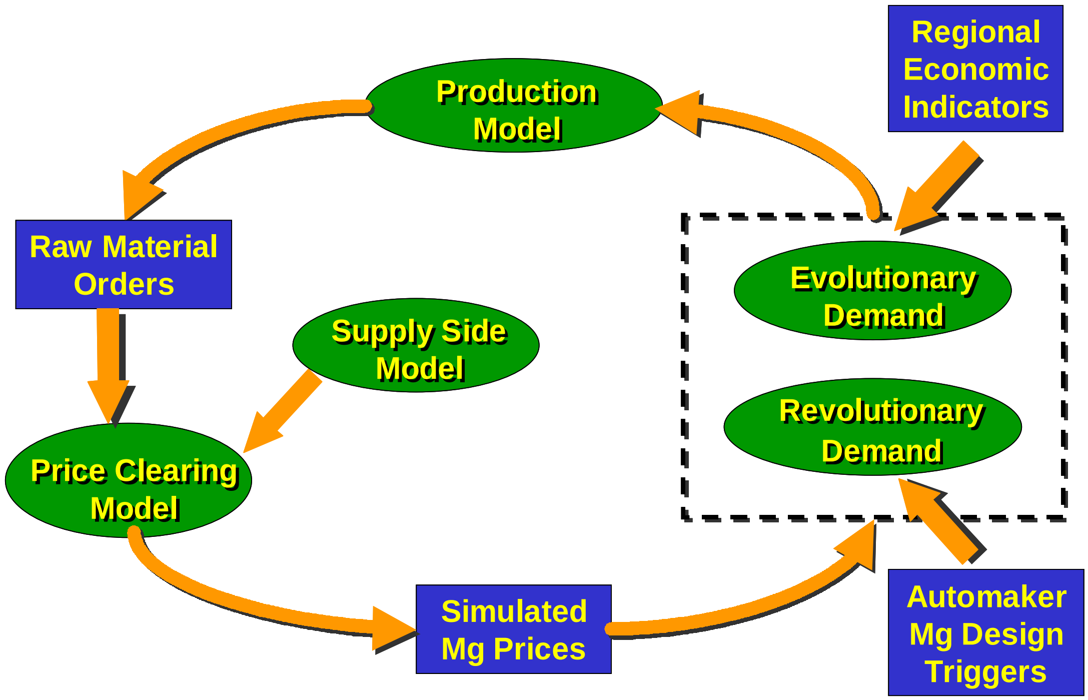

Figure 9: Simple Magnesium Market Model Schematic

The supply side model assembles the supply curve for the magnesium market from historic production capacity and operating cost data using the microeconomic method described in Section 5.3. Each current production facility is added to the supply curve in order of its increasing operating cost. The supply curve can also be altered due to tariff restrictions against shipments from certain regions or facilities. The addition of future sources of magnesium supply, using exogenous overrides or automated algorithms based on feedback mechanisms, is also contained in this section of the model.

The demand side models are spilt between two types of demand, evolutionary and revolutionary. The evolutionary demand sub-models utilize the econometric curve fits described in Section 5.1. These demand curve-fits utilize magnesium price histories and regional industrial indicators to approximate historic and projected future demand for magnesium material in evolving sectors like aluminum alloying, chemical and ferrous applications. The revolutionary demand models are concerned solely with representing the rapidly changing demand for magnesium in the automotive industries of North America and Europe. These models use the information on magnesium design and price triggers gained from the engineering utility interviews described in section 5.2. This information was integrated into a tracking system that follows the life of individual magnesium components from design initiation, through their useful product life and on to possible redesign or replacement. The two demand sub-sectors, evolutionary and revolutionary, can be combined generate total magnesium product demand figures for all world regions.

The production models are divided up along the same lines as the demand sectors. Separate sectors are assigned to each industry and region. The production models include detailed inventory management systems for raw material, finished products and, in some cases, product in use and recyclable material. Besides dealing with material management there is a system in place to manage raw-material orders and inventories based on a desired level of safety stocks needed at the producers. A record of possible backlogged orders is also kept in cases where demand outstrips available product inventories. The main output of the production sectors is a summation of the total raw material orders from all industry sectors and regions that are then sent on to the final sub-sector of the simulation model, the price-clearing model.

The price-clearing model completes the market model loop by reconciling the summed orders submitted by the production models and the supply curve created from the Supply Side Model. There are actually two separate price-clearing operations performed to create separate figures for pure magnesium and die casting alloy. These separate calculations are based on the quality of some production facilities, and will be described in further detail in the following sub-sections. In either case, however, the model performs a similar operation. The price-clearing model first dices the supply curve into five tiers based on four operating cost cut-offs. The clearing model then locates the tier in which the current level of primary material orders falls and approximates the market-clearing operating cost based on a linear approximation of the supply curve between the two adjoining cost cut-offs. This market-clearing cost is then adjusted with a pricing model to reflect acceptable levels of supplier margin to obtain the market price. These pricing figures are then tracked over a five-year period in order to generate the material pricing histories necessary to generate the demand figures in the Demand Models.

6.2 Supply Side Model

The supply side model consists of a large set of data points and graphic representations that correspond to each of world's known magnesium producers. A list of these facilities is shown in

Table 7. Data for the production capacities and operating costs are derived mainly from information in the Solomon Smith Barney report on Australian Magnesium and USGS Magnesium Mineral Yearbook entries [68]. The cash cost in the table represents the marginal cost of operating a facility and does not include the cost of capital and other financial considerations.

Table 7: Current Magnesium Producers [68]

Company	**Location**	**Capacity**	**Cash Cost (estimated)**
Magnesium Corp of America	Rowley, Utah	38,000 tpa	\$0.94 / lb
Northwest Alloys (Alcoa)	Addy, Washington	41,000 tpa	\$1.10 / lb
Norsk Hydro	Becanncour, Quebec	45,000 tpa	\$0.74 / lb
Norsk Hydro	Porsgunn, Norway	55,000 tpa	\$0.81 / lb
Pechiney	Marignac, France	18,000 tpa	\$1.33 / lb
Dead Sea Magnesium	Dead Sea, Israel	28,000 tpa	\$0.81 / lb
Brasmag	Brazil	12,000 tpa	\$0.94 / lb
Russian & Eastern European Magnesium	Various Plants in Russia, Ukraine and Kazakhstan	~105,000 tpa	(\$0.75-1 / lb)
Chinese Magnesium	Various Scattered Plants	~160,000 tpa	(\$0.75-1 / lb)

The capacity and cash costs for Russian and Chinese magnesium producers are consolidated and approximated, due to the fact that few specifics are known about these facilities. Additional capacity is also available from smaller facilities in Canada and Asia. For this study these were bundled into the above facilities as an approximation of regional magnesium production. The current sum total of all of capacities for these facilities comes to nearly 550,000 tons of magnesium production per annum.

The production sites are added into the supply curve using the general econometric method detailed in section 5.3. Figure 10 shows a graphical representation of the mechanics of the operation. Each facility’s cash cost is compared to the cost tier upper and lower bounds. If the facility’s cash cost falls between the bounds, the total capacity of that facility is added into the tier. This method allows the facilities to be ordered according to ascending cash costs.

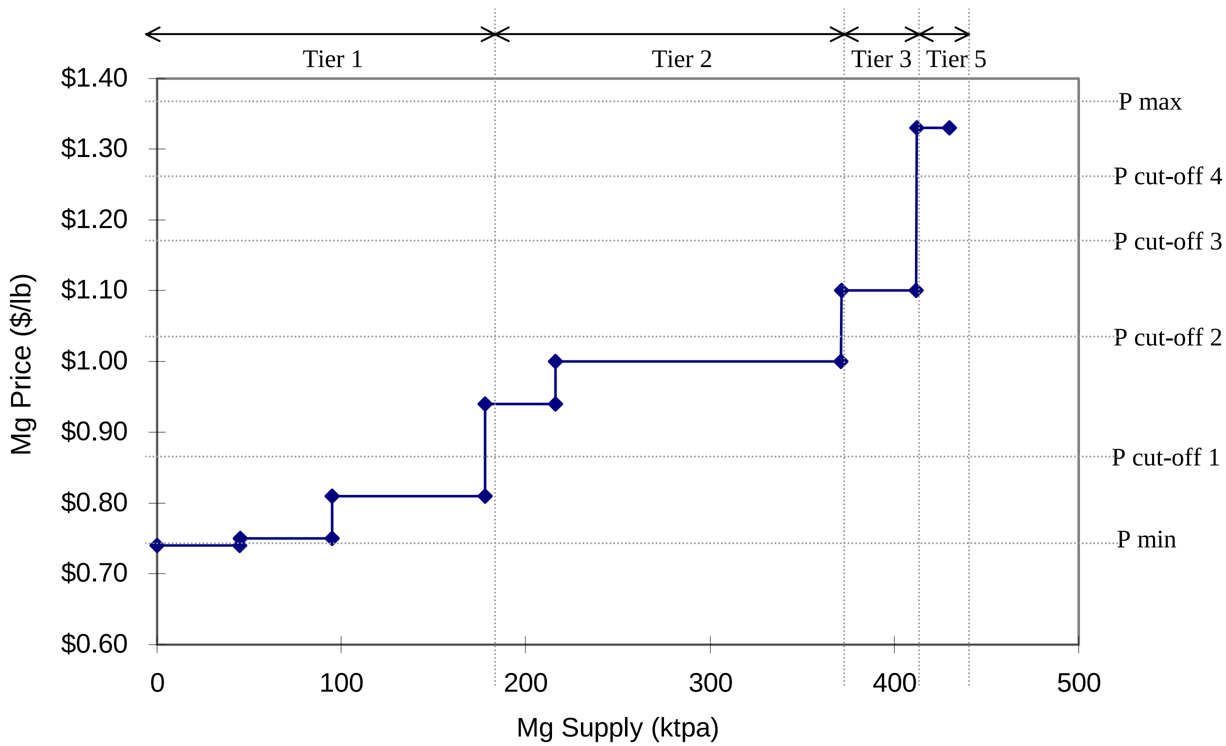

Figure 10: Graphic Example of the Supply Model Mechanics

Production capacity figures were usually introduced as time series graphs so that historic and future expansions of capacity at individual facilities could be shown over time and these expansions could be tracked in the maturation of the supply chain. One such time series for the rapid expansion of Chinese magnesium supply is shown below in Figure 11. As the capacity of magnesium suppliers in China matured during the 1990s, China's contribution to its appropriate supply tier grows within the supply side Model.

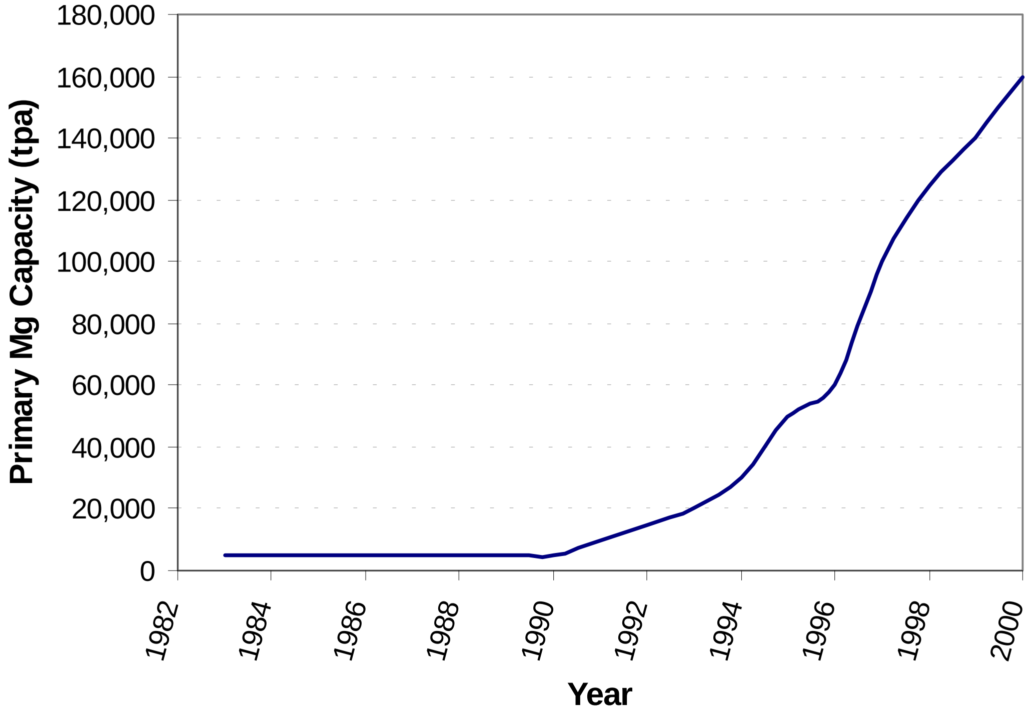

Figure 11: Magnesium Supply Time Series: e.g. the Maturation of Chinese Magnesium Supply [69]

Constructing the supply curve also presented an opportunity to introduce the costs of import tariffs on the supply curve. In the supply side model tariffs were introduced as multiplicative constants that inflated a facility's cash cost and would raise their plant into a higher supply tier. Actual import tariff percentages were taken from USGS Magnesium Yearbook Entries. Most notable tariffs against magnesium imports into the US have been those against Russia (repealed in 1998) and China (still in effect). These tariffs were assumed to apply to the whole world market because the United States is the largest magnesium consuming and importing nation. The US was assumed to be the only bloc of purchasing power that could adequately impact the magnesium market when implementing trade restrictions. US import tariffs were also implemented with time series graphs, similar to the maturation of suppliers. The tariff mark-up ratios were varied with time to reflect the historic changes in US trade policy.

Also included in the supply side model is the ability to add additional magnesium sources to the supply curve by either exogenous or automated mechanisms. Additional magnesium facilities are in these additional sources have been give generic qualities to simplify their addition to the supply side model. First, additional plants are assumed to come on in minimum blocks of capacity of 60,000 tons per year. This quantity was selected by examining the future magnesium plants analyzed in the Solomon Smith Barney Report on the Australian magnesium industry. The proposed size of a majority of the projects, including those coming up in the short term, like Noranda and Mt. Grace, were on the order of 60,000 tpa [70]. For the purpose of modeling future expansions a generic single plant size of 60,000 tpa was therefore used. These plants were also assumed to be ramped up over a three year period with 1/3 of their capacity coming on in the first year, ramping to 5/6 of maximum capacity (an addition of another ½ of capacity) in year two and finally reaching full capacity in the third year of operation. This reflects the fact that most production facilities, of any type, rarely start production at full capacity.

These future supply expansion plants were also given a generic cash operating cost of $0.75 / lb of material. This cost is roughly on par with a large number of the proposed greenfield expansion plants currently in planning. This figure also corresponds well with the estimated operating costs of all of the Australian projects investigated by Solomon Smith Barney, as well with the current supply structure [71]. Operating costs of $0.75 / lb correspond to the lowest current operating costs in the supply chain. One would expect any new entrants would be targeting this level of operating cost in order to ensure successful entry into the magnesium market. At this level of cash cost, which would fall squarely in the lowest capacity tier of the Price-Clearing Model, any expansions of the magnesium supply base would have the expected impact of flattening out the supply by adding capacity to the bottom of the market.

As stated previously, these new supply additions can be added to the simulation model exogenously by the user or automatically by using feedback mechanism. Users of the model can exogenously insert new plants, as in the case of expected short-term projects coming on line, by indicating the number (or even fraction) of 60,000 tpa plants that start-up in a given year. These figures are inserted into a time series and can be changed for certain runs of the model. The user can also turn on and off an automated loop of similar plant additions. In this automated case, plant additions are linked by user specified feedback logic to add plants in certain years in response to events within the simulation. Additional details of both of these features will be given in the analysis sections of this study where they will be used extensively.

6.3 Demand Side Models

Demand side models were created to complete the market dynamic and complement the supply side model. These demand models simulate the affects of magnesium price and other macroeconomic factors on the quantities of material required for each industry and region. For more mature demand sectors econometric models based on historic data were used to simulate demand in what is termed "evolutionary" demand sectors. These sectors are called evolutionary because they are not expected to change rapidly and their history can be assumed to be a good indicator of how future demand will behave. For more innovative applications, as in the automotive industry, "revolutionary" demand models were created. These model sectors were based on expert opinion of the future of magnesium demand in the automotive sector. In either case magnesium demand was modeled as a function of material price, which provided the relationships necessary to complete the system dynamics feedback structure.

6.3.1 Evolutionary Demand Models

Evolutionary magnesium demand, in the case of this market simulation, is meant to indicate magnesium demand in industry sectors that is expected to behave in a manner very similar to past demand trends. This assumption appears well justified by those studying past and future trends in the most magnesium consuming industry. Solomon Smith Barney projects expected growth magnesium usage in traditional materials industries, like aluminum, ferrous and chemical sectors to be only 1.5%, 0.5%, and 1% per annum respectively, while die casting demand is projected to increase at rate of nearly 10% per year or higher [72]. The summed evolution demand sectors comprise a majority of the demand sectors for world magnesium demand.

Demand trends were used in the model by introducing econometric curve-fits, described in Section 5.1, for demand in the three major magnesium-consuming regions. The primary consuming regions were North America, Western Europe and Asia. These curve-fits were also divided along five separate industry sectors. The five industry sectors into which demand was aggregated were, Aluminum Alloying, Die-casting (curve-fit up to 1999), Steel Desulfurization, Nodular Iron, and Other Applications.

Example graphs from each of the regions ors are shown below in Figures 12-14. These graphs include real demand figures, the econometric curve-fit equation, the R^2 value and t-statistics for each variable constant. R^2 values, the coefficient of determinism, indicates the variation in the observed data that is explained by the factors included in the model equation. R^2 values are of particular interest as they are often a good indicator of fit. As the value of R^2 approaches 1, the variables contained in the model equation explain a greater portion of the observed behavior within the data set [73]. As no mathematic approximation can ever explain all observed behavior, "perfect" fits were never attained. However, acceptable R^2 values greater than 0.6, at least over a selection of the most recent data points, were usually attained that indicated that the equations were good models of demand trends. For most of the large demand sectors, R^2 values greater than 0.75 were attained. T-statistics were also tracked as an indicator of the confidence in the relationship between the observed trends and the model equation variables. T-stats of 1.8 and above, indicating ~90% confidence in the relationship between dependent and independent variables, were pursued as indicators of good fit [74]. A complete set of curve-fit graphs for all regions and sectors is located in Appendix A for further review.

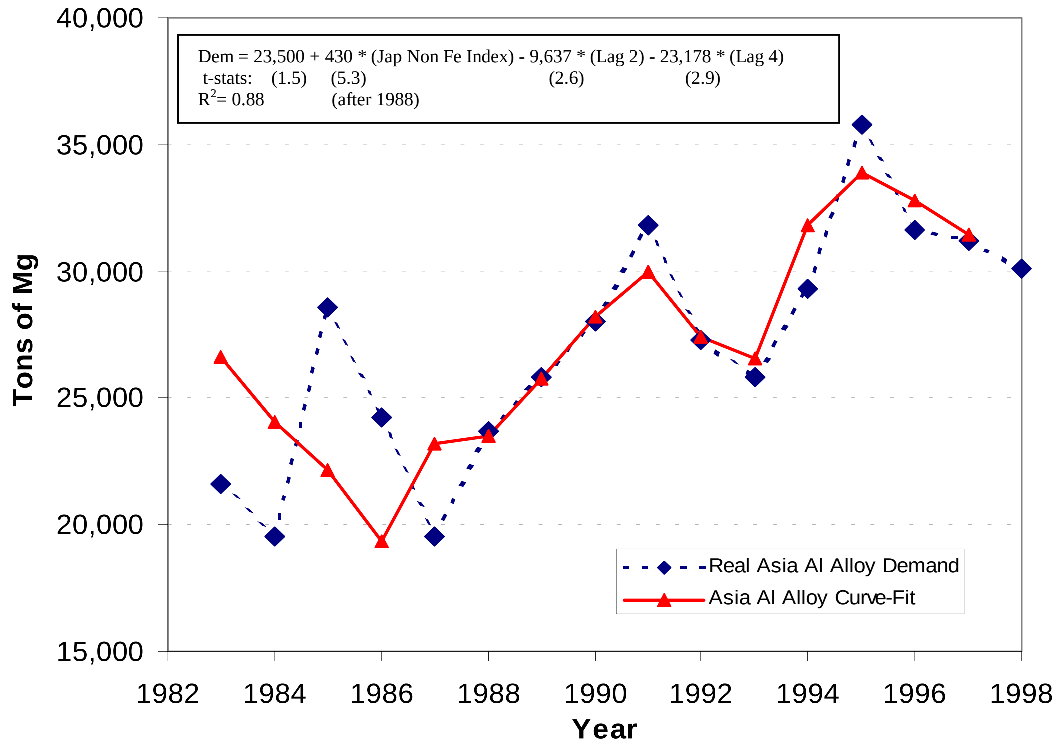

Figure 12: Asian Aluminum Alloying Demand and Econometric Curve-Fit

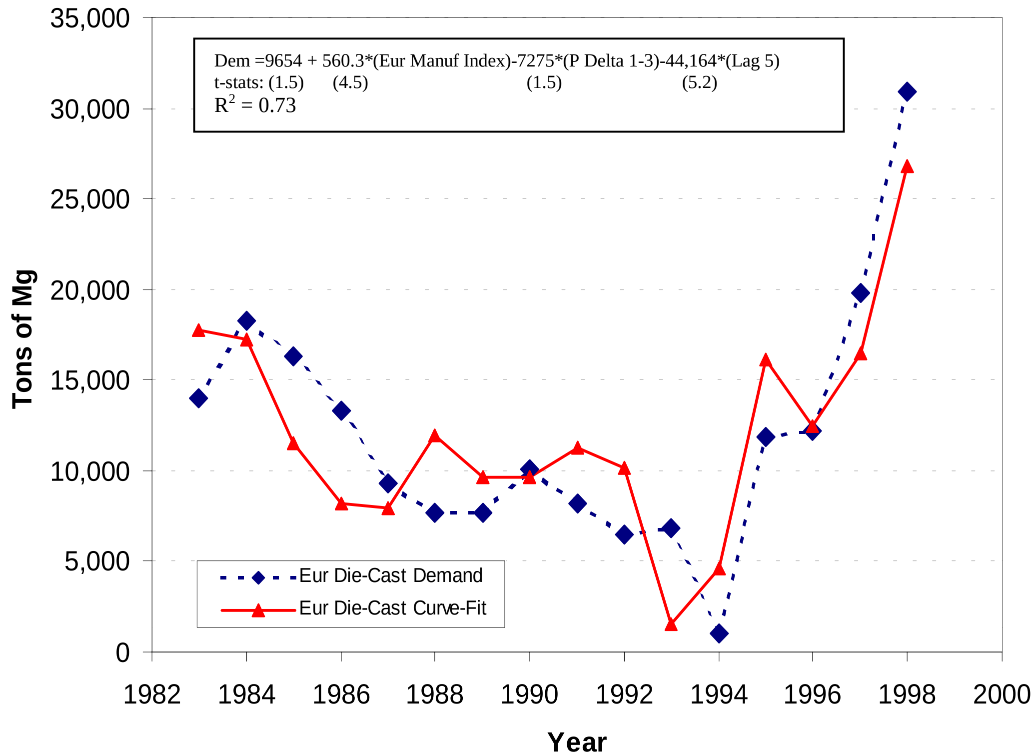

Figure 13: European Die-Cast Demand and Econometric Curve-Fit

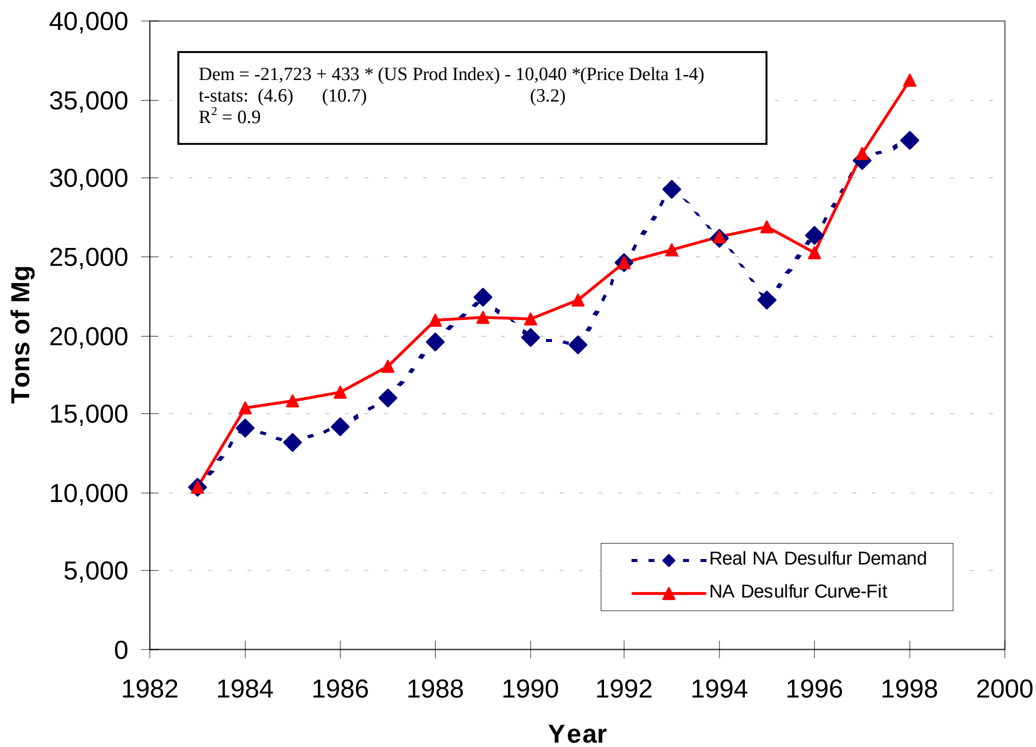

Figure 14: North American Steel Desulfurization Demand and Econometric Curve-Fit

As seen in these demand curve-fits, the answers to the first research question are beginning to surface. The econometric analysis describes what is believed to be the future trends in the evolutionary industry sectors in the three major magnesium-consuming regions. The curve-fits in Appendix A display the impact of economic conditions and material price on these magnesium demand trends.

There are a few unique assumptions on which the evolutionary demand models rely on. These assumptions revolve mainly around the organization of the evolutionary demand models and the projections used to simulate future demand.

The first set of assumptions concerns the categorization of the smaller industry demand sectors as a summed term “Other” demand. The category of “Other” was introduced to help simplify the demand equations and limit the necessity to track small individual trends by replacing them with a larger and more general demand trend. The minor demand sectors that contributed to these sectors rarely exhibited a good curve fit when examined independently using the econometric method. To combat this issue, these sectors, including various chemical, metal reduction and physical applications, were consolidated in order to track more substantial volumes and more general trends. Summed together (~10% of demand), these small sectors rarely reached the size or impact of the larger demand sectors, such as aluminum alloying, ferrous applications or die-casting. As they have only a minor market contribution, lumping these sectors into “Other” demand created a more analyzable data series.

The second assumption, explains the initial treatment of the die-cast demand sector as a portion of evolutionary demand. Despite its recent revolutionary nature, die-cast demand is partially modeled in the set of evolutionary curve-fits. This was necessary in order to accurately simulate die-casting demand, up until the recent spike in automotive interest. After 1999, however, the demand for magnesium in automotive die-casting is simulated exclusively by the revolutionary demand model. After this point the die-cast curve-fit is only used to supplement the automotive die-cast demand figures. The die-cast curve fits are scaled down to 25% of their normal values to reflect the non-automotive demand. This percentage reflects the current non-automotive share of the die-casting industry [75]. For simplicity it is assumed growth in the non-automotive sectors will maintain a trend similar to recent history and that these trends will be slower when compared to the growth of die-casting demand in the automotive sector.

The final important assumption used in the evolutionary demand models involves the importance of future economic trends on future magnesium demand. As seen in the curve-fits the regressions are not only linked to the price of magnesium, but also to regional economic indices. These indices were obtained from a variety of sources. North American indices were assumed to be associated heavily with the economic performance of the United States. A historic record of economic indicators, for general industrial output, military spending and specific industries, were obtained from the Economic Report of the President [76]. A similar record of historic economic performance for the European Union, and its member Nations, and Japan, the largest economic power in the Asian region, was found in the Organization for Economic Cooperation and Development (OECD) publication Indicators of Industrial Activity [77].

While these indices were useful for historic simulations of the magnesium market, they could only provide a basis for the future magnesium demand trends. Still estimates and assumptions about the future of the economies of the simulated regions were necessary to simulate future market dynamics. For the purpose of the simulation, and because it is virtually impossible to predict future economic conditions, it was assumed that the indicators used in the model would continue to exhibit steady growth similar to that observed in the closing years of the 1990s. This assumption would allow demand in most of the evolutionary demand sectors to also grow at a slow steady rate (assuming stable magnesium prices) and allow the simulation to reflect the interaction between competing industries from the evolutionary and revolutionary sectors. Follow-up simulations could employ new data and updated indicators as the data becomes available.

The Evolutionary Demand Model consists of fifteen separate sections for the three world regions and five industry sectors. These sectors were modeled with econometric methods and simple assumptions in order to provide an accurate picture of magnesium demand in slowly evolving industries.

6.3.2 Revolutionary Demand Models

Demand trends for slowly evolving material industries like aluminum, steel and chemicals have been shown to behave along trends of past behavior, but this is not the case with new applications of magnesium. With the increasing interest in magnesium by the world's automakers, it was assumed that future die-cast demand could not be wholly modeled by an extension of the demand trends of the recent past. To reflect the revolutionary nature of expanding automotive magnesium demand, a new set of models were instituted that incorporated information garnered by interviewing automotive materials and design engineers about their tendencies to switch a select group of automotive components to and from magnesium design.

A general schematic of the revolutionary demand model is shown in Figure 15. Market prices and design triggers are compared to create kick-off and/or replacement decisions for a magnesium component. These decisions, after the appropriate delay for engineering design, then affect the balance between magnesium and equivalent non-magnesium components in production. To estimate the appropriate amount of magnesium demand for these components, the model takes the list of current magnesium parts and scales them according to the appropriate production volumes and component masses. These expected magnesium demand figures are summed over the each of the 26 target components and 10 vehicle segments, including small, medium and large cars and trucks in North America, small and medium cars in Europe, as well as low volume specialty vehicles in North America and Europe.

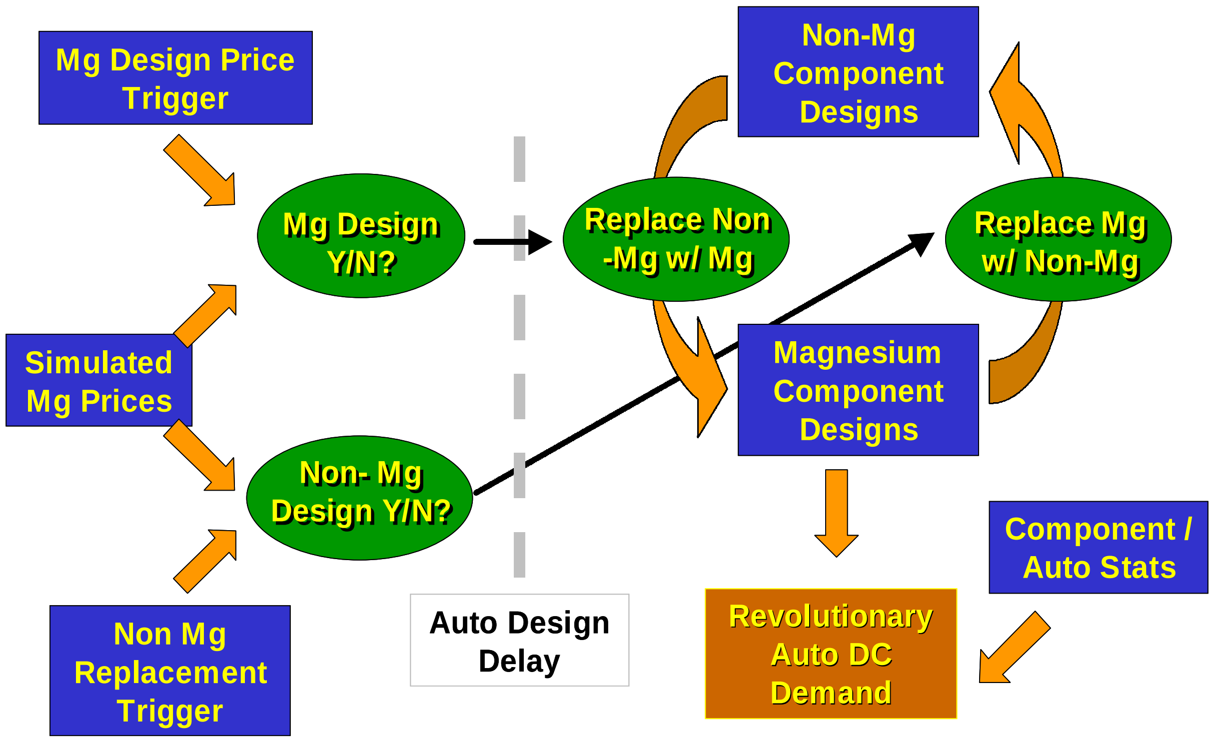

Figure 15: General Schematic of Revolutionary Demand Model

On the macro-scale the revolutionary demand models are aggregated into three categories to reflect the materials that magnesium is competing against in component design. The competitive categories include traditional steel, aluminum and polymer components. Examples of steel competitive components include a wide variety of parts, including steering wheels, instrument panel beams and door inners. Aluminum parts are most commonly involved in powertrain applications, like transmissions and transfer cases, but also include components like road wheels. The few polymer components include mostly small brackets and under hood parts, like cam covers and intake manifolds.

The models were aggregated along the lines of competing materials for a good reason. In the actual design decision, the price of magnesium alloy is compared to its competing material, either steel, aluminum, or polymer, by creating a price ratio. This ratio is compared to a ratio of the design trigger to the same competing material price. While this in no way alters the design trigger data obtained from the engineering interviews, it does offer the ability to use the revolutionary demand model to examine the impact of increases or decreases in competing material prices on the demand for magnesium in the auto industry. A listing of trigger prices for each of the target components, as well as their corresponding trigger ratio and component weights is available in Appendix B for further review.

If the price ratio for a specific component is below the introduction design trigger, this signifies that a magnesium component would be desired in the next redesign period. Likewise, if the price ratio is above the replacement design trigger, this signifies that any current magnesium components would likely switch back to competing materials at the next redesign phase. In the model these decisions are not made instantaneously. The model records a residence time over which these price ratios are maintained. If the prices and ratios are stable for a half-year period, an adequate price stability interval according to the auto engineers interviewed, the introduction/replacement decision would be made [78].

Following the design decision, an indicator is held in the model for a period of corresponding design before actual magnesium parts are created or replaced. For the purpose of the simulations, this period was assumed to be 2.5 years, which is roughly the current automotive design cycle target. This design target is user controlled and could be adjusted to investigate the impacts of shortening or lengthening design cycles.

If magnesium designs are selected, the balance between available magnesium and non-magnesium design shifts. Magnesium components are subtracted from the non-magnesium pool and are introduced to the magnesium component stock at a relatively conservative rate. This conservative introduction rate is a base case assumption reflecting some of the technical and manufacturing challenges to introducing magnesium auto components en masse. Small, previously introduced magnesium applications, like steering wheels and cam covers, are allowed rapid introduction at a maximum rate of four platform switches per vehicle type per year. These parts appear rapidly in vehicles because of familiarity, but do not contribute much to demand due to their small size. Larger parts with some auto design experience, like instrument panel structures and transfer cases, are introduced at slower rate of two platform switches per vehicle type per year. These parts can come on relatively quickly, but may be slowed by some residual technical hang-ups or lack of die-casting capacity for large parts. Finally, the next generation applications that constitute a majority of the target components, like door inners, powertrain components, or road wheels, are only introduced at the rate of one platform switch per vehicle type per year. These new applications come on very slowly due to technical and manufacturing challenges, but constitute the largest target areas for demand growth in the automotive sector.

The revolutionary demand sector must keep track of all magnesium and non-magnesium components and the balance between them to accurately model the total amount of magnesium in the vehicles, as well as how much potential part can yet switch. Once the total number of magnesium components of each type is known, they are scaled up by the average number of vehicles per platform, the average component penetration in that vehicle type and the mass of the magnesium component. This yields the total mass of magnesium to supply these parts. This magnesium usage is further scaled by an expected scrap material rate, 40% was used for an average expected manufacturing scrap in die-casting processes, to yield total revolutionary magnesium demand for the automotive sector.

There are several important assumptions used in the Revolutionary Demand Models to describe the introduction of magnesium designs into the automotive industry. These assumptions deal with the vehicle sectors and regions used in the model, economic aspects of automotive material purchasing and the methods used to approximate some of the data points required to complete the revolutionary demand model

Auto components from Asia were excluded from the models because of Japan's limited magnesium die-casting capability and limited interest in automotive magnesium technology in their domestic market. Figure 16, below, shows the recent trends in Asian, European and North American die-cast demand. The graph shows slowly growing Asian die-cast demand. Despite this growth it is unlikely that it will gain enough manufacturing maturity to contribute to Asian auto design in the near term.   Asian manufacturers are showing little interest in magnesium components, except for vehicles manufactured for the other two major regions. As Japanese manufactures continue to expand their transplant manufacturing facilities in the US and Europe, potential magnesium auto designs would likely occur in the areas already tracked by the in the other two regions.

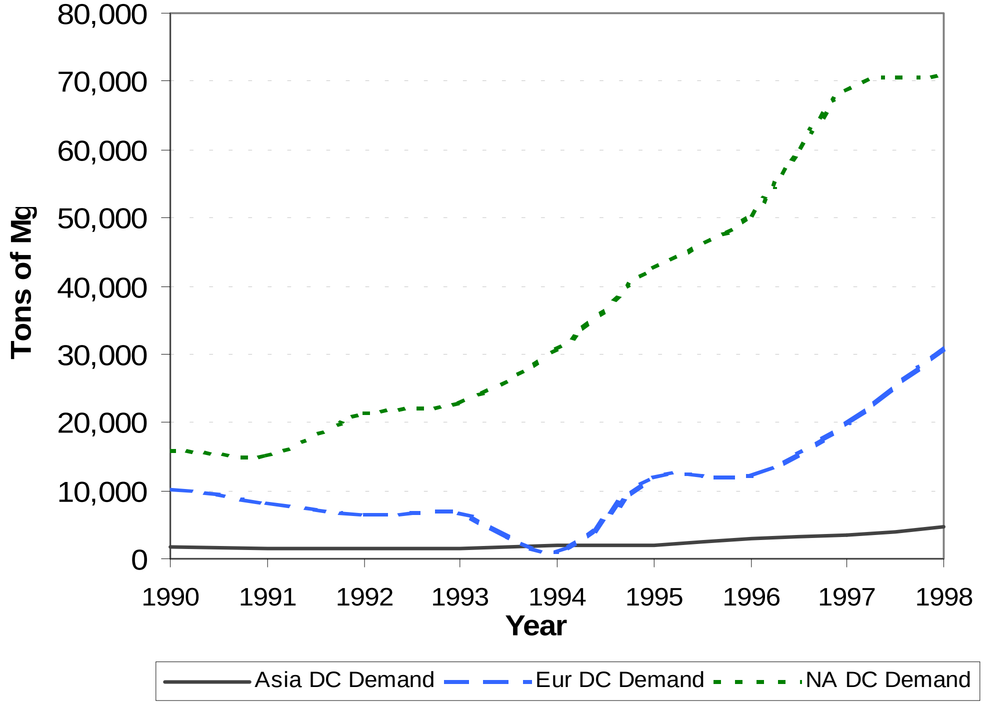

Figure 16: Die-Casting Demand for Asia, Europe and North America, 1990-1998 [79]

The second source of revolutionary demand assumptions arises in the estimates about the size of the vehicle markets in North America and Europe. To estimate the sizes of these markets data on production of vehicles were obtained from two sources, the Automotive News: 2000 Market Data Book [80], for US production numbers, and Motor Industry of Great Britain, 1999 World Automotive Statistics [81], for European data. The European data was aggregated into fewer categories due to the comparatively smaller sized vehicles and the relative absence of light-truck production. Yearly production volumes, estimated platform size and average yearly design turnover (assuming four year design life) are shown in Table 8, below. These assumptions account for production volumes on the order of 16 million and 14 million vehicles per year in North America and Europe respectively. The estimated turnover rates ensured that, on average, a vehicle would be redesigned every four years, which also corresponds well with current industry trends and automaker goals. In general, the market data near the close of the 1990s was used to approximate the state of the automotive industry in the near future assuming recent production trends remain similar.

Table 8: Automotive Production Assumptions, North America and Europe [80], [81]

	Vehicle Type Category						
	NA Sm Car	NA Med Car	NA Lrg Car	NA Sm Truck	NA Med Truck	NA Lrg Truck	NA Special
Production Vol. (1999)	2,630,000	3,990,000	1,200,000	200,000	4,730,000	3,770,000	310,000
Est. Platform Size	300,000	300,000	250,000	150,000	300,000	300,000	60,000
Est. Platform Trnovr (/ yr)	2	3	1	1 / 2 yrs	4	3	1

	Vehicle Type Category		
	European Small Car	European Medium Car	European Specialty Car
Production Volume (1999)	10,100,000	3,300,000	200,000
Estimated Platform Size	300,000	200,000	30,000
Estimated Platform Turnover Rate (per year)	9	4	2

The third set of assumptions is connected to adjustments to the simulated price data to reflect the prices automakers actually pay for the magnesium that they use in their parts. During the automaker interviews, the engineers made it evident that the transaction prices they paid for magnesium were often much less than the market prices that are reported in market literature. This price reduction margin was revealed as a “volume discount” for automakers that consume large quantities of magnesium for producing magnesium parts. This discount was estimated to be in the range of $0.15-0.20 per pound of material. A $0.20 discount was used in the base case market simulations. This figure corresponds well with Norsk Hydro’s quoted market price of $1.60 per pound and the general consensus transaction price of $1.40 per pound for casting alloy revealed during the engineering interviews. The design triggers that were discussed during the interviews also incorporate this discount factor.

The last set of assumptions deals with the way some minor holes in the data set were filled. These were mostly connected to magnesium part masses in light trucks and the European design triggers. The extrapolation of data and design triggers were made in a reasonable manner and were checked and adjusted during the engineering interviews in order to maintain sensibility.

The magnesium part mass data set, as stated in section 5.2, was based primarily on data from SAE technical papers on potential magnesium components [82]. This catalog of magnesium parts was based solely on the three sizes of passenger cars and specialty vehicles, and did not explicitly include light-trucks. To fill in the magnesium part masses for the three light truck categories, the part masses for cars one size smaller were used. For example, medium car IP Beam masses were applied to Small Trucks and Large Car Transmissions were applied to Medium Trucks. Large Truck part masses used Large Car data with a slight addition to reflect an even larger vehicle size. These initial estimates were also reviewed during the engineering interviews. This allowed the engineers to comment and adjust the estimates to make sure the data sets for trucks were sensible.

Similarly there were holes in the data sets for magnesium design triggers in explicitly for Europe design. Although it was impossible to interview European auto engineers about their design preferences from the US, it was believed that the data from the North American automakers would likely be acceptable. Because the vehicle size preferences are scaled down in Europe when compared the US, it was assumed that the engineering desirability of magnesium could be translated from vehicles of a slightly larger size. For example, this suggests that the design considerations for a European small car are likely very similar to those experienced when designing a North American medium car. This assumption was deemed sensible despite their size differences, because small cars in Europe and mid-size cars in the US perform the same market function. These two vehicles compose the largest fraction of car sales and are usually the foundation of an automakers customer base. Similar to small car, mid-size European cars employed scaled up price triggers similar to those for North American large cars. Despite translating the engineering design triggers, part masses for European cars corresponded directly to the same sized vehicles in North America. Similarly sized vehicles were expected to have similarly sized parts.

The output of these models is record of the amount of magnesium demanded by the automotive industries of North America and Europe. These figures combined with the demand figures from the Evolutionary Demand Model provide a complete model of the world demand for magnesium and are used to continue the feedback loop of the market model

6.4 Production Models

Demand figures in the magnesium market model are derived from the evolutionary and revolutionary demand models. These demand figures, however, cannot be directly translated into a market dynamic. Before this can be done, the balance between demand, products and the materials used to make them be reconciled. Production is a complicated system of material stocks and flows. Raw materials are ordered, inventories are maintained and demand backlogs are reconciled. All of these acts add possible delays and complications to the market dynamic. To deal with these issues simple production models of the regional industries were constructed.

The purpose of the production models is to translate the demand figures from each region and industry sector with available material constraints in order to produce the desired output, raw material orders. The model manages the inventories of magnesium material, finished products and even backlogged orders. Figure 17, below shows a general schematic of a production model.

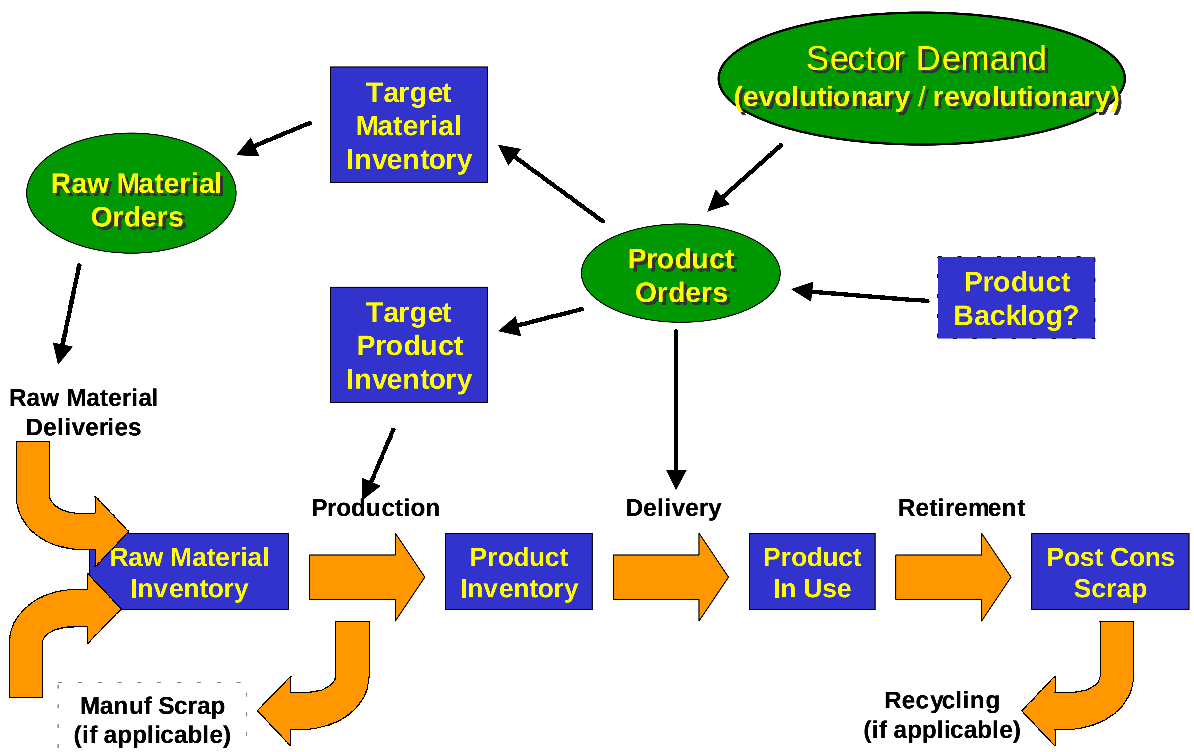

Figure 17: General Schematic of a Production Model

In the production models sector demand enters from the demand models. This demand is added to any potential product backlog. These two figures, together, create product orders. Product orders are shipped directly from the finished product inventory if there is enough available for delivery. If enough product is not available, the difference between demand and product inventory is added into the pool of product backlog as delayed orders.

Product order figures are also used to manage the other operations of inventory management in the production model. Product orders are first used to schedule production of products. Orders are scaled up by a target product inventory percentage that is used to buffer against rapidly changing demand. The target inventory is compared to the current inventory in order to schedule future increases or decreases in production.

Orders are also used to schedule raw material orders. Again, a desired safety stock of raw material scales up observed orders so that a material inventory can buffer against swings in demand. The target raw material inventory is compared to the current level in order to plan future material orders.

Other features of the production model account for the tracking of manufacturing and post-consumer scrap. These scrap trackers are only applicable to the die-casting sector, where the physical components contain enough magnesium content that they might be recycled as secondary material. Die-casting is the only industry that produces pure magnesium scrap in large enough quantities. Because the scrap is relatively pure, the used material can be recycled to effectively reduce primary material demand. The other chemical and alloying applications of material effectively consume the magnesium, even in the case of manufacturing scrap. Isolating the magnesium in the scrap from these sectors for internal or secondary uses not economic and is not currently done.

Magnesium scrap from the manufacturing scrap is assumed to circulate quickly back through recycling channels. This recycled secondary material can then be used to reduce the total level of primary orders. This secondary material is very useful in cases where material quality constraints are less stringent, as in the steel desulfurization sector.

Post-consumer scrap takes a much longer route through the system. The production model, in this case, tracks materials over the expected life of the product. Only after this product life can the material be retired and recycled. The Production model assumes an average 10-year lifetime for die-cast components. Following this period, die-components are retired and allowed to enter the recycle stream, where they can contribute to the market by reducing the primary order rate.

The output from each of the production models yields a crucial component of the market model, the raw material orders. These orders, however, are directly related to several of the assumptions about the operation of the manufacturers in the production. These assumption are mainly concerned with the target inventory margins utilized in the model and the recycling sectors of the production models.

The first assumption concerns the assumed material and product inventories necessary for stable production of magnesium products. In the case of most of these safety margins were usually kept in a range of 15% to 25% of expected demand. Margins on the low end of this range were used in cases of large, slow growth industries like aluminum, and were more than ample to keep backlogs under control. Safety inventory margins on the higher end of this range were reserved for demand sectors where growth has been rapid in the past, like die-casting and desulfurization. Using these margins allowed the model to keep inventories and backlogs under reasonable control. The assumed average inventory margins also corresponded well with observed inventories of magnesium materials that are kept on hand. Average world-wide magnesium inventories have hovered in the range of 6-12 weeks of demand over the last decade. This would indicate that a buffer between 11% and 23% of yearly material consumption could be considered typical adequate by industry standards [83].

The second set of assumptions in the production model concerns the aspects of recycling. First, the model assumes that magnesium die-cast parts will have an average lifespan of about ten years. This corresponds well with the lifetime of the average consumer durable product, like automobiles, televisions and refrigerators. Because the die-cast sectors are dominated by the automotive application of magnesium applying the ten-year product life appears to be an appropriate delay. Other assumptions concerning the recycling sectors of the Production Model include the recycling efficiency of the process, which was selected at 70%. This efficiency rating reflects the amount of secondary material recovered from the process as a ratio of the magnesium products that enter the recycle stream. This efficiency rating was selected as a conservative estimate of the process efficiency, that corresponds to the lower end of the range of expect non-ferrous recycling yields.

The output of the production models, the sector raw material order rates, are then summed up over all industry sectors, the available secondary material is subtracted away and the final primary magnesium order rate is sent on to the final link in magnesium market loop, the price-clearing model. With this step the system dynamic model comes full-circle reconciling the material orders with the supply curve, to determine the market prices for pure and die-cast alloy magnesium.

6.5 Price-Clearing Models

The price-clearing model completes the linkage from market prices, through demand trends in evolutionary and revolutionary sectors, to production scheduling and material management, through raw material ordering, and finally ending with resolution of the supply and demand balance. This sector of the model yields the factors that started the dynamic loop, the market prices for pure magnesium and casting alloy.

The price-clearing model uses two important inputs to determine market prices, one from the supply side of the model and one from the production model. The first input is the supply tiers created by ordering the world supply sources by their operating cash costs. These tiers, along with the cost cut-offs used to create them, will create the basis for the market clearing operation. Raw Material orders from the production models determine which of the price tiers will be used to create the market's clearing-cost.   The clearing-cost is then scaled up to reflect operating margins, depending on the type of magnesium, pure or alloy. These scaled figures are then used to create the market price trends and histories for the material. Once the market prices are determined, the dynamic loop begins again.

The cost-clearing process begins by comparing the summed raw material orders with the supply side model. Figure 18, below, shows a graphic of the clearing cost equations, which may assist the following description with a visual representation. The cost-clearing tier is assigned by checking if the total summed orders is mathematically less than a series of the summed capacity tiers. For example, are Orders less than Supply Tier 1, or Supply Tier 1 plus Supply Tier 2, or Supply Tier 1 plus Supply Tier 2 plus Supply 3, etc…? The minimum tier where this condition is met, indicates where the supply curve and demand will intersect.

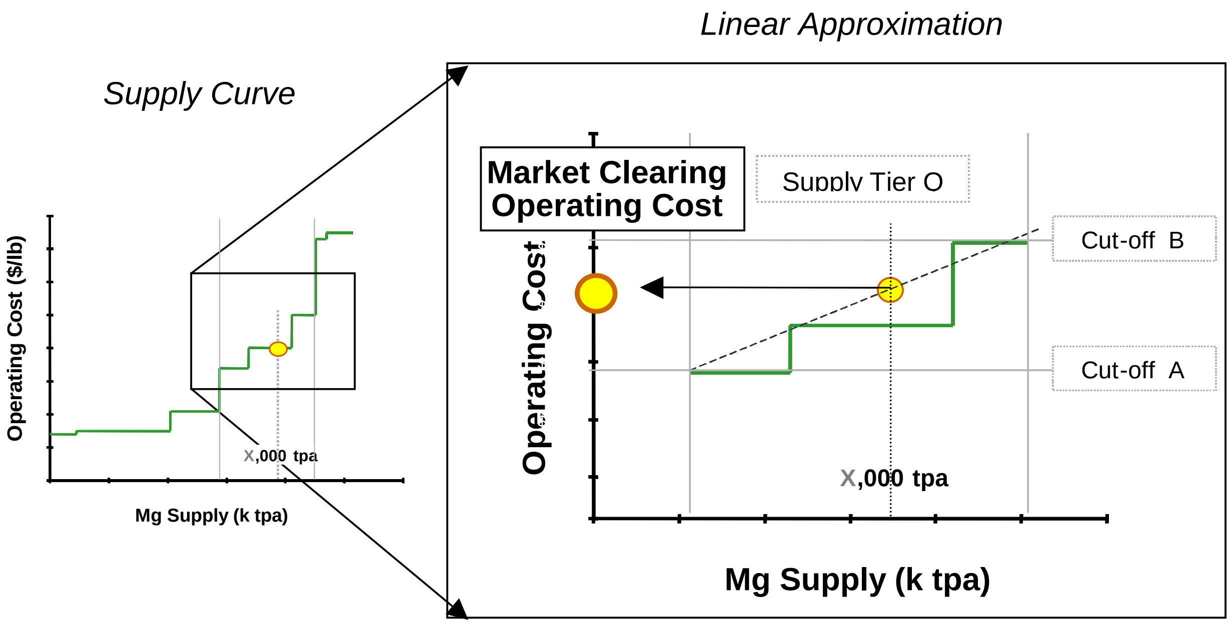

Figure 18: Graphic Representation of Cost-Clearing Linear Approximation

The model then linearly interpolates the clearing cost in order to estimate the point at which the Orders and Supply Curve intersect. This linear interpolation has a horizontal length equal to the capacity of the tier (e.g. Supply Tier Q in the figure) and is defined by the capacities of all the facilities that have operating costs that fall between the two nearest cost boundary cut offs (Cut-offs A & B in the figure). For the purpose of the magnesium market model, four price cut-offs at \$0.85, \$1.05, \$1.30 and \$1.55 per pound magnesium were used. This linear approximation creates a set of points over which the demand could possibly intersect the supply curve. At this point of intersection a single market clearing cost is created.

This clearing cost, however, does not represent the final market price for magnesium. In the case of the supply side model this only accounts for marginal operating cash costs. To reflect total costs, clearing cost needs to be scaled up by a reasonable operating margin to account for other factors like, investment costs, process improvements, development and capital costs. For the purpose of the initial runs of the market model this margin was set at an added flat margin of \$0.35 per pound of magnesium. By employing this margin, the Market Model was able to accurately model observed market prices over the past 15 years. An additional industry capacity variable \$0.15 per pound margin was attributed to pure magnesium market clearing to reflect an observed high market price volatility of pure magnesium, when compared to casting alloy magnesium.

The only other difference, between the market clearing calculations for pure and casting alloy, is that the operating cost of the Chinese facilities are penalized an additional \$0.20 per pound in the casting alloy calculation. This fee is charged as a hypothetical cost for improving the quality and purity of Chinese magnesium to a level acceptable for casting operations. At present, Chinese operations are not yet acceptable for casting and would need to be cleaned. This cost penalty reflects any necessary purification costs that could be assigned if demand was large enough that reserves of Chinese magnesium supply would be tapped specifically for die-casting.

Following the cost mark-up phase, the price figures are smoothed to reflect small lags in the translation of market dynamics to market price trends. This operation also reduces overly rapid swings in price not observed in the reported pricing trends. The more volatile pure magnesium price was smoothed over a very short half-year period, while the more stable casting alloy price was smoothed over full year period. Again these smoothing times reflected the actual dynamic of material prices very well. Following the smoothing operation the market prices were stored for a five-year period in order to provide inputs for future demand model trends.

The main assumptions that are used in the price-clearing model are concerned with the method by which market prices are assigned and how pure and casting alloy magnesium are differentiated. The first major area of price-clearing model assumptions revolves around operating margins. In large commodity markets it is often observed that the marginal cost of operation at the point where the supply and demand curves intersect can be correlated almost exactly to market prices. While this is true in large commodity markets, in small commodity markets like magnesium, this is not always the case. Despite recent expansions in the supply base, magnesium is still a relatively rare and uncommon engineering material. As a result it can be expected that material prices will still incorporate an adequate amount of operating margin to pay for further developments, cover capital costs and contribute to company profits. As a result of this small market, even the last supplier at the margin of demand should be able to cover a degree of cost beyond those expected by looking only at covering short-term cash operating costs. Initially when performing simulations adding margins of $0.30 to $0.40 per pound material yielded acceptable tracking of historic pricing trends. Furthermore, initial financial analyses of many of the Australian magnesium projects in the Solomon Smith Barney report showed that market prices of $1.10 per pound ($0.35 per pound above their average cash cost of $0.75 per pound) were the minimum cut-off for profitable projects [84]. Thus it appears that a margin of $0.35 per pound is an acceptable estimate of the minimum operating margin to maintain profitable magnesium operation.

The second set of assumptions surround the separation between the pure and die-cast alloy magnesium price models. In the initial stages of the modeling effort interviews with magnesium experts at Norsk Hydro yielded concerns about the viability and comparability of Chinese magnesium when compared to magnesium produced in other facilities. As stated in the market background section, the thermal processes often do not produce material of adequate purity for use in physical applications. As a result Norsk and other western producers, contend that Chinese magnesium is not truly equivalent to the rest of the magnesium market. Despite quality issues, however, the presence of the Chinese producers and their low cost product is felt across the spectrum of magnesium demand. In fact, in cases where magnesium purity is not currently a great constraint, as in desulfurization of steel, lower cost Chinese sources can be preferred. The negative pressure on market prices created by low-cost Chinese sources cannot be ignored, but neither can the non-equivalence of material quality. To compensate for these factors separate cost clearing sectors were created for pure and casting alloy magnesium were implemented. The only differences between these sectors was the fact that in the case of die-cast alloy the Chinese producers were penalized $0.20 per pound to clean their material up to acceptable casting alloy standards.

To assist with the calibration of the Pricing Model for the separate materials, Norsk Hydro was also able to provide documentation on the separate market prices between pure and casting alloy magnesium material. This data followed a dynamic similar to those reported in the USGS records of magnesium pricing, while exact data points and magnitudes differed. Examination, of the data from Hydro yielded another problem with the differentiation, the differentiation between the volatility in pricing for the two varieties of magnesium.

Given the added costs expected with cleaning Chinese magnesium, it would be expected that observed die-casting alloy prices would be similar or even more than those observed for pure magnesium. The data submitted by Hydro, however, proved the exact opposite trend. Pure magnesium prices were often higher than those for casting alloy. These prices also exhibited much larger swings, at times spiking up to $0.15 - $0.20 per pound higher than alloy prices. On the other side, occasionally, volatility in pure price dragged pure prices close to or below alloy prices. This suggested slightly higher margins for pure magnesium that could be varied due to market conditions. As a result an additional $0.15 per pound margin was linked to the market capacity utilization.

Volatility toward price movement for alloy magnesium was also reduced relative to pure pricing by increasing its smoothing period to a year. This, increase also corresponded well with the fact that the general trend of the pricing for casting alloy appeared to lag that of pure by about a year according to the Norsk data. Implementing these assumptions yielded acceptable correlation with both USGS pricing trends as well as the Norsk data. Price swings and crossover points for pure and casting alloy were reasonably tracked.

7 Market Modeling Results: Validation, Trends and Market Analyses

The magnesium market model is a useful tool for analyzing past behavior, investigating the current trends and hypothesizing about future scenarios of the maturing magnesium market. The investigation using the market model was performed in four primary steps. First, the model's general format and assumptions were validated by simulating historic market behavior. In this phase of the analysis the historic magnesium demand and pricing (1983-1998) was simulated to verify that the structure of the model reflected past market behavior. Second, magnesium demand trends were examined to estimate the potential for future growth in the industry. The consumption potential for the industry was estimated by observing the model's response to long-term, stable material prices. This analysis identified a large consumption potential for low priced magnesium, especially in the automotive industry, over the next 15 years. Getting the market to mature to these levels of demand, however, will not be easy due to temporal and market constraints. The third step in the analysis involved using the model to examine the magnesium supply industry's near term plans to see if their policies will promote or threaten market stability. Finally, the last section of the analysis examined market stability strategies that used in the model to promote growth and limit price volatility. These strategies involved model mechanisms that used additional logic and feedback loops to prevent large swings in pricing and demand. The conclusions drawn from these analyses will supply the insights necessary to answer the remaining research questions of this study.

7.1 Simulation of Historic Magnesium Market Pricing

In order to be sure of the validity of the model mechanics and assumptions, verification runs of the model were performed routinely. The base verification criteria were the model's fit to the historic pricing data obtained from the USGS reports on year end magnesium prices for the years 1983-1998 as well as the data for regional and sector demand for magnesium. After separate pricing models were introduced pure and casting alloy magnesium, the original verification criteria were expanded. The new pricing categories not only had to fit with USGS data, but also needed to show similar relative separation and cross-over period as seen in the data provided by Norsk Hydro. Balancing the fit between the two data sources (which do not match up exactly) was difficult, but with some compromise, fit and agreement between the simulation and the data sets were eventually achieved. The simulation results of market pricing and market demand for the period 1983-2000 are shown below in Figures 19 and 20.

The pricing simulation, shown in Figure 19, shows a relatively good match with observed market pricing history. Magnesium prices exhibit the expected price peaks in the '88-'89 and '95-'96 timeframes with price dips resulting in the following years.

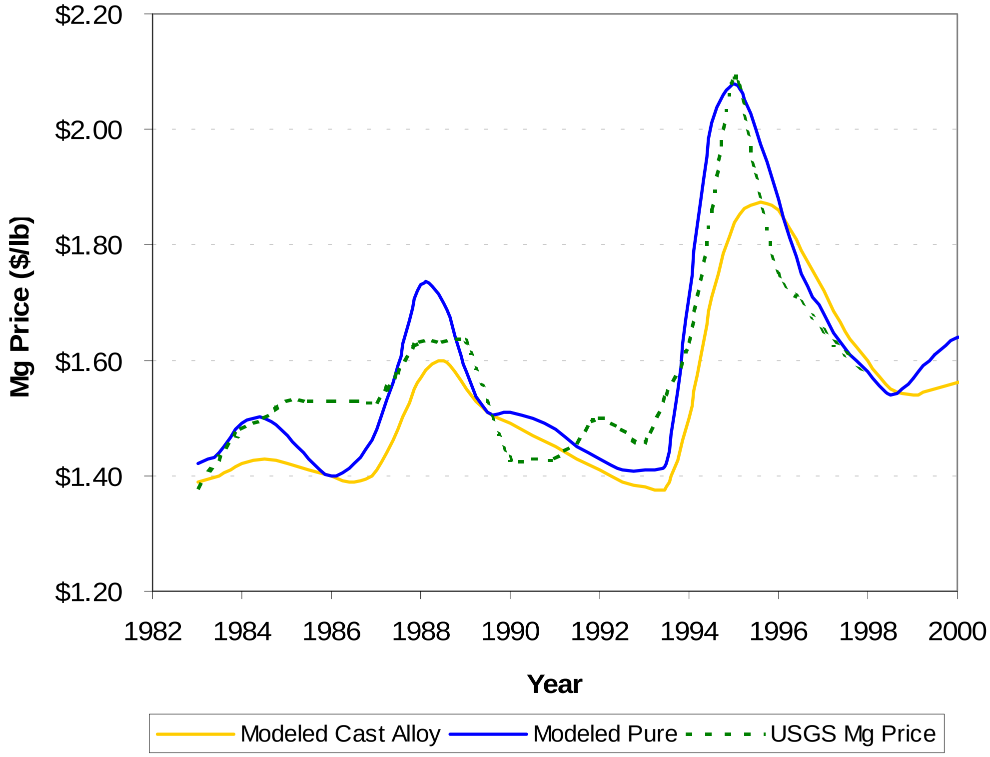

Figure 19: Magnesium Market Model Simulation of Historic Pricing for 1983-2000

The assumptions about the volatility and market observation delays also produced the observed offsets in price and timing between casting alloy and pure magnesium as suggested by Norsk Hydro. The prices for the two types of magnesium alloy cross in late 80s and 90s following spikes in the pure magnesium price. Casting alloy prices also exhibited a damped and slightly delayed behavior (~one year offset) similar to the general dynamic of pure pricing. These behavioral differences were characteristic of historic material price observations revealed during conversations with Norsk Hydro.

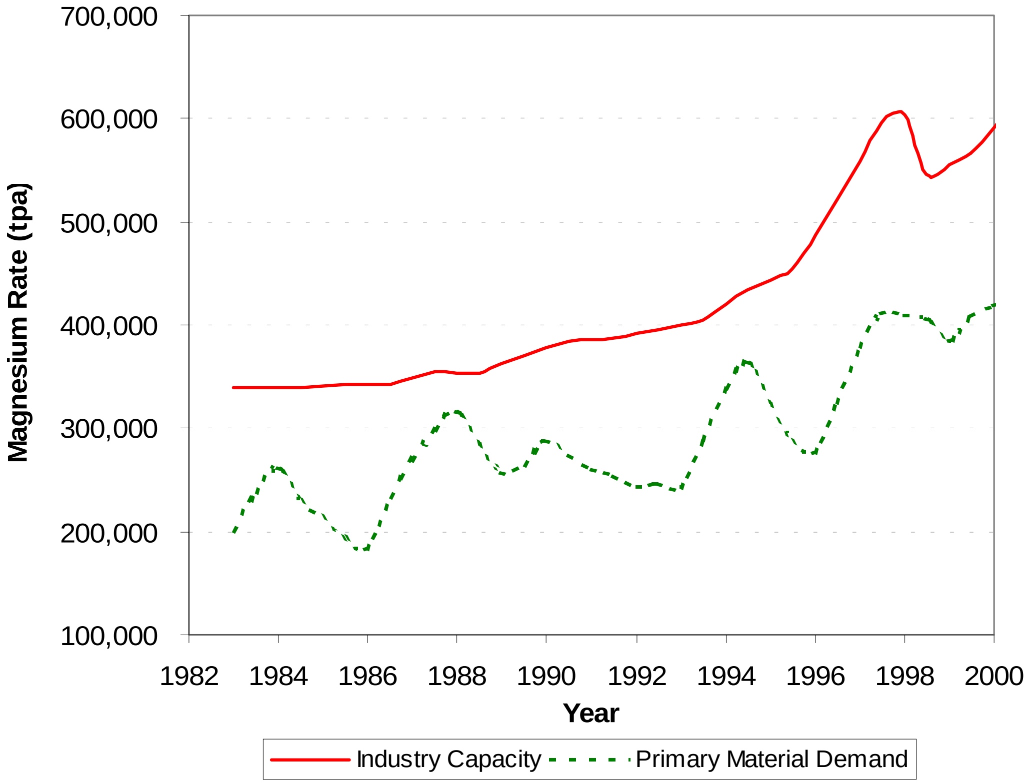

Figure 20: Magnesium Market Model Simulation of Supply and Demand 1983-2000

Figure 20 shows how the model accounts for the supply and demand trends over the recent history of the market. The supply side models reflect the steady rise in industry capacity during the 1990s, primarily linked to the emergence of Chinese and Russian producers. It also accounts for the closing of Dow's Freeport facility in 1998 after which industry capacity declines. Demand grows along with industry supply, but fluctuates in response to economic conditions and pricing fluctuations.

The model fit is also evident in the demand trends shown in the figures below. Figures 21-25 show the simulated and observed demand trends for the 5 largest regional and industrial sectors. The graphs show Aluminum Alloying in Asia, Europe and North America, as well as die casting trends in North America and Europe.

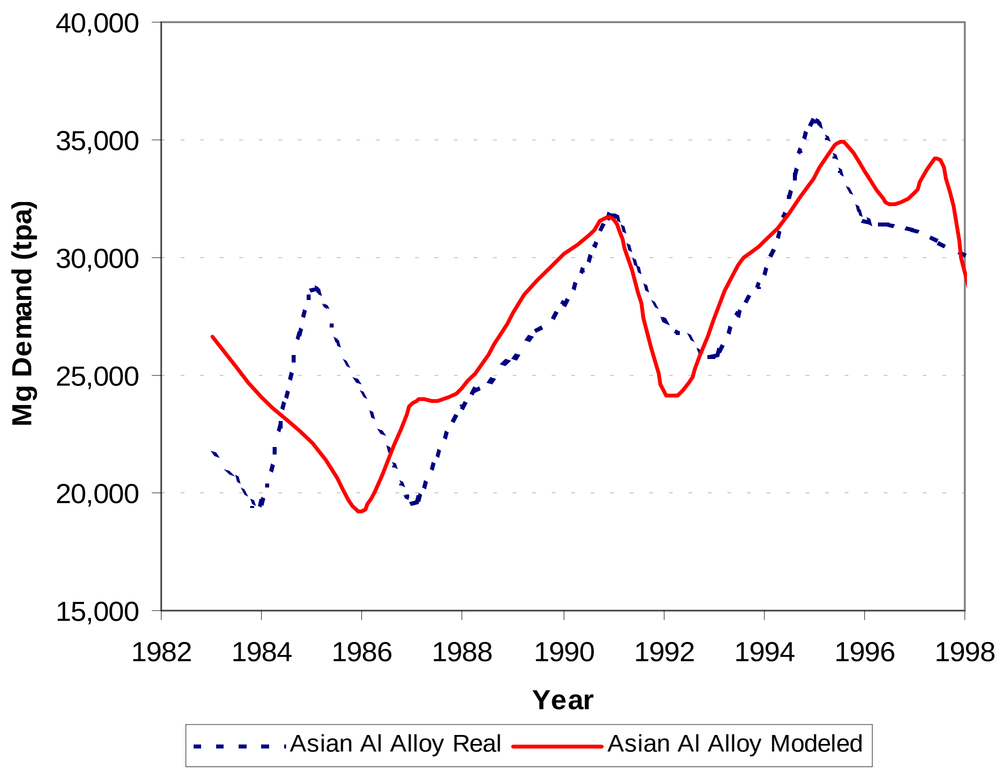

Figure 21: Magnesium Model Demand Trend: Asian Aluminum Alloying 1983-98

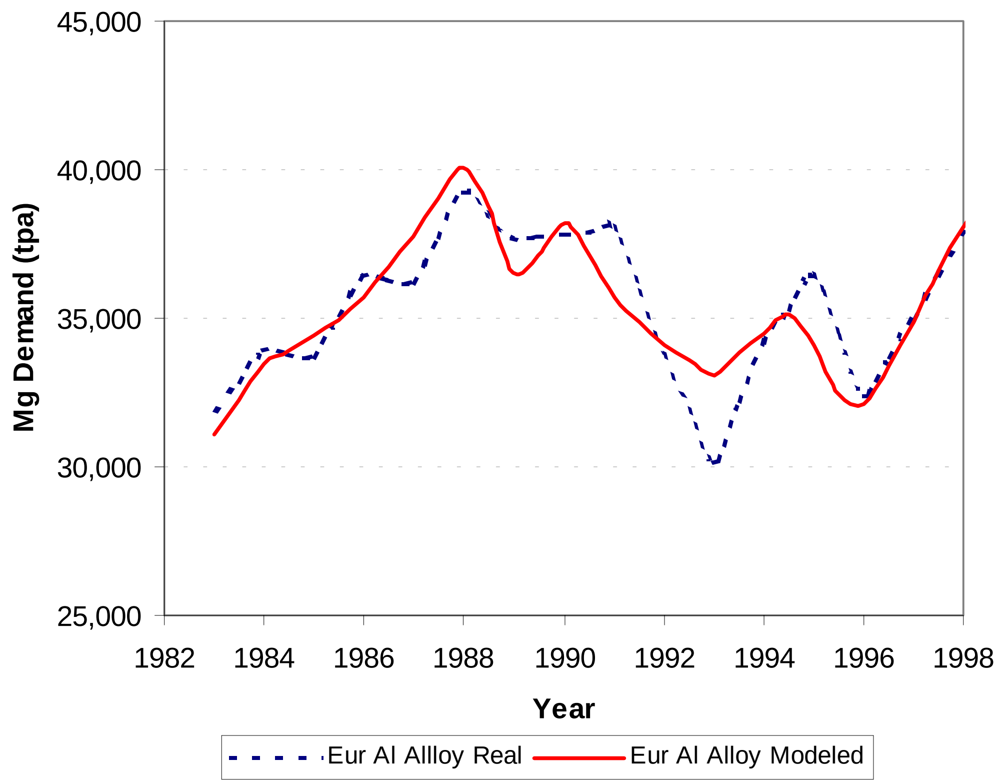

Figure 22: Magnesium Model Demand Trend: European Aluminum Alloying 1983-98

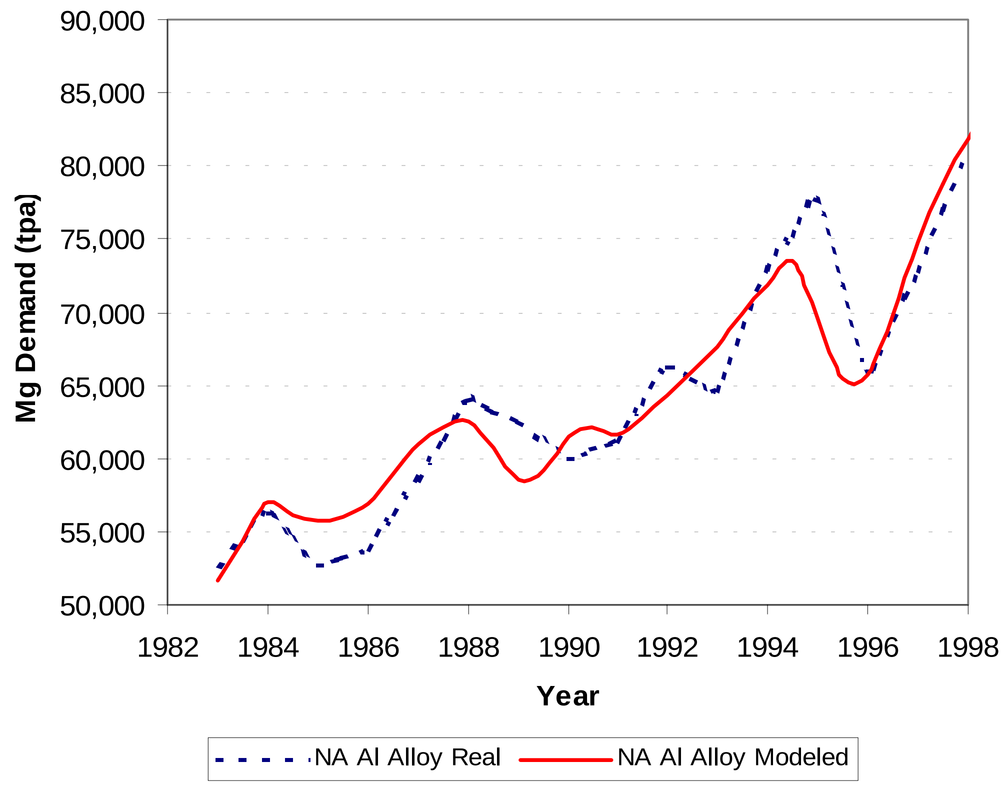

Figure 23: Magnesium Model Demand Trend: N. American Aluminum Alloying 1983-98

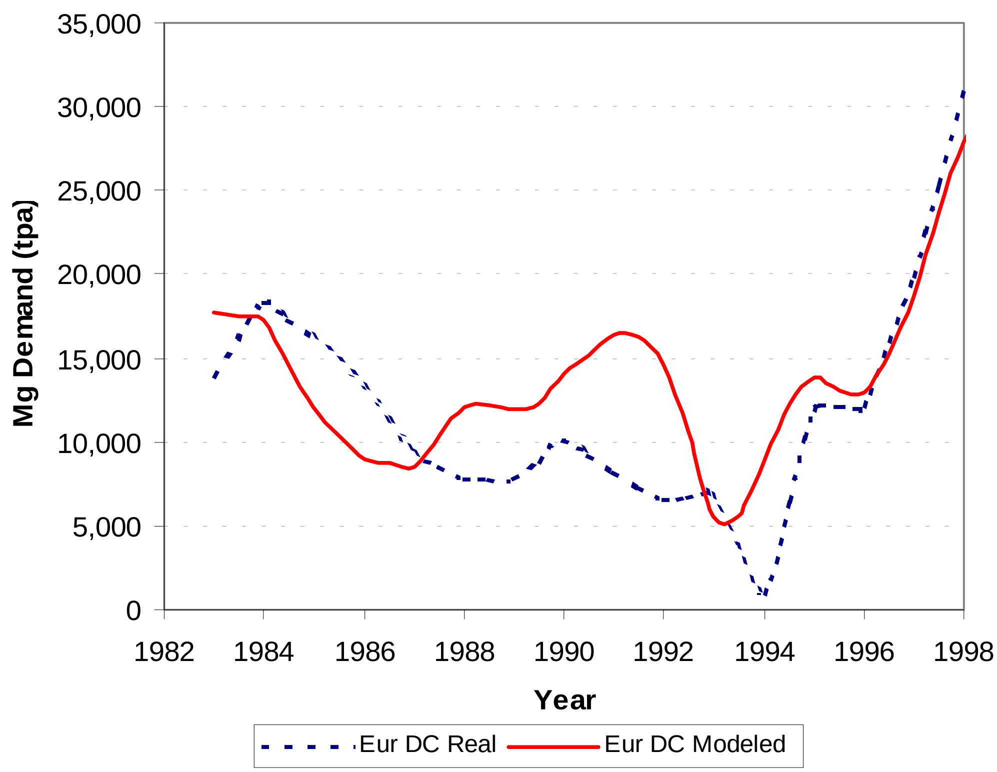

Figure 24: Magnesium Model Demand Trend: European Die Casting 1983-98

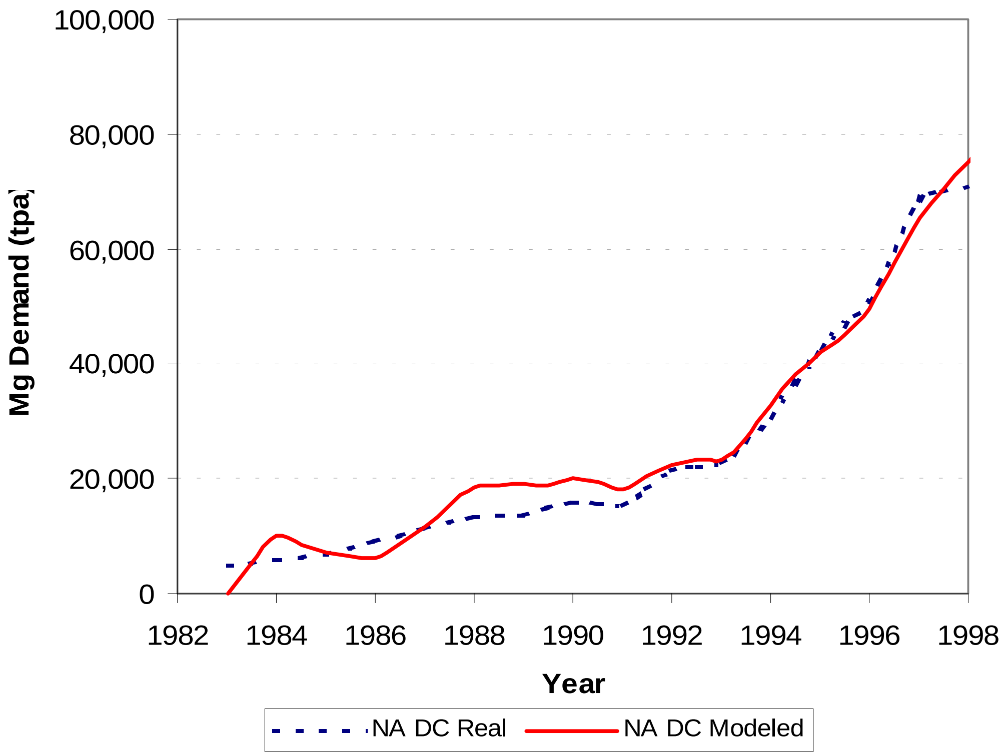

Figure 25: Magnesium Model Demand Trend: North American Die Casting 1983-98

After obtaining acceptable historic pricing and demand fits, the model was deemed suitable to begin the scenario analyses. These first round of analyses were focused on understanding the potential for magnesium usage, the industry plans in place to reach this potential and possible market strategies for achieving market growth while maintaining pricing and demand stability.

7.2 Magnesium Consumption Potential

Analyses of different market scenarios were conducted in order provide insight into the possible future of the magnesium market. The first of these analyses centered on investigating the market consumption potential given the demand trends that were uncovered in the evolutionary and revolutionary demand sectors. The investigation was intended to gain an idea of the optimistic and pessimistic bounds for overall market and automotive demand in the future based on the demand trends uncovered during the research project. If these bounds could be quantified, the future potential of the magnesium market could be better understood and could provide a goal for growth in the market.

In order to simulate the magnesium consumption potential within the confines of the feedback mechanism, it was necessary to bypass the supply-side model. To do this a constant material price override mechanism was introduced that would allow the prices of pure and alloy magnesium to be set without regard to actual material capacity constraints. By doing this, consumption scenarios at various levels of stable material prices could be investigated. Low price overrides created upper consumption bounds, while high price overrides simulated lower consumption scenarios. For the purpose of this study the constant price overrides were initiated in the year 2002, the year following the present, and were allowed to run until the end of the market simulation horizon, the year 2015. During these simulations the total market demand across all sectors and the demand in the automotive sectors were recorded at three points during the simulation, at times representing the years 2006, ’10 and ’15. The results of these consumption potential scenarios are contained in Figures 26 and 27.

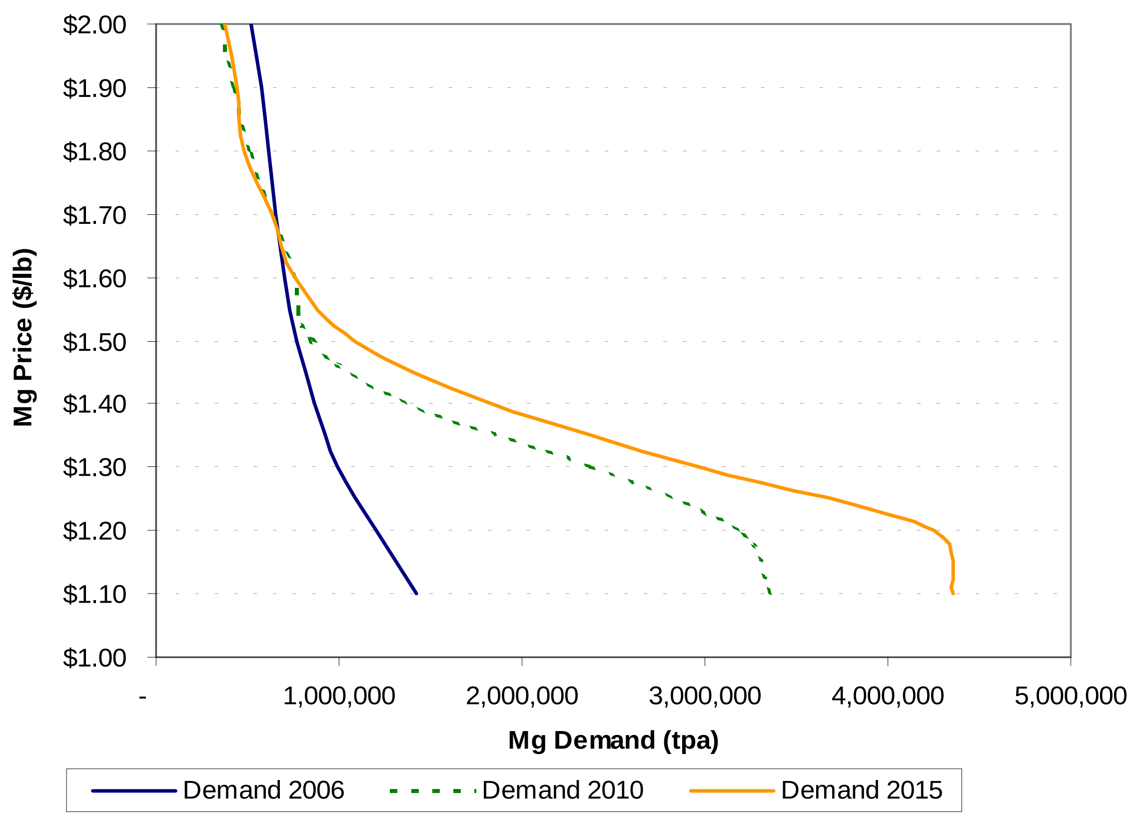

Figure 26: Yearly Total World Magnesium Consumption Potential Under Long-term Constant Material Pricing

The consumption scenario curves offer a few insights into the demand dynamics of the market. First, the near term demand for magnesium, represented by the “Demand 2006” line in both figures is far less sensitive to pricing changes than the other curves. In Figure 26, total world consumption hovers in the 600-750 k tpa range for prices from $1.80 / lb (above current prices) to $1.50 / lb (below current pricing levels). These total consumption levels in 2006 only begin to show larger increases at prices below $1.40 / lb, well below current market pricing. This relative price insensitivity seems to reflect the fact that observation delays associated with market demand have not had time to greatly impact the market in this relatively near-term scenario. Unless prices drop substantially, world primary magnesium demand is likely limited to a band of values in the range of 600-700 k tpa for a horizon of 4-6 years.

Automotive consumption curve, in Figure 27 below, displays a similar short-term demand lock-in effect, linked to the required price residence period and component design lag times. The material prices that are determining the demand for automotive magnesium in the 2006 timeframe are presently in effect and are not affected much, if at all, by the pricing overrides. As a result, for material prices between $1.90/lb and $1.40/lb, automotive magnesium demand ranges only between 200-350 k tpa respectively in the simulation. Again, extremely low material prices impact the automotive demand by increasing demand to 600 k tpa, but this would require substantial, but unlikely, near-term market price decreases. As a result the price sensitivity of the consumption scenario in the near-term is relatively small compared to the longer-term scenarios. The incredibly large market demand potential in the total or automotive sense is only evident by examining the medium and long-term results.

From the above figures it can be seen that magnesium consumption, both in total and in the automotive sector, increase greatly as prices fall below current levels ($1.60/lb) and as the time horizon of the simulation is extended. This allows the market ample time to assess the price drop and to introduce many additional advanced magnesium applications.

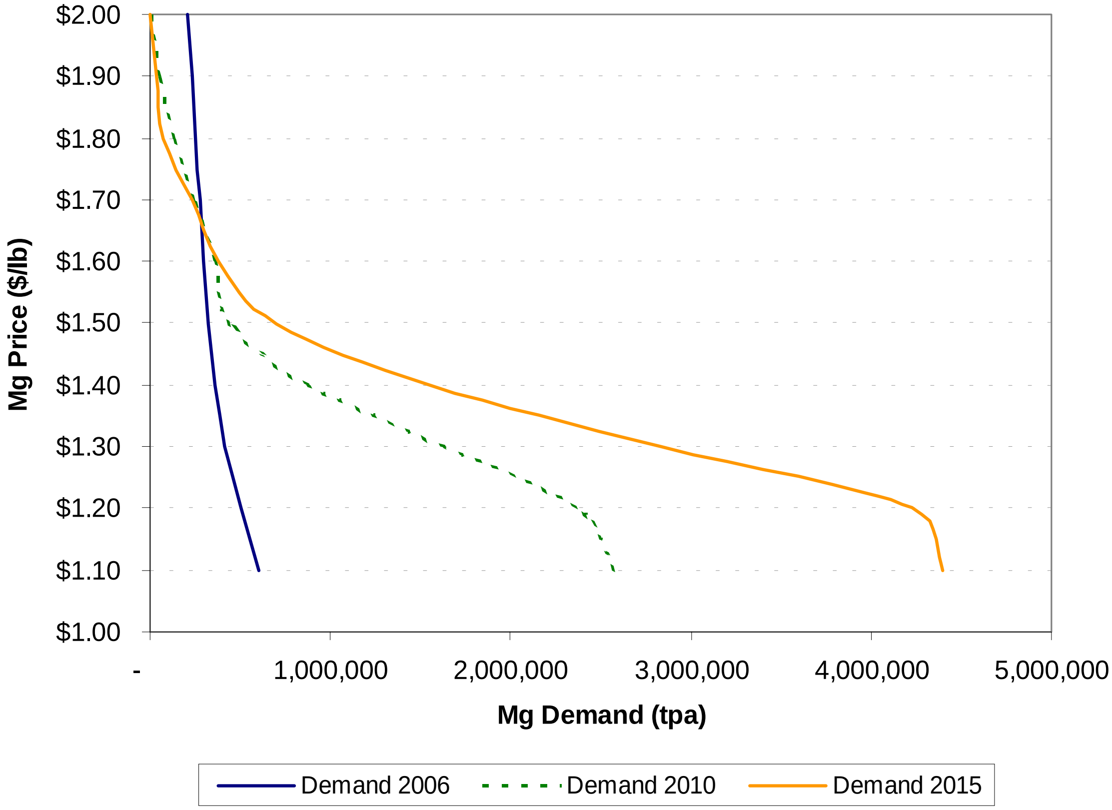

Figure 27: Yearly Automotive Magnesium Consumption Potential Under Long-term Constant Material Pricing

The first insight from the extended time horizon consumption curves is the dominance of the market by automotive demand. By comparing the total world demand and automotive consumption curves it is evident that, given extended periods of low material pricing, the introduction of magnesium auto parts will account for an increasing fraction of total world primary demand. Figure 28, below, shows the automotive share of world magnesium demand. In the lowest pricing runs the production of magnesium auto components completely dominates the world demand for magnesium. In these scenarios all other industry sectors could essentially be satisfied by material from die-casting scrap and post consumer sources. While the exact balance of usage is not specified in the model, i.e. die-casters could recycle their own scrap and/or aluminum smelters could buy primary material, the rapid dominance of the magnesium industry by automotive die-casting is a likely effect of any low price magnesium market scenario.

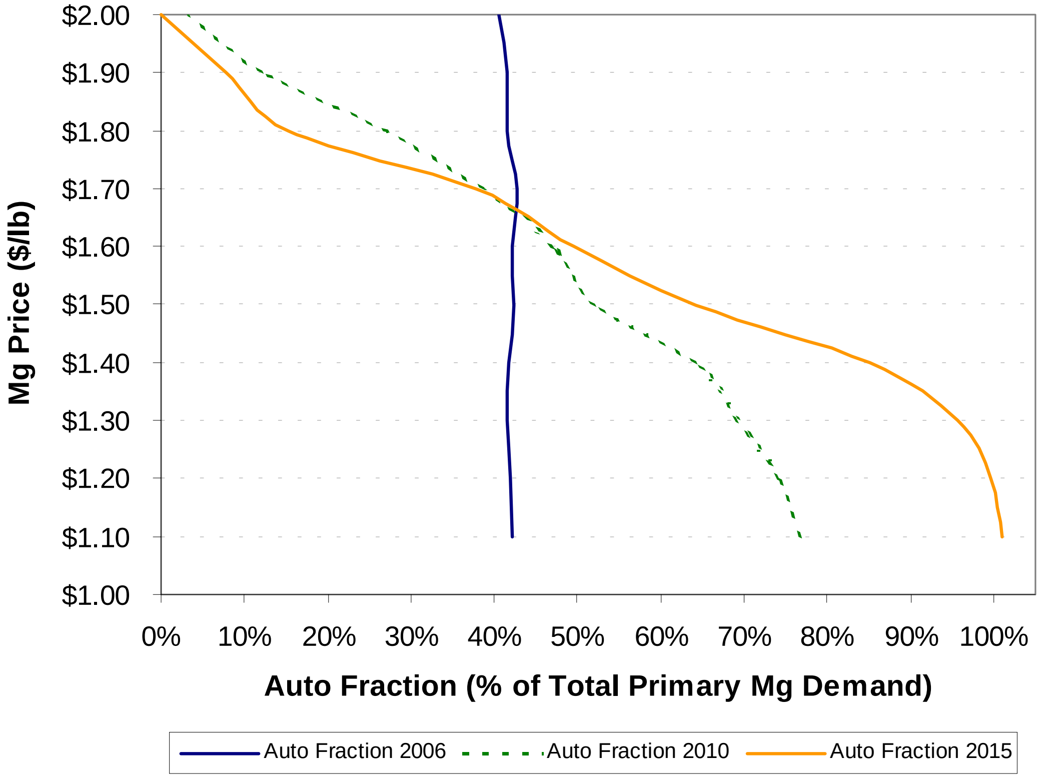

Figure 28: Automotive Share of Magnesium Consumption Under Long-term Constant Material Pricing

The second insight for the extended time horizon consumption curves is the steep slope of the demand for material as prices fall below $1.50/lb. At prices just slightly above this level, the figures show that all of the consumption curves converge to an equilibrium level of roughly 700 k tpa for all industries and 275 k tpa for automotive usage. As prices fall beneath this level, however, demand increases rapidly in the medium and long term. Substantial growth demand is generated primarily by expansions in automotive usage, as large volumes of big parts are introduced. The curves show that a reduction in long term prices from $1.50/lb to $1.40/lb expands yearly automotive consumption potential by 500 k tpa in 2010 and 800 k tpa in 2015. Further decreases in long term material prices only accelerate this trend. Upper bounds for industry demand approaching 2.5 million tpa and 4.5 million tpa of material in 2010 and 2015 respectively are possible, as material prices near $1.00/lb.

At prices below $1.10/lb, the curves show that consumption levels off. This phenomenon is reasonable and results from the limitations instituted to constrain the introduction of automotive components. At prices this low magnesium parts are being introduced as rapidly as possible given the model constraints. Further material price reduction will not accelerate consumption based on the limits placed upon the automotive design process.

The explosion of magnesium consumption potential at low material prices, while remarkable, is not completely unexpected given the design preferences obtained during the automaker interview process. Looking back at the example of Automotive Magnesium Deployment, in Figure 6 of Section 5.2, the shape of the curves for deployment of magnesium automotive design and the two potential consumption scenarios are remarkably similar. The deployment chart shows that at low material prices, larger advanced magnesium component designs come under consideration and boost magnesium content of vehicles rapidly. Likewise, under constant low material pricing scenarios these large components, in large automotive volumes, rapidly boost the potential demand tracked in the consumption scenarios.

This potential, however is not without some risk for producers and consumers alike. Considering that the current world primary magnesium capacity is on the order of 500-600 k tpa, the greenfield expansion necessary to satisfy this large demand would require capital planning on a heroic scale. Stabilizing prices in the long term given these small material reserves will be a challenge as growing demand in the automotive sector competes with the establish demand sectors.

7.3 Supply Expansion Plans: Impact of Near and Medium Term Magnesium Projects on Market Behavior

The previous section showed the large worldwide demand potential for low priced magnesium, especially in the automotive sector. In response to this potential, current magnesium producers and new companies have initiated many magnesium supply expansion plans. These ventures hinge on the hope that new facilities with lower operating cost will be able to provide low priced material desired for revolutionary automotive applications.   The impact of these new players in the market is far from certain, however, as the small size of the magnesium market could be easily over shadowed by the demand of large global industries, like the automakers.

Given the massive potential demand for magnesium in the automotive world and the relatively immature state of the current material supply base, it is easy to understand why there has been so much recent attention to expanding the magnesium supply base. Magnesium smelters in various stages of planning are being proposed in areas like Australia, Congo, Netherlands, Iceland and Jordan. The positive outlook for these projects hinge on the continued growth in die-casting demand stemming from automotive interest. These new facilities expect, and need, the auto industry to absorb large amounts of new supply in order to be financially successful.

Previous examples of dynamic feedback systems and their volatile behavior, like those observed in the commodity markets, could imply that large scale expansion plans may not deliver such an easy solution. Magnesium consumers are championing the new entrants to the supply base because of the expected negative pricing pressure. Lower prices could lead to expanding design applicability and continued growth in the market. These effects, however, are not always positive market developments. Market conditions that create lower prices also have the potential to generate so much interest, especially in the automotive sector, that material supplies could be completely stripped. The magnesium pricing swings following the total absorption of supply would likely slow automotive growth. Abandonment of materials with high price volatility is common in the price sensitive auto sector and has been even observed in the 1990s when US tariff policy caused price swings in the magnesium market [85]. If the magnesium industry wishes to continue its growth trends in the automotive industry, suppliers and automakers alike will need to understand the impact of their own behavior on the stability of the magnesium market.

Exogenous additions were instituted into the Supply Side Sector of the Magnesium Market Model to simulate the entrance of these new magnesium suppliers. The first analysis focused on a small set of exogenous capacity expansions, which represent the near-term published plans of magnesium suppliers. These first expansions have been deemed for this study, based on industry studies and experts, as those projects most likely to start production with successful processes over a time horizon of three years (up to 2004) [86]. The analysis was then expanded to include the vast array of other magnesium projects, many of which are much less certain than those in the near-term, as possible sources of market stability and growth. Again these expansions are introduced as exogenous additions, but are reserved for years after 2004. The final part of the section examines a completely exogenous supply expansion scenario as a possible solution to the growth and stability problem of the world magnesium market.

7.3.1 Near Term Magnesium Supply Expansion Plans

The near-term plans for magnesium supply revolve around a small set of magnesium projects discussed in many literature sources. These projects in Canada, Australia and the Congo, discussed previously in Section *3.1.2 A Historic View of the World Market Supply of Magnesium*, Table 5, have been often cited in magnesium literature sources like the SSB report on Australian Magnesium and the USGS Mineral Yearbook reports as the most likely successful supply expansions in the near-term [87]. These projects have attributes deemed to give them advantages over other similar projects and amplify their chances for commercial success. These ventures are already in the ramp-up stage, like Noranda's Canadian facility or already have substantial consumer support, like QMC's with backing from Ford Motor Company. Other likely ventures offer extremely low operating costs, like Mt. Grace's Australian Project or the Congolese Facility, which enhance their chances for competitive entry into the market. As a result of these attributes and a relatively good standing in the planning process, these facilities were used as a base case for future projections in the market simulations.

For the purpose of the simulations these facilities were added via the exogenous supply expansion mechanism explained in section *6.2 Supply Side Model*. For simplicity, the facilities were assumed to come on in sets of roughly 60,000 tpa of capacity with an operating cash cost of \$0.75 / lb. The near-term expansion scenario brought a total of four facilities on line, one in 2000 (representing Noranda), one in 2003 (Mt. Grace) and two in 2004 (QMC and Congo). With these expansions it was possible to chart a possible future market dynamic based on the evolutionary and revolution demand trends and the model's feedback system. The results of this "near-term only" expansion scenario for market prices, industry capacity and market demand are shown below in Figures 29 and 30.

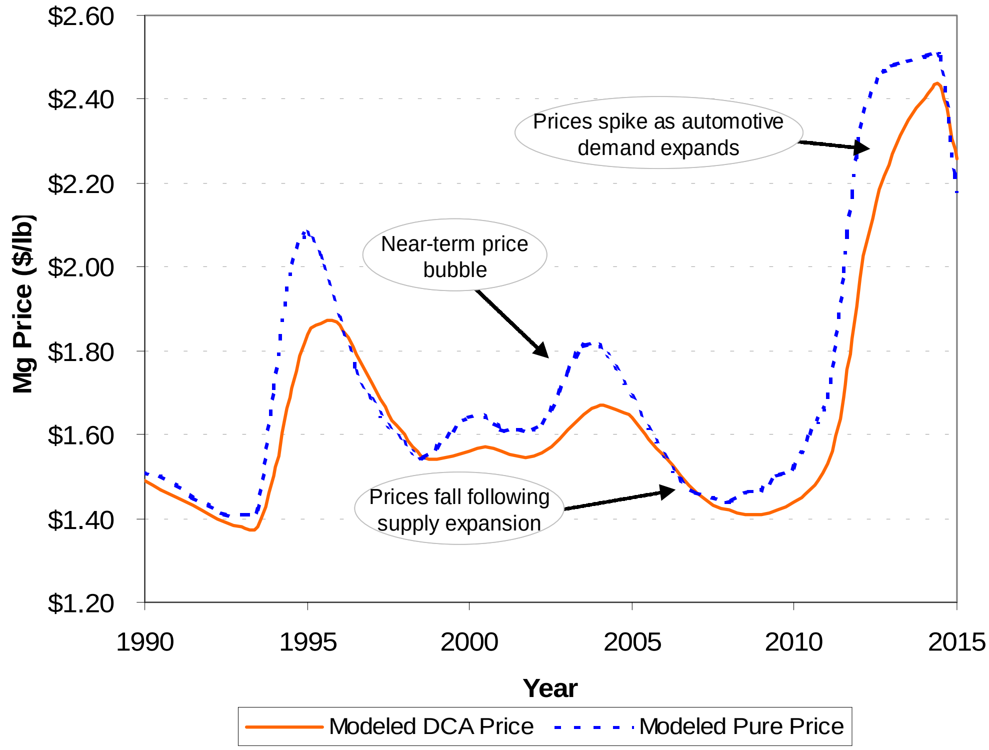

Figure 29: Near-Term Magnesium Supply Expansion Scenario, Projected Material Prices 1990-2015

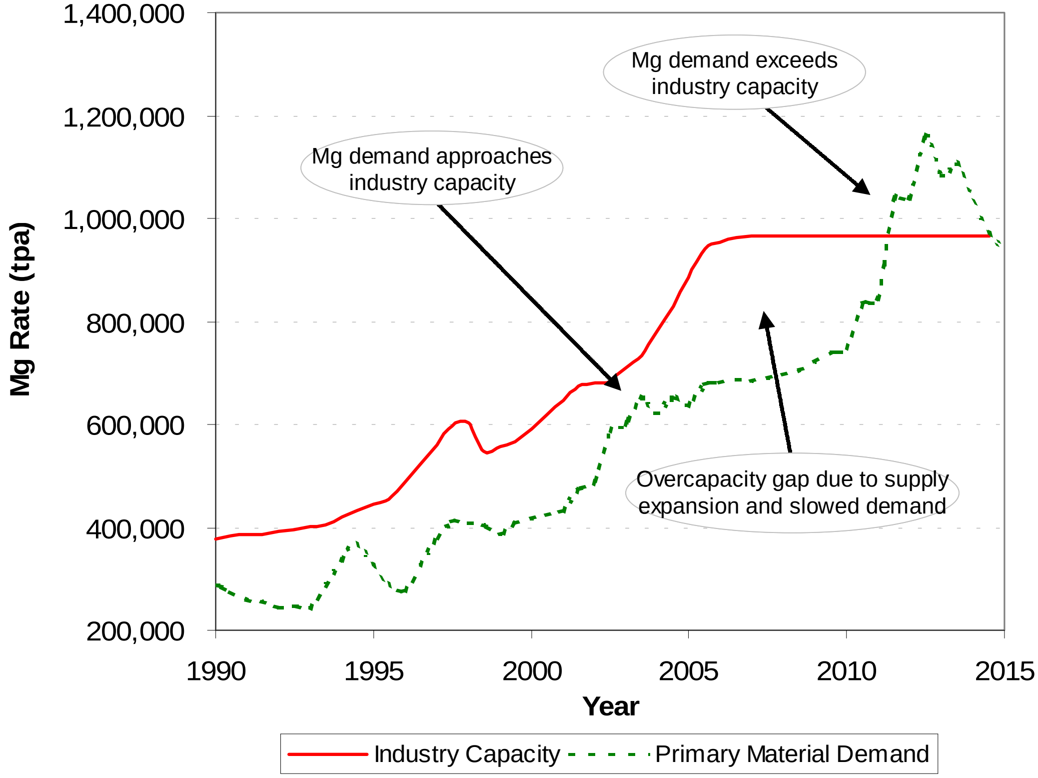

Figure 30: Near-Term Magnesium Supply Expansion Scenario, Projected Industry Capacity and Material Demand 1990-2015

The market simulation scenario indicates that there may be some possible supply and pricing instability in the market in the near future in spite of the near term supply expansion plans. The two plots above tell an interesting story of the maturing magnesium supply base and its problems with growth.

With the rapid expansion of magnesium applications, the model suggests that the demand for primary magnesium in the near future may come near current material capacity, as shown in Figure 30. As demand nears capacity limit, prices rise in the near term, as observed in Figure 29 during the 2003-2005 timeframe. As the majority of the near-term expansion supply facilities are only ramping up during this period, they have little immediate effect on this simulated price bubble. The bubble, however, slows demand for primary material, especially in the automotive sector, in the following five years, just as the new facilities reach their full production levels. Slowing demand causes a glut in material capacity, which results in a steep drop in material prices to nearly \$1.40/lb for the years 2006-2010.

This oversupply is not such a bad development for the demand side, however, as consumers, especially the automakers, finally get what they desire, inexpensive material. The emergence of cheap magnesium causes the automakers to expand the scope of their magnesium designs and pursue more advanced applications. This magnesium design rush, however, eventually produces the market instability that the original supply expansions were attempting to prevent. When the automakers finally hit the market with a large variety of advanced magnesium applications, 2-3 years after the material price bottoms out, the shear volumes of material they desire quickly outstrips the overcapacity and prices spike. In the years following 2010 the rush of automotive demand pushes material prices over \$2 / lb.

The design life of the vehicles maintains high levels of demand during the price spike, as magnesium components are locked-in for about four years despite the outrageous prices. During the price spike, however, automakers abandon all new magnesium projects and switch current applications back to other materials. Three years later most automotive components abandon magnesium, demand plummets and material prices are dragged down yet again. At this point the demand oscillation could begin anew, but this would be unlikely given the bitter taste left last boom and bust cycle.

7.3.2 Medium-Term Magnesium Supply Expansion Plans

The near-term expansion simulation suggested that the growth in auto demand could incite a magnesium shortage in the next decade. Luckily these near term facilities are not the only magnesium supply projects being planned. There are a large number of other magnesium projects, much like the Congo, Mt. Grace and QMC ventures, which are also hoping to capitalize on expanding automotive magnesium demand. These projects, however, are less technically and financially certain. While these ventures may not have pilot facilities running or the backing of large automotive sponsors, they may be able to provide medium-term possibilities for expanding the magnesium supply base as magnesium applications expand.

Beyond those discussed and analyzed in the previous section, facilities proposed in Australia, Iceland, China and Jordan, account for another possible 550,000 tpa of material supply. If these plans are realized this would constitute a rough doubling of the current availability of magnesium worldwide.

In the medium-term expansions simulations, new facilities were assumed to enter the market in units of 60,000 tpa and cash costs of roughly $0.75 / lb. Given these published potential expansions plans, the additional expansions could be approximated by a set of nine generic plants. The medium-term case assumed that these nine generic facilities would be introduced exogenously one at a time on a yearly basis beginning in 2005, the year following the completion of the near-term facilities. By the end of 2013 all nine facilities are running and have added over 500,000 tpa of capacity to the magnesium supply curve. The results of the base case medium-term expansion scenario are shown in Figures 31 and 32 below.

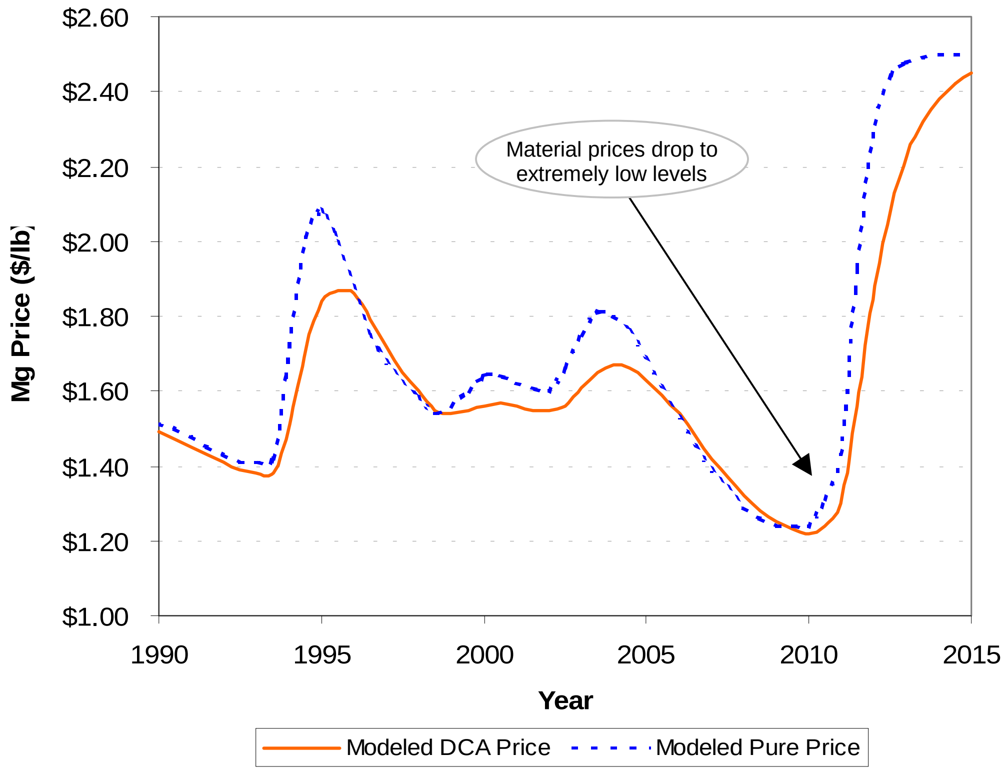

Figure 31: Medium-Term Magnesium Supply Expansion Scenario: Single Plant Introductions 2005-2013, Projected Material Prices 1990-2015

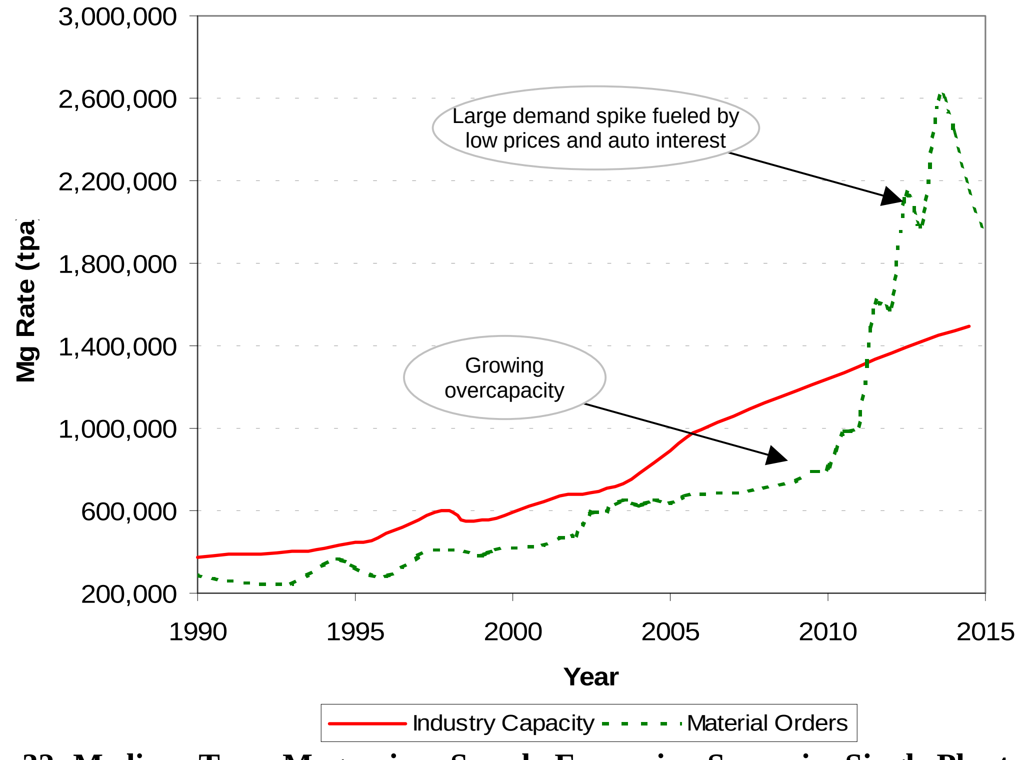

Figure 32: Medium-Term Magnesium Supply Expansion Scenario: Single Plant Introductions 2005-13, Projected Industry Capacity and Material Demand 1990-2015

The medium-term supply expansion scenario creates a similar, but more dramatic, example of the boom-bust dynamic caused by low material prices and a following explosion in demand. By introducing more primary material supply into the magnesium market in the years following the price bubble, the oversupply problem late in the decade is exacerbated. Prices fall to even lower levels approaching $1.20/lb. The increasing overcapacity could be viewed as a preemptive move to get ahead of the automotive design delay, but it fails. Reserving supply before the boom in advanced automotive designs pushes prices to extremely low levels and even larger volumes of material enter the automotive design process. The price drop removes all the financial and technical hurdles to implementing magnesium designs. The boom in demand locks in millions of tons of automotive designs across many applications, which easily outpaces the reserve material capacity. Again the boom and bust dynamic is created in response to capacity expansion and the quest for inexpensive material.

7.3.3 Magnesium Supply Expansion Needed for Market Stability

Given the challenge of maintaining market stability, it is difficult to imagine how supply expansions and demand growth could be possible given the price sensitivity trends and huge volumes of the automotive industry. The negative impact of the shear size of the auto industry on the small magnesium market seems insurmountable. The flexibility and power of the simulation model, however, makes running scenarios and experimenting relatively quick. Exogenous supply additions were altered in many runs in an effort to discover if any expansion scheme could prevent the boom and bust cycle. Figures 33 and 34 show pricing projections and supply and demand history, for an exogenous introduction scheme that achieves a relatively stable market dynamic. Again, the introductions exhibit the same assumed process characteristics as used in the exogenous additions before.

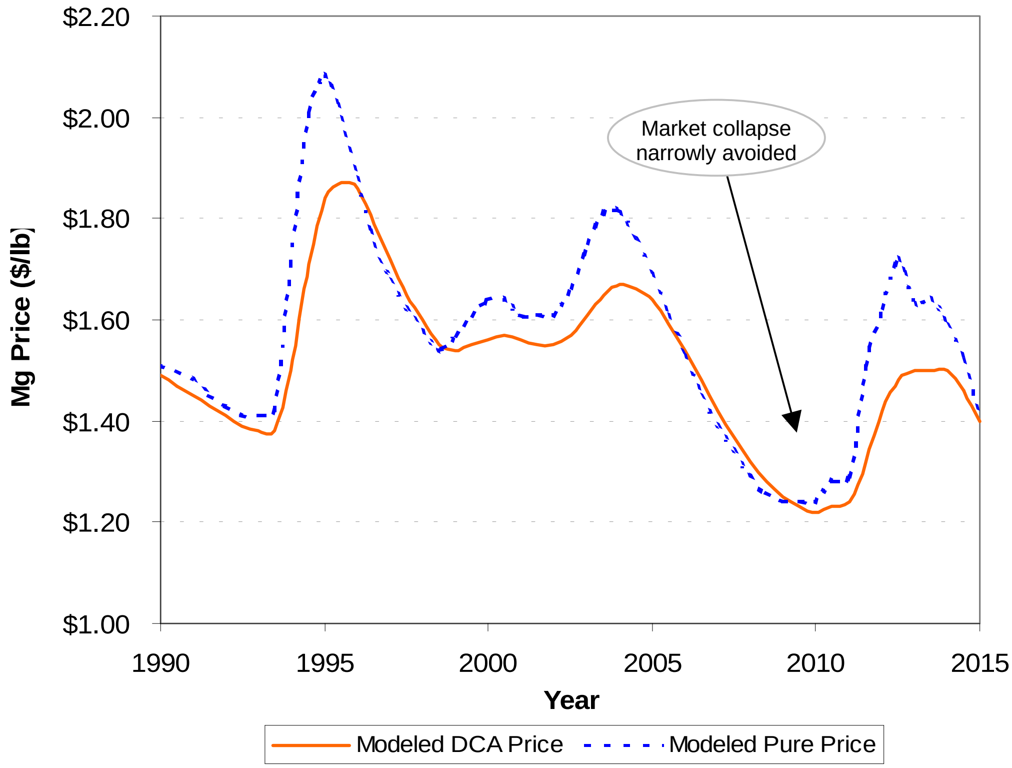

Figure 33: Medium-Term Magnesium Supply Expansion Scenario: Forcing Market Stability Exogenously, Projected Material Prices 1990-2015

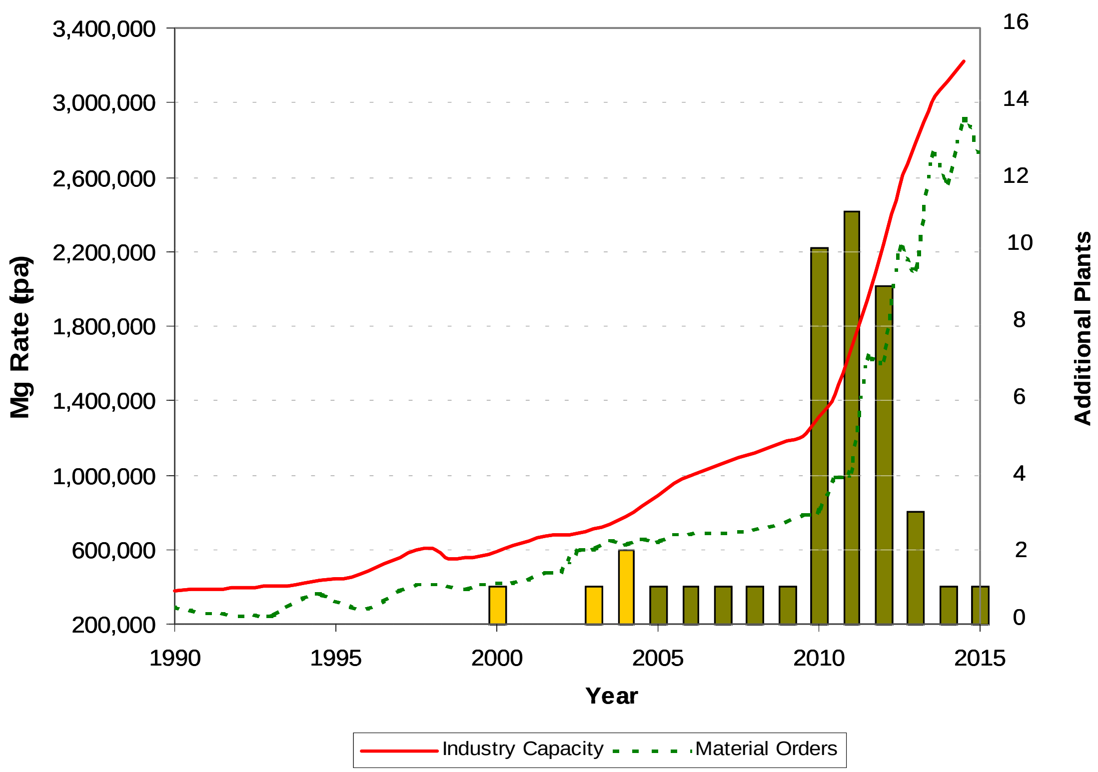

Figure 34: Medium-Term Magnesium Supply Expansion Scenario: Forcing Market Stability Exogenously, Projected Industry Capacity and Material Demand 1990-2015

As shown in the above forced market "stability" scenario, the expansions necessary to prevent a boom and bust cycle in the magnesium market are substantial, especially following planned expansions during the present decade. The resulting simulated material price spikes are only narrowly avoided by introduction of huge numbers of facilities at the turn of the decade, 10 and 11 total plants in the years 2010 and 2011 respectively. The total additions beyond those planned in the near term account for 41 additional 60 k tpa facilities, which would account for a nearly 4.5 times increase in supply relative to current production levels. Even with these huge investments in material supply capacity a price bubble of nearly $0.25 / lb in the period 2010-2015 would surely be cause for concern for the stability of the magnesium market.

The problems with this scenario, are evident, the technical, economic and physical challenge of initiating the planning and ramp-up of the equivalent of 41 new magnesium smelters is nearly impossible to fathom. Not only would quadrupling the current supply base be unlikely, but the solution suggested by the exogenous forced stability scenario is also very fragile. The removal of a single plant introduction from the exogenous addition model, especially in the years 2008 and beyond, causes the simulation to return to a boom and bust dynamic, where automotive demand rapidly strips away all available supply and material prices spike. This presents a huge challenge to the proposed expansion solution, as most industrial process are subject to technical uncertainties and financial constraints that can lead to project delays or cancellations. The presence of minor delays in plant ramp up could prove catastrophic to the industry. The economic viability of these heroic expansions could also cause problems, as the majority of the exogenous expansions are set to launch immediately following a period where material prices hit their lowest levels. The financial outlook of these projects at this point would likely be so poor due to depressed market prices, the chances for investor approval seems dim at best. Due to the uncertainties of planning and supply economics, ensuring the on-time, flawless launch of such large numbers of facilities almost seems impossible.

This result of the exogenous supply expansion scenarios appears very disheartening. The future growth and stability in the magnesium market seems hindered by the double-edged blessing caused by low material prices and rapid growth in the automotive sector. Expanding the supply base exogenously and forcing prices downward can result in industry growth, but the resulting recoil of demand from the large automotive players quickly undermines the market. These scenarios, however, are based solely on the expected, but uncertain, plans of many separate magnesium ventures that are being introduced into the model as fairly certain events. These exogenous additions enter the market regardless of whether they are warranted by expanding demand or financial gain. Coordinating these supply additions based on logical feedback, rather than expectation and projection, may offer improved expansion plans. Supply-side interactions, too, are only half of the market equation. Demand-side feedback mechanisms could also be employed to address the difficulties witnessed in the expansion and growth scenarios.

7.4 Supply-Side Feedback: Capacity Expansions Linked to Automotive Design

In order to better implement coordinated supply expansion plans an automated mechanism was introduced into the market model. The mechanism utilized to create these expansion plan improvements tracks automotive designs, anticipates magnesium demand and initiates supply expansions when demand is necessary to meet these new applications. This strategy is slightly different than the current expansion plans within the magnesium supply base, which is pursuing automotive attention through expansions and inexpensive material prices. Extensive corporate coordination between automakers and magnesium suppliers would also be necessary to create a strong supply-side feedback. Current trends suggest a trend toward strengthening magnesium-automotive industry ties, which could, if allowed to mature, lead to the cooperation necessary to maintain market stability for the good of both parties.

The supply-side feedback loop has two main components. A tracking sector follows the initiation of magnesium designs from the beginning of the automotive design cycle. This sector catalogs new magnesium parts in the design phase and scales these up by mass and vehicle volume. This sector effectively creates an automotive magnesium demand predictor three years in advance of their introduction.

The second portion of the supply-side feedback loop is a logically controlled duplicate of the exogenous supply addition sector. The difference between the applications of these two capacity addition sectors is contained within the logical control. In the previous analyses, all supply additions were controlled by intentional overrides to the supply side model. In this new sector the model automatically adjusts the supply curve. The logic of the additions can be based on any expansion rule or factor, but for the purpose of this analysis it is linked directly to the automotive demand prediction described previously. The automotive demand prediction is translated directly into the new capacity required and the corresponding number of new plants. Plant capacities of 30,000 tpa, half of the standard size used in the exogenous expansion analysis, were used to allow the automated scenarios more closely match the predicted need for new material. The automated necessary expansions were also rounded down to avoid oversupply tendencies witnessed in the exogenous addition scenarios. The automation also assumes that the three years necessary to design and introduce automotive components is enough to build pilot plants and begin ramping up a magnesium production facility. This was deemed appropriate given the large pool of expansion plans currently in the planning stages. Three years would seem plenty of time to bring these projects to fruition, but this expansion planning delay can be adjusted to examine its impact on the market dynamic

Several different scenarios were used to examine the impact of coordinated supply expansions. The first automated run is a scenario in which all of the future expansions are handled exclusively by the model itself. From the year 2000 onward, no exogenous plants are added to the model. This signifies a completely clean-slate plan where none of the near-term supply expansions, nor the medium-term plans, force their way into the market. In this run, the logic associated with the automated supply expansion is the only mechanism adding to the industry supply and is based solely on the growth in automotive demand. The remaining three scenarios expand on the original run by forcing exogenous additions to the supply curve outside the automated mechanism. These runs signify the three near-term expansion plants studied previously, Mt. Grace and QMC in Australia, as well as the Congolese facility. Each of the runs introduces an additional facility in the order of their proposed start-up dates. A table explaining each of the four scenarios is shown below.

Table 9: Automated Supply Expansion Scenarios

Scenario Number	Exogenous Expansions	Notes
Scenario 1	none	All future plans are triggered solely based on increased automotive demand
Scenario 2	single plant in 2003	Exogenous addition could represent Mt. Grace facility

Scenario 3	single plants in 2003 and 2004	Additions represent Mt. Grace and QMC
Scenario 4	single plant in 2003 and two more plants in 2004	All near-term planned plants are added (Mt. Grace, QMC, Congo)

Several significant insights were garnered from these four scenarios. The separate runs displayed significantly different supply expansion plans and material pricing behavior. The expansion plans determined by the automation logic suggest that adding more near term plants will require progressively more medium term (post 2004) expansions to maintain market stability and satisfy growing automotive demand. Figures 35-38 show the expansion histories of the four scenarios including the maturing supply, evolving demand and the number of plant expansions required each year (dark bars indicate exogenous additions). The figures also include average vehicle magnesium content figures assuming ~16 million and ~14 million vehicles produced in North American and Europe respectively.

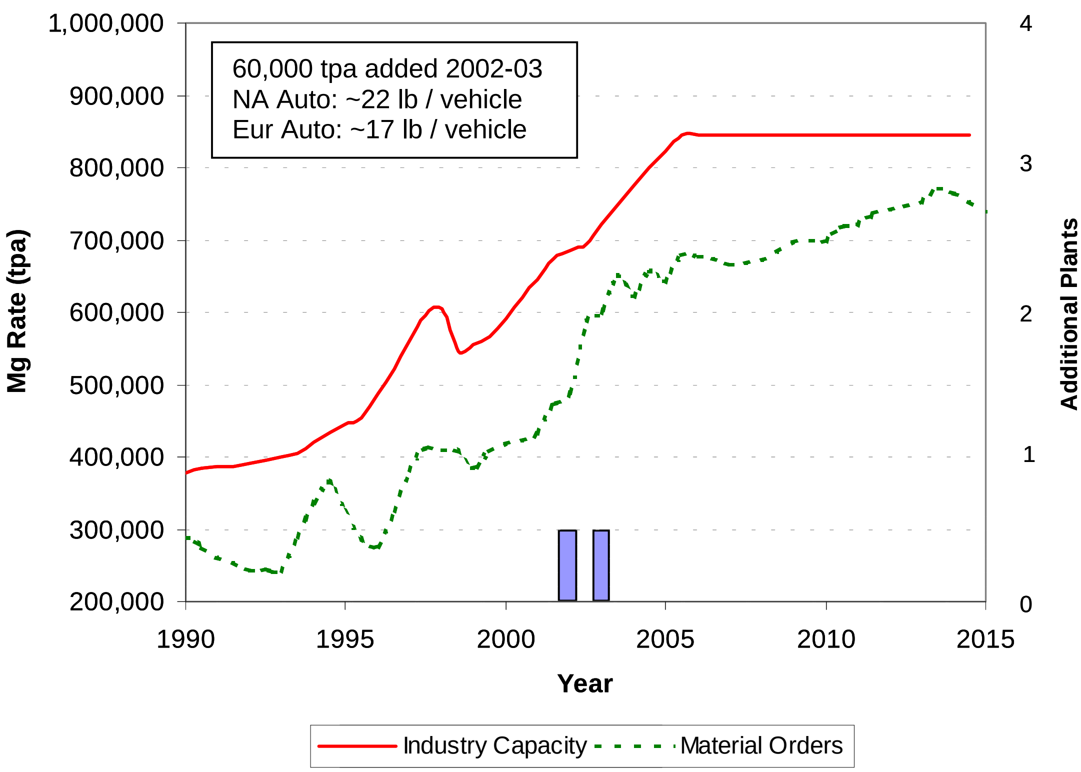

Figure 35: Automated Supply Expansion Scenario 1: Low Supply / Demand Growth

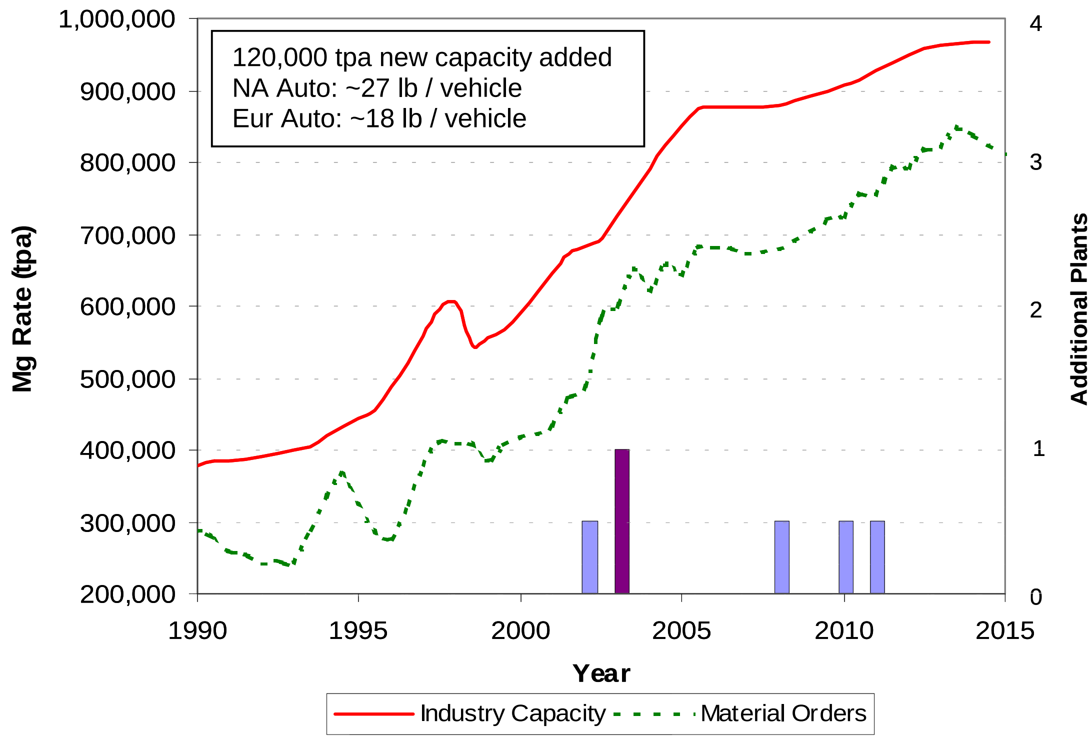

Figure 36: Automated Supply Expansion Scenario 2: Slow Supply / Demand Growth

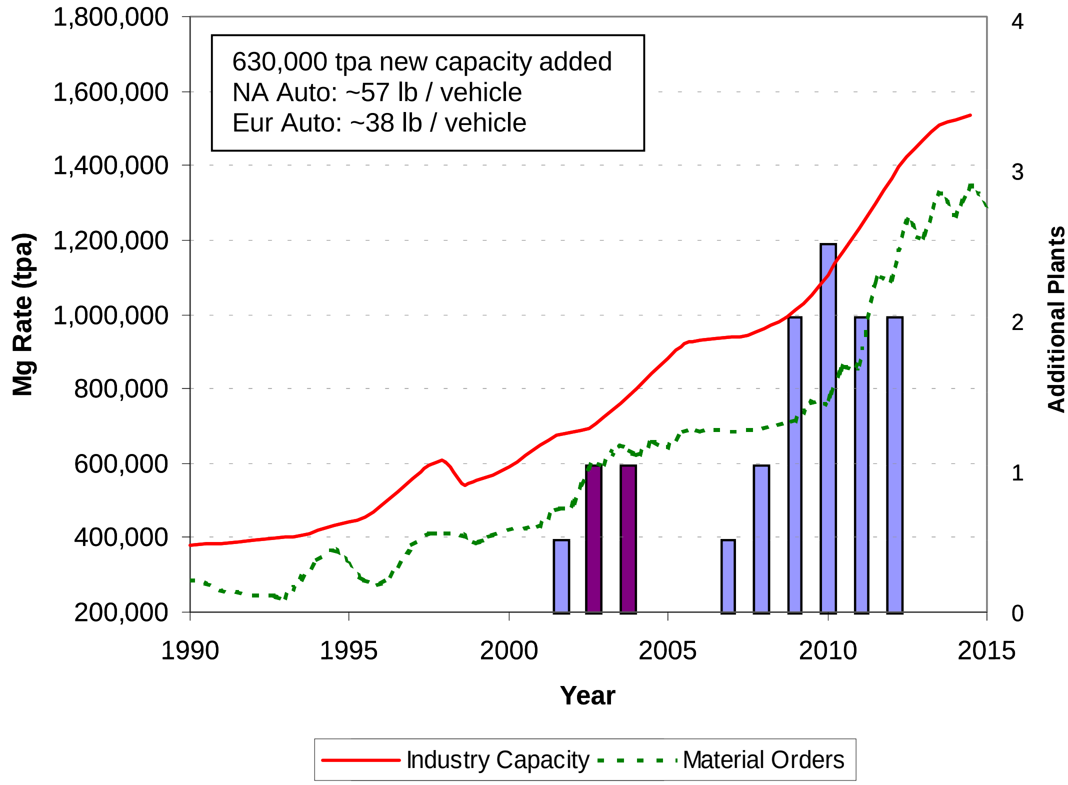

Figure 37: Automated Supply Expansion Scenario 3: Moderate Supply / Demand Growth

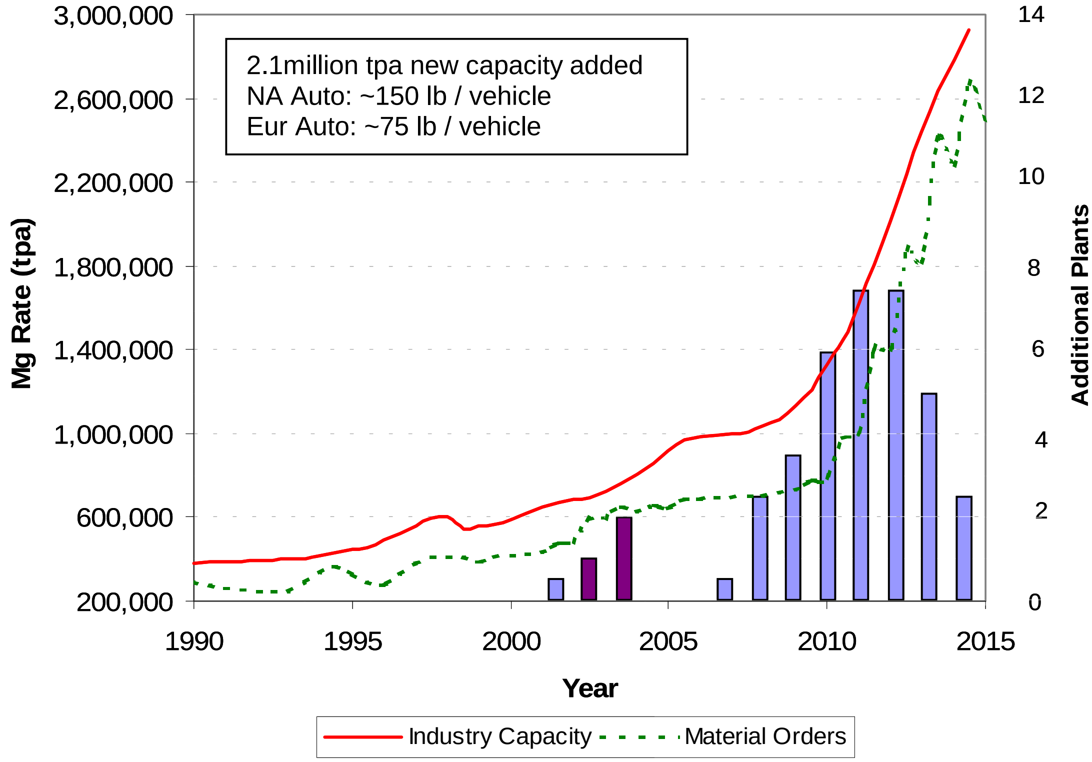

Figure 38: Automated Supply Expansion Scenario 4: High Supply / Demand Growth

The expansion histories show that the addition of the proposed near-term supply expansion can have a profound impact on the maturation of the magnesium industry and the expansion of demand in the automotive sector. As more plants are added in the near-term, the supply base can generate larger and larger demand. Scenarios one and two add few additional plants and raise supply to relatively lower levels. Adding more facilities, as in Scenarios 3 and 4, generates a sizable automotive interest that must be satisfied by increasingly large supply expansions.

The larger required expansions are generated due to the negative price pressure generated by the exogenous near-term expansions. The addition of new magnesium facilities pushes the price of material down. Figure 39, shows the price projections of die-casting alloy for the four scenarios.

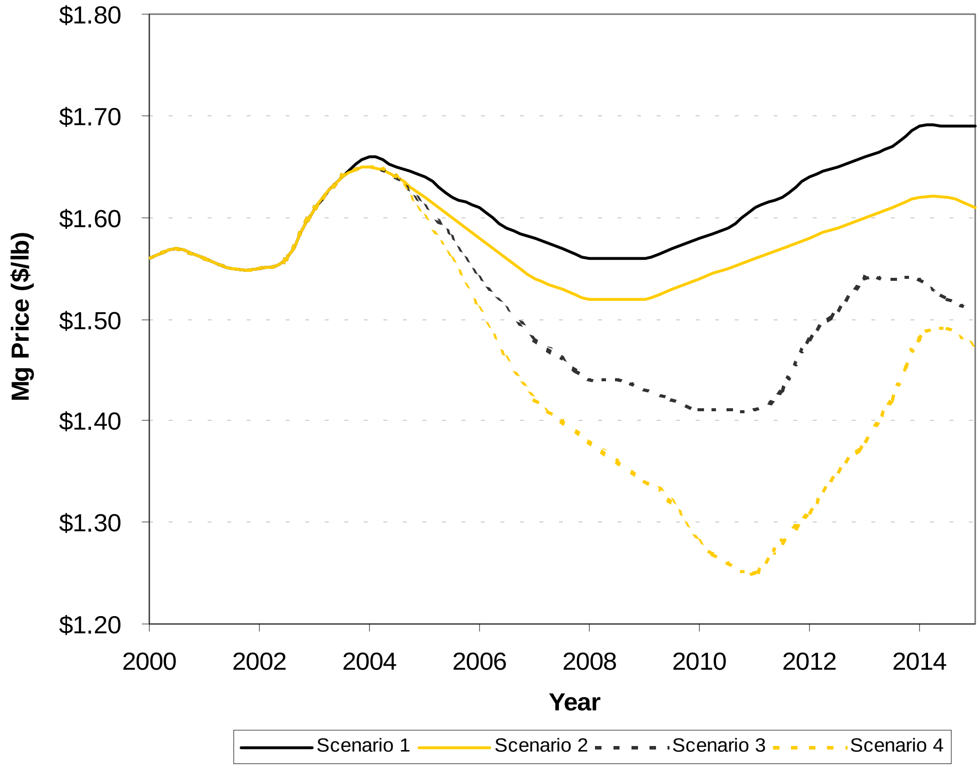

Figure 39: Automated Supply Expansion Scenarios: Die Cast Alloy Pricing Projections

From the figure its is easy to see that more aggressive near-term expansion leads to progressively lower and lower market prices for material in the medium time horizon. Scenarios 1 and 2 maintain relatively high prices and thus a lower growth in demand and automotive adoption. The more aggressive near-term expansions in Scenarios 3 and 4, lead to lower material prices and wider adoption by the automotive industry. This expansion is not without some cost however as these two scenarios exhibit a more volatile pricing projection (more intense amplitudes and more rapid swings).

The automated supply expansion teaches several important lessons about the nature of the magnesium market. There are several levels of supply, demand and pricing that appear to be stable. Scenarios 1 and 2 signify possible futures for the market featuring relatively high material prices, lower demand and a smaller supply base. Prices remain relatively stable at levels close to those observed today. Magnesium, while remaining a niche player in the automotive world, gains a respectable penetration into auto design, accounting for nearly 20-30 lb per vehicle by 2015 (up from 8 lb today). Scenario 3 represents a medium growth scenario, where prices are held at levels slightly lower than today and demand, supply and automotive interest grow at a moderate rate. This scenario is fairly consistent with the current expansion plans for the magnesium industry. The addition of roughly 11 new 60,000 ton facilities should be possible given the industry's current supply base plans. The low and medium growth scenarios exhibit common themes for near and medium-term expansion strategy. These runs suggest that being slightly more reserved in supply expansions in the near-term pays big dividends later in the decade by not driving prices too low and inciting excess demand.

Scenario 4 is not quite as stable as the other three runs. This scenario shows a similar story to the scenarios investigated in Section 7.3.3, where magnesium growth is pursued aggressively in the near and medium-term. In this scenario the near term expansions overshoot demand following the price bubble in 2003-04 and drive magnesium prices below $1.30 / lb. Substantial medium-term supply expansions following early in the next decade on the order of 2 million tpa are just barely enough to contain a rapid demand spike near the turn of the decade. Each year between 2010-2012, six or more plant openings are required to maintain market stability. As in the previous examples many of these new facilities will need to be ramping up immediately after prices hit their lowest levels. Again, these expansions are an unlikely market response to low material prices.

The source of all the demand growth is centered in the automotive industry that is pursuing advanced magnesium designs after material prices fall. The automotive industry's rapid expansion of applications results in an average magnesium content of nearly 150 and 75 pounds per vehicle in North America and Europe respectively. Much of these gains will likely be lost, however, as the large rebound in prices early in the new decade will send new auto designs back to their competitive materials.

The initial conclusions gained by instituting the supply expansion feedback loop suggest that tracking the automotive design pipeline is indeed a good method of coordinating primary magnesium capacity expansion in the future. By following the growth sectors explicitly, only the necessary supply is added to the supply curve. The automated supply sector suggests that being slightly reserved in near-term supply expansions is also a wise plan of action. Adding too much supply quickly, especially when prices are strong and demand is slowing, is likely to destabilize the market in the longer-term. These enthusiastic expansions end up driving prices down and incite rapid increases in demand, well beyond the capacity of the industry.

By using these conclusions it is possible to construct positive future scenarios of low and moderate growth for both the magnesium supply industry and automotive magnesium designs. Market expansion scenarios creating supply bases in the range of 800,000 to 1.5 million tpa seem technically feasible. These scenarios create stable pricing projections ranging from $1.65-1.45 / lb magnesium which also appear relatively attractive for suppliers and consumers alike. Automotive usage expands to respectable levels as well, netting automotive magnesium content between 20 and 60 pounds per vehicle. Pursuing industry growth more aggressively by expanding rapidly in the short-term and coordinating supply later by following expected automotive demand, seems an unlikely solution and displays less stable behavior. The coordinated addition feedback mechanism can only barely contain the price spikes of the aggressive growth strategy with heroic, but very unlikely, expansion plans.

7.5 Demand-Side Feedback: Storing Material and Market-Making Mechanisms

The growth and stabilizing strategies investigated have shown that some of the aggressive expansion plans suggested by the magnesium supply industry, while generating the large automotive interest, may have a long-term destabilizing effect on the world magnesium market. The strategies investigated so far, however, have focused primarily on supply-side effects to promote growth and stability and have not addressed demand-side effects. Demand-side feedback could provide stabilizing effects necessary to supplement the aggressive supply expansions and give the market the added stability it needs to actively pursue aggressive growth.

To investigate demand-side feedback a new sector of the market model was created as a “market-maker”. This sector was instituted as a storage mechanism for purchasing excess low cost magnesium in times of overcapacity and releasing this material when prices rise. The storage mechanism can be thought of as an organization with enough capital and space to hold onto magnesium metal in times of low demand in order to turn a profit when demand heats up. It is a similar to a storage battery for excess material supply. This mechanism could be a large financial organization akin to the London Metals Exchange, which deals in other metals, or even an automaker holding onto low priced material in anticipation of new magnesium designs.

The most important aspects of the market-maker are the rules used to direct the flow of material into and out of the storage pool of excess magnesium. The purchasing and release rules were selected in order to obtain stable prices that fall on the cusp of rapidly expanding magnesium demand. From the previous runs of the model in the sections on exogenous and automatic supply expansion, it was shown that material prices falling near $1.40 / lb tended to encourage very rapid expansions in demand. The market-maker in the model was instituted with logic that would initiate magnesium purchases at $1.40 / lb and quickly ramp up to maximum stockpiling levels at all prices below $1.35 / lb. This stockpiling logic would supplement magnesium demand in times of low prices and high overcapacity in order to prevent overly rapid drops in material prices and over-enthusiastic booms in demand. Releasing material from the stockpile was initiated in periods when material prices exceeded $1.50 / lb and releases were ramped to maximum levels as prices moved above $1.60 / lb. Releases from the stockpile to the market were used as a method of reducing primary material consumption and satisfying rapid increases in magnesium demand. These triggers for magnesium stockpiling and release were used to target the pricing levels that were most often associated with market instability.

Additional restrictions were instituted to cap the purchasing of material based on a maximum percentage of annual production, a maximum level of automotive demand and/or a maximum level of material in the storage pool. These restrictions were used to place common-sense limitations on the operation of the storage mechanism. For most of the runs the maximum purchase rate was limited to 35% of the overcapacity gap in the supply – demand interaction and/or 5% of the total yearly production of primary magnesium, whichever was less. This base assumption was only relaxed in cases where large, but unrealistic, stockpiles were necessary to maintain market stability.

The first run of the market-making stockpile mechanisms was centered around stabilizing the magnesium market given the known near-term expansion plans in 2003 and ’04 along with a relatively aggressive near term expansion that adds additional plants exogenously into the model in the years following 2004. These aggressive expansion plans were controlled solely by the exogenous mechanisms in the model. This was done in order to keep supply-side and demand-side feedback results separate and to avoid the problems of optimizing two separate sets of logical feedback instructions simultaneously. Given the initial near-term and medium term expansion plans and the base stockpiling logic assumptions, the appropriate number of additional exogenous plant additions were added in order to maintain a relatively stable demand and pricing simulation. The first results are shown in Figures 40-42, below.

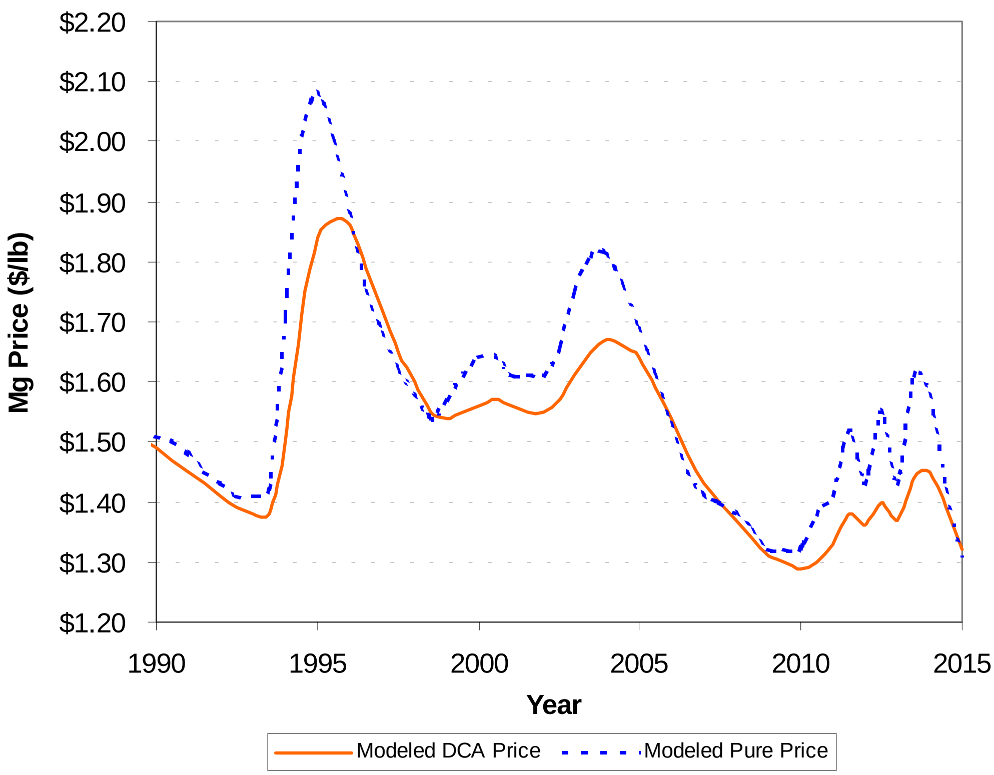

Figure 40: Demand Feedback Scenario 1 - Aggressive Supply Expansions: Material Pricing

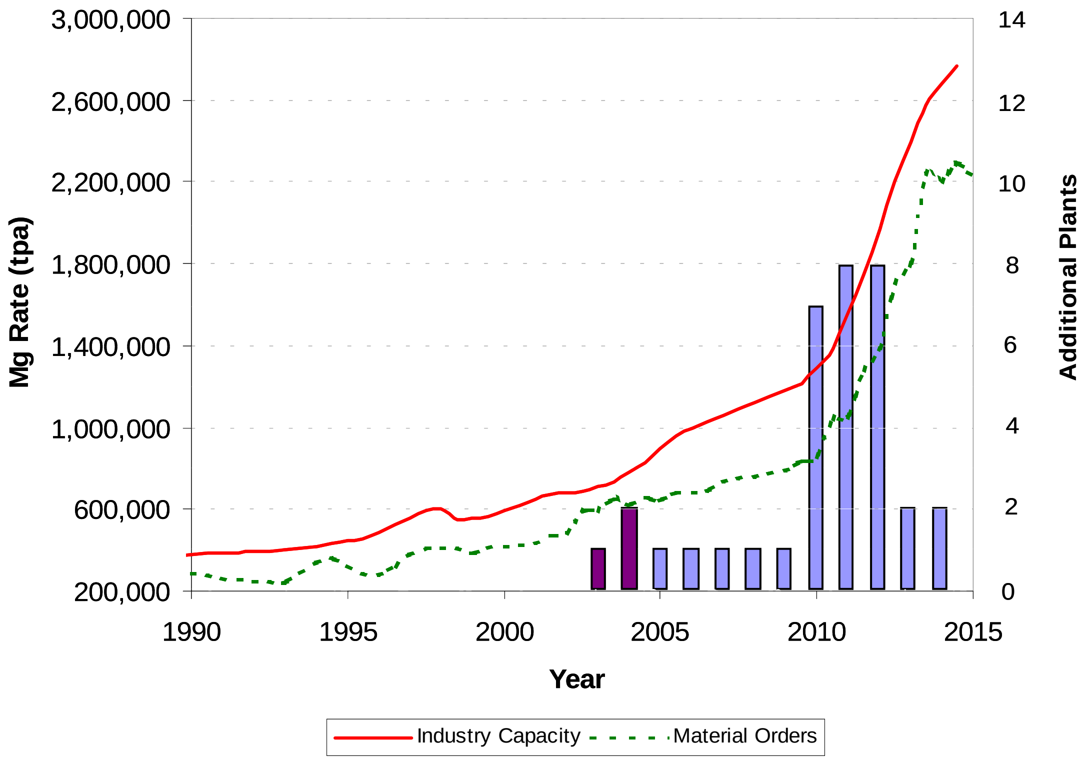

Figure 41: Demand Feedback Scenario 1 - Aggressive Supply Expansions: Supply and Demand

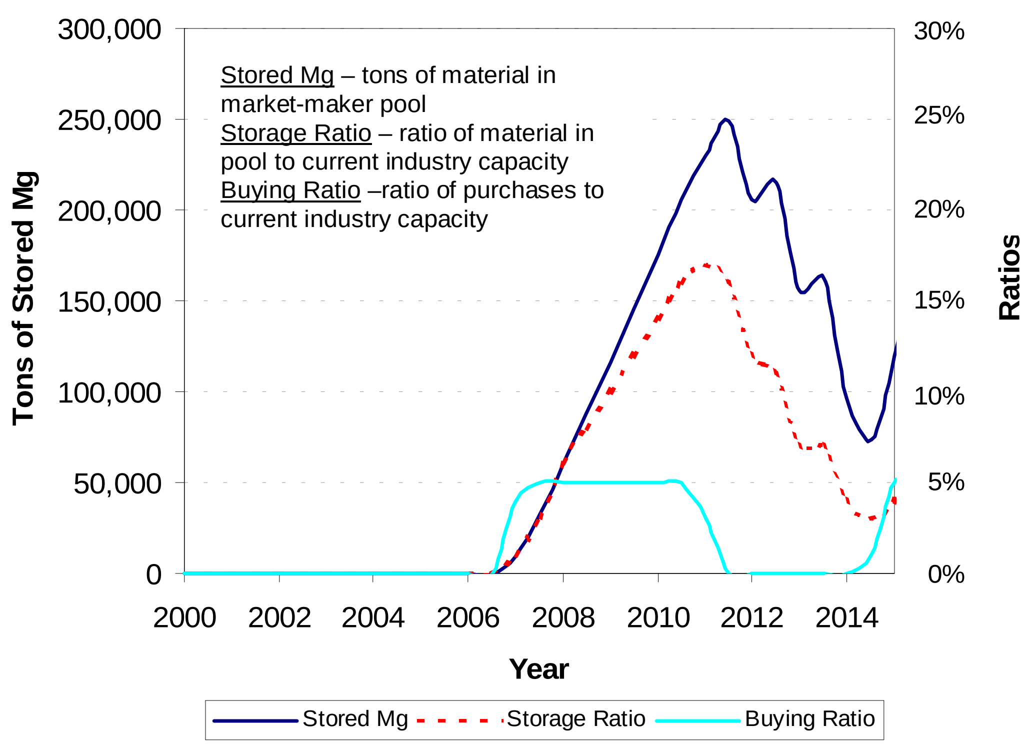

Figure 42: Demand Feedback Scenario 1 - Aggressive Supply Expansions: Material Storage Profile

The demand feedback scenario shows that that the storage mechanism in conjunction with the supply expansions can keep prices for magnesium material in the range of $1.40-$1.50 / lb. When material prices are below this range the mechanism quickly accelerates to maximum buying ratios of 5% of industry yearly production. When prices rise above this range material is released and satisfies a portion of primary demand. As effective demand is reduced prices fall back to acceptable levels.

The expansion plans and the size of the material store, however, presents some concerns for the viability of the demand-size feedback stability solution. The plant expansions required to maintain market stability are still rather large. Similar to the plans termed technically "unrealistic" in Scenario 4 of the automated supply feedback analysis, over seven plants openings are required in peak demand years to prevent market collapse.

Another disheartening result is size of the material store generated by purchasing material during the low price period of the simulation. Figure 42 shows that the size of the material store peaks at 250,000 tons or roughly 17% of the industry's yearly production. Assuming material purchases are being performed at roughly $1.40 / lb, a final investment of over $700 million would be necessary. Investments of this size, with hopes of making $0.10-$0.20 / lb in the final transaction, might be hard to justify financially.

Additional runs were performed in hopes of producing a demand-side solution to the aggressive expansion scenario with more reasonable expansion plans or smaller material stores. The base case was first examined by capping the maximum level of material in the store. It was discovered that only 140,000 tons was required to prevent a market collapse if some additional price volatility is deemed acceptable. Stores less than this level will not be sufficient to prevent demand from outstripping supply. A store of this size, however, would still cost over $400 million to accumulate. Splitting this cost amongst several automakers and a few large financial organizations might be feasible as a market damping strategy, but this still does not address the problem of launching eight magnesium plants in a year.

To investigate the problem of unrealistic expansion plans in the aggressive supply expansion scenario, the limitations on material purchases were loosened to accommodate larger magnesium reserves. New scenarios were the tried with restrictions on the maximum allowed expansions. The minimum required stores for these new scenarios are shown below in Figure 43.

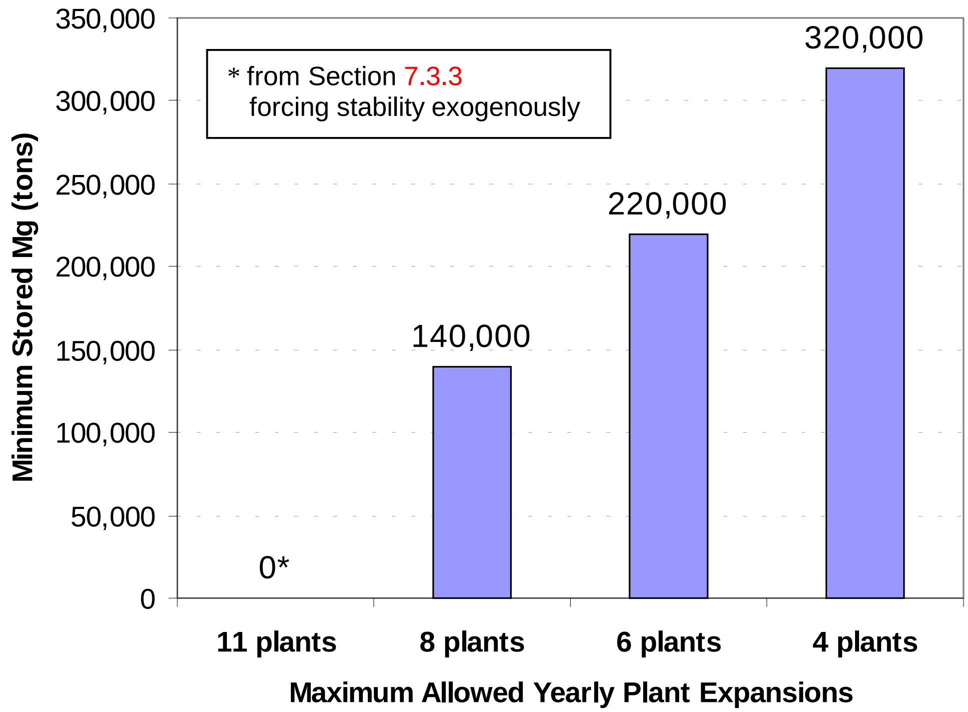

Figure 43: Demand Feedback Scenario 1 – Aggressive Supply Expansions: Minimum Required Material Storage after Limiting Yearly Supply Expansions

From the figure it is evident that any reduction in the maximum amount of yearly supply expansion will result in larger stores of material to maintain market stability. By limiting yearly expansions to six plants per year, stores of 220 k tons (investment ~$675 million), or 18% of yearly production, are required. Getting yearly maximum supply expansions to a more reasonable level, four facilities per year (or maybe 2-3 larger ones), pushes the required storage to immense levels near 320 k tons (investment ~$ 1 billion), or a quarter of industry yearly production. These examples show that getting the expansion plans down to reasonable levels requires ridiculous levels of stockpiling and associated financial resources. Storing this much material and investment for 3-5 years for the sole goal to maintain material availability and market stability is not likely a viable solution for the aggressive supply expansion scenario.

The initial insights from these runs indicate that the overly aggressive supply expansion scenario will not likely be solved by a demand-side feedback mechanism, like a stockpile or market-maker. Semi-reasonable levels of storage still require technically infeasible supply expansion plans, while more reasonable expansion plans require financially, and likely logistically, infeasible levels of material storage. Again, it appears if expansion of the magnesium supply base is pursued too quickly, the negative consequences of over-enthusiastic automotive demand will overcome even well thought out market damping devices.

A second scenario for the demand-side feedback mechanism was constructed to examine its applicability to a more moderate supply expansion scheme. This scenario accounted for the addition of all the near term plants in Australia and Congo, but continued exogenous expansions at a much slower pace during the period of simulated slow demand (2005-2010). This scenario was stabilized by the storage mechanism without huge stockpiles, nor extremely large expansion plans. The results are show in figures 43-45 below. Several similar runs of this moderate expansion scenario were run, limiting the purchase rate of material or capping the top level of material in the stock, but results were all very similar.

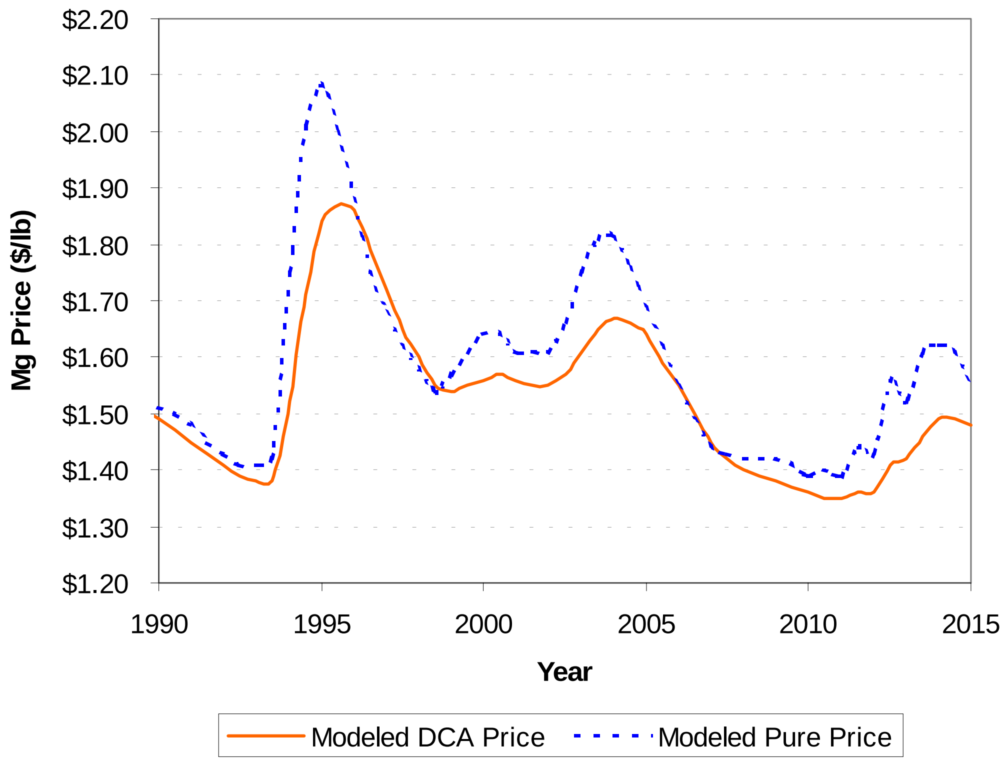

Figure 44: Demand Feedback Scenario 2 - Moderate Supply Expansions: Material Prices

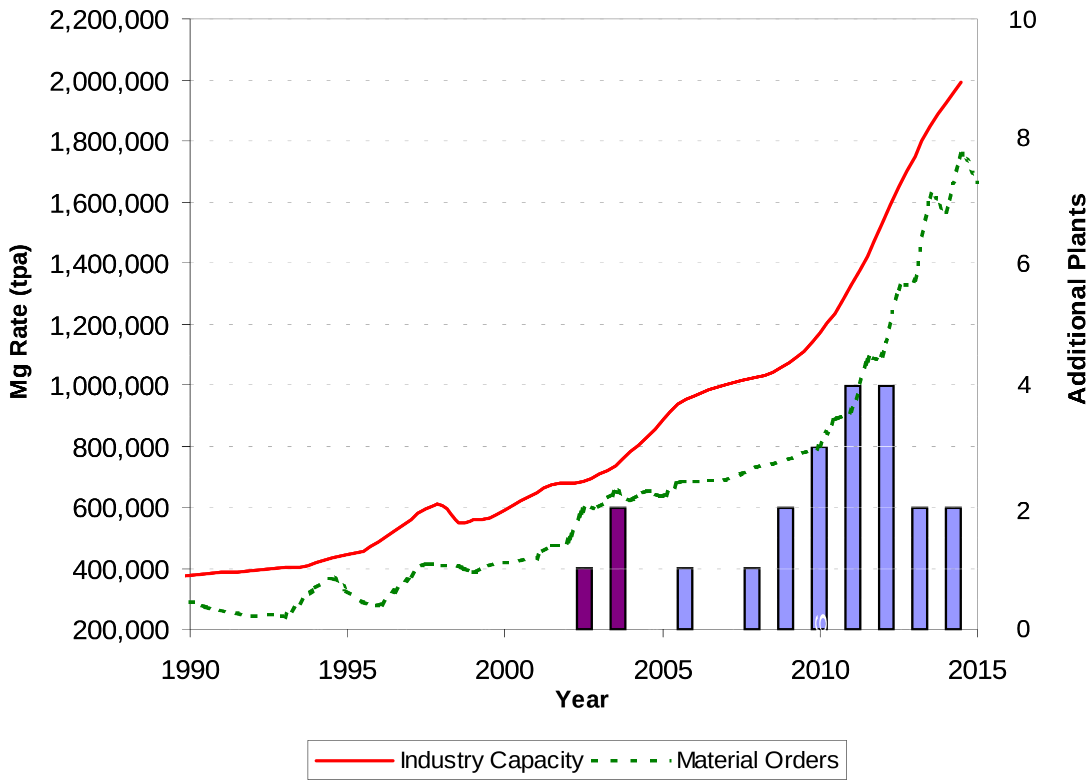

Figure 44: Demand Feedback Scenario 2 - Moderate Supply Expansions: Supply and Demand

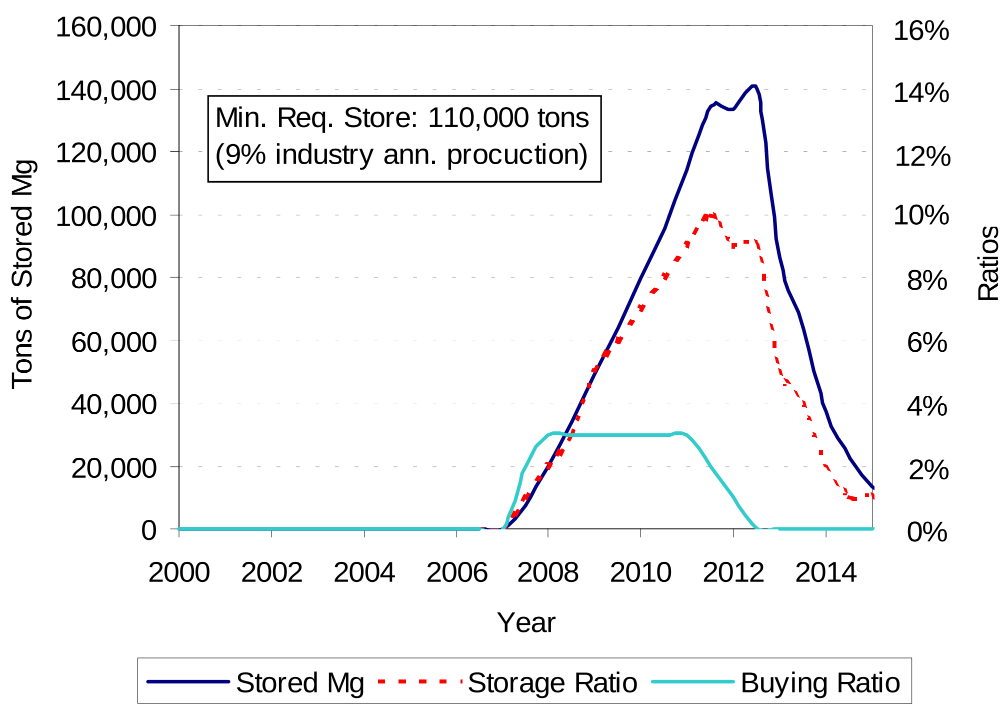

Figure 45: Demand Feedback Scenario 2 - Moderate Supply Expansions: Material Storage Profile

The general results from the runs of the moderately aggressive supply expansion scenario suggest that a moderately large stock pile coupled with reasonable expansion plans could be used to create a stable market price for magnesium in the \$1.40 - \$1.50 / lb range. Maximum yearly expansion rates can be kept at or below four plants per year. The required stored material to prevent extreme market swings ranged between 100,000 and 150,000 tons. The capital needed to generate this store at prices ~\$1.40/lb is still rather large, at \$300 - \$450 million, but this total cost could be reduced if several organizations, automakers or institutions share in the role of stockpiling magnesium. Though the size and cost of this store was the lowest obtained in the scenarios, getting the individual costs down into reasonable investments would likely be the greatest challenges.

The demand-side feedback scenarios continued to reinforce the ideas already discovered in the previous analyses. The small size of the supply base and the large potential for automotive demand dictate that expansions in the supply base must be initiated with a degree of restraint. Stocking up material in periods of low prices can help only slightly when facing the sheer volume of potential automotive demand. If the magnesium industry pursues rapid supply expansion a stockpiling of any reasonable size or investment will likely have little impact on the market. A moderately aggressive expansion scenario including all the expected near-term facilities in Australia and Congo, as well as a few other entrants in this decade, could be helped by a stockpiling mechanism on the order of 100 k tons of material. Having a pool of ~10 % of yearly industry production on hand could be a worthwhile insurance policy against price swings.

8 Magnesium Market Model Conclusions

From the analyses and scenarios that were performed with the magnesium market model it is easier to characterize the challenges that surround the future of the magnesium industry. Supply expansions are pursuing the potential automaker demand by providing low cost material. The entrance of low cost material producers, however, jeopardizes market stability by increasing the automakers' interest in the limited supply of magnesium. The volume of material that automakers could potentially demand at prices that fall substantially below current levels can easily surpass the capacity that any reasonable industry expansion plan could hope to create.

Because of these challenges two distinct methodologies were investigated to see if forward looking strategies on the supply and demand side of the market could help prevent the problems of wildly swinging market behavior. The supply-side strategies linked industry expansion plans directly to the expected increases in automaker demand for magnesium components. This yielded an improved market dynamic and eliminated the most violent swings in material price volatility. Even when challenged by falling prices, caused by exogenously controlled supply expansions representing likely near-term entrants, the automated expansion scheme was able to stabilize prices and demand by coordinating the appropriate new supply to satisfy growing auto demand. Despite its initial successes, however, the automated supply-side feedback scenarios left a few loose ends open to question.

The main concerns generated by the automated supply scenarios are linked directly to the degree of coordination that is necessary to successfully maintain market stability. First, the coordination between separate industries, the material suppliers and the automakers, would need to be nearly seamless. The magnesium suppliers would need perfect information about the future magnesium automotive designs. Any new applications of magnesium, or designs abandoning the material would need to be virtually broadcast to the suppliers as soon as the decisions were made. Information channels this transparent would essentially open up the design decision up to world-at-large, and could erase any competitive advantage the new magnesium design offers an automaker. While the likelihood of a transparent material design choice might be hard to fathom, the automakers are increasing their involvement in the magnesium supply base as is evident by Volkswagen’s investments in Dead Sea Works, Ford’s purchase of Queensland Metals Corporation and GM’s long term purchase contract with Norsk Hydro Magnesium. In these relationships it conceivable that the individual automakers might have enough influence on their supply partners to affect their supply expansion plans, but this only highlights the next coordination problem.

The amount of coordination between magnesium suppliers in the automated expansion scenarios would also need to be substantial. If the individual players in the magnesium supply industry all decide independently on their own expansion plans the effects could lead to increasing market instability. The analysis investigated the impact of individuals expanding the supply base independent of the automated mechanism. With each additional exogenous expansion, the mechanism was forced to deal with an increasingly volatile pricing and demand reaction. This illustrates the fact that a virtual supply cartel would need to be instituted to maintain market stability. Only with this much coordination, could the industry effectively prevent excessive expansions in times of weak demand and coordinate rapid capacity increases when demand strengthened. The last scenario of the automated supply feedback analysis, which includes the complete introduction of three near term facilities by 2004, displays the weakness of the coordinated expansion strategy to independent entrants. This final scenario shows that the introduction of too much supply when demand softens will flood the market with cheap material and require massive expansions later when automotive demand expands. Again the coordination required by the industry, as a synchronized unit, to prevent material shortfalls would need to be incredible. Could they industry pull off such harmonized behavior? It seems unlikely that established western producers, Israeli and Australian start-ups and notoriously independent producers in Russia and China would be able to completely harmonize their expansion plans to promote the market stability necessary for stable demand growth.

The most aggressive near-term expansion plan highlighted the inability of the completely coordinated supply expansion strategy to create a complete solution to the problems of low prices and oversupply. A second method of demand-side coordination was investigated as a possible solution to the problem. The concept was to store low price material during times of low prices and weak demand for release when prices and demand rise in a market-making device. The mechanism propped up prices during oversupply periods and lowered the need for expansions when automotive demand expanded. From the perspective of stable market dynamics, the mechanism was able to control the most aggressive expansion plans in the near and medium term. Prices were stabilized in the \$1.40-\$1.50 / lb range and demand was kept within the limits of the industry capacity. From a financial and industry planning point-of-view, however, the solution seemed unlikely. The aggressive expansion solution had one of two possible weaknesses, either the size of the magnesium store became too large of an investment or the scope of the supply expansions necessary to maintain market stability were too large to be realistic. When the size of the magnesium store was restricted to reasonable levels on the order of 100 k tons, or roughly 10% of industry capacity, heroic expansion plans were necessary to keep up with demand. Conversely, if expansion plans were capped to an optimistic, but technically possible, four plants per year, magnesium stores of over 300 k tons (nearly 25% of industry capacity, costing nearly $1 billion in investment) were necessary. A combination of smaller stores (~100 k ton or ~ $300-400 million in investment) and smaller plant expansions (maximum 4 plants per year) was only possible if the near and medium-term expansions were more restrained. In the final run of the demand-side scenario, only the three near term plants and a few other expansions (single plants in alternating years) were included in the expansion plans for the current decade. While this was a slightly more aggressive scenario than those recommended in the coordinated-supply feedback analysis, it yielded similar market stability.

The results from the two feedback scenarios teach several lessons. First, more coordination between automakers and magnesium suppliers, and even amongst the supply community, could be very useful to promoting market stability. The seeds of this coordination are already apparent in increased automaker involvement magnesium supply ventures discussed previously. The true challenge in the market will be with coordination of supply among the material providers. Several possible questions arise from these challenges. What is to prevent the Chinese from expanding production and flooding the market with low cost material? What would stop several Australian projects from ramping-up simultaneously? Why would the supply industry plan for any supply expansion after periods of low material prices? Why would producers of material not plan expansions of their current facilities? The technical, financial and political challenges of the coordinated supply scenario seem to almost overshadow its possible benefits.

This leads to the second conclusion, if a rapid of influx of low priced material is inevitable due to a fractured supply base, it could be wise to store some material for future use. Whether this storage is done via a market-making financial organization or individual automaker stockpiles, it could be wise to have ~100 k tons of material in reserve as an insurance policy against rapid increases in automaker demand. A store of this size is no guarantee of market stability when faced with the most violent demand spikes, but could offer stability in some borderline cases. At a cost of over $300 million, stockpiling material may appear an awfully expensive investment with little return (actually found to be of 2% per year via IRR calculations), but when compared to paying upwards of $2 / lb for tons of magnesium auto components, it could prove invaluable.

Due to the negative price effects and correlated spikes in automotive demand, however, supply-demand coordination and investment in reserve material could prove to be ineffective if of rapid supply expansions are done haphazardly. This fact leads directly the study's final conclusion, maintaining more reserved expansion plans for the magnesium industry appears to lead to much safer and more stable market dynamics. Pushing magnesium market prices below \$1.40 / lb often resulted in wild spikes in automotive demand followed by material shortages and higher prices. This netted the industry no gains in the long term as automakers rapidly abandoned magnesium designs. Expanding the supply base slowly and maintaining market prices slightly above \$1.40 / lb, however, led to more stable demand and supply growth. At the end of these less aggressive expansion scenarios respectable gains for magnesium in auto design, ranging from 20 to 80 lb per vehicle (from ~10 lb today), can be obtained. It seems better to be more reserved in capacity planning and bank on slow, steady growth, than loose it all on an aggressive expansion gamble.

9 Future Work in Magnesium Market Modeling

The magnesium market model was a very useful tool for investigating the challenges facing a small, rapidly maturing material market. While the insights gained were valuable for thinking about the future of the market, all academic studies and models can be improved and expanded. Any future work in the magnesium market modeling effort should be pursued via two avenues, either improving the system dynamics model itself, or continuing the analysis of the magnesium market with additional scenario studies.

Additional data and model mechanisms could always be incorporated into the simulation model. Additional data on magnesium usage that is continually being evaluated would strengthen the evolutionary demand trends, as would additional economic data. A few areas that could incorporate additional effort include gathering additional automotive design data, re-evaluations of the simplifying assumptions used in the model and examining some of the smaller players and demand sectors in the model. Additional interviews with automotive engineers that are involved in the material section process, especially in Europe, could be used to improve, refine and validate the assumptions used to trigger the revolutionary magnesium demand models. Any new data on future magnesium designs, component masses and changing design preferences targeting mass reduction should be included in the model in order to accurately reflect the state of automotive magnesium demand. Continued monitoring of material use trends areas of small impact, like the Asian automotive industry, the chemical industry or titanium, may be useful as well. Keeping track of the trends in these small sectors will either validate their minor role in the current version of the model or alert researchers to increasing interest if new trends emerge. In a similar vein, an in-depth examination of die cast magnesium usage in non-automotive applications of magnesium in consumer electronics could reveal additional insights. The current treatment of this smaller portion of non-automotive die-casting is overshadowed by the rapid deployment and huge volumes of automotive demand, but could become important if magnesium begins to play a larger role in laptop computers, personal digital assistants and cellular phones. Study of the evolving magnesium supply base should be continued. Incorporating emerging potential supply projects and removing those facilities and plans that fail to be financial viable will create a better picture of the operating and potential future supply curve. Observing the future pricing trends in the market will also be of value. This will ensure that the operating margin and volatility assumptions incorporated into the pricing model remain up to date. These standard maintenance and improvement efforts will ensure that the model remains relevant and accurate to the actual dynamics of the world magnesium market.

Beyond improving and maintaining the model, the scope of the magnesium market studies could be extended to many more analyses and scenarios than are described in this document. Due to limited time and space this document only addressed a few of the possible market scenarios and stability strategies that were possible. Scenarios investigating the impact of changes to the base data and assumptions in the model could provide many more insights into possible futures for the magnesium industry. Altering the evolutionary demand trends could simulate the effects of greater or lower competition over material resources. Incorporating feedback systems linking other material prices to fluctuations in magnesium price could introduce the effects of material application completion into the revolutionary demand model. General sensitivity analysis centered on the revolutionary demand triggers assumptions could also reveal how future market dynamic simulations would change given small changes in magnesium price triggers, required price stability times, magnesium component introduction rates and vehicle volumes. Any additional insights into the possible future of the magnesium market would add to and strengthen the results already obtained.

10 Appendices

APPENDIX A: Econometric Curve-Fits For Magnesium Demand Sectors

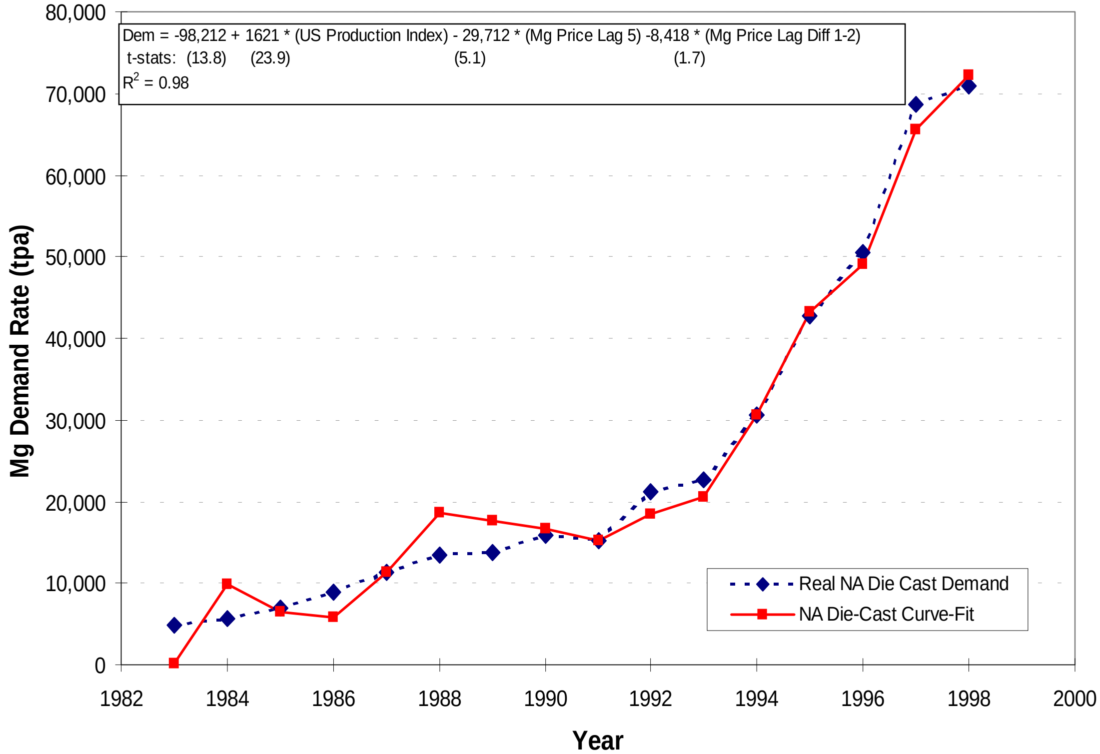

Figure A-1: North American Die-Cast Mg Demand and Econometric Curve-Fit

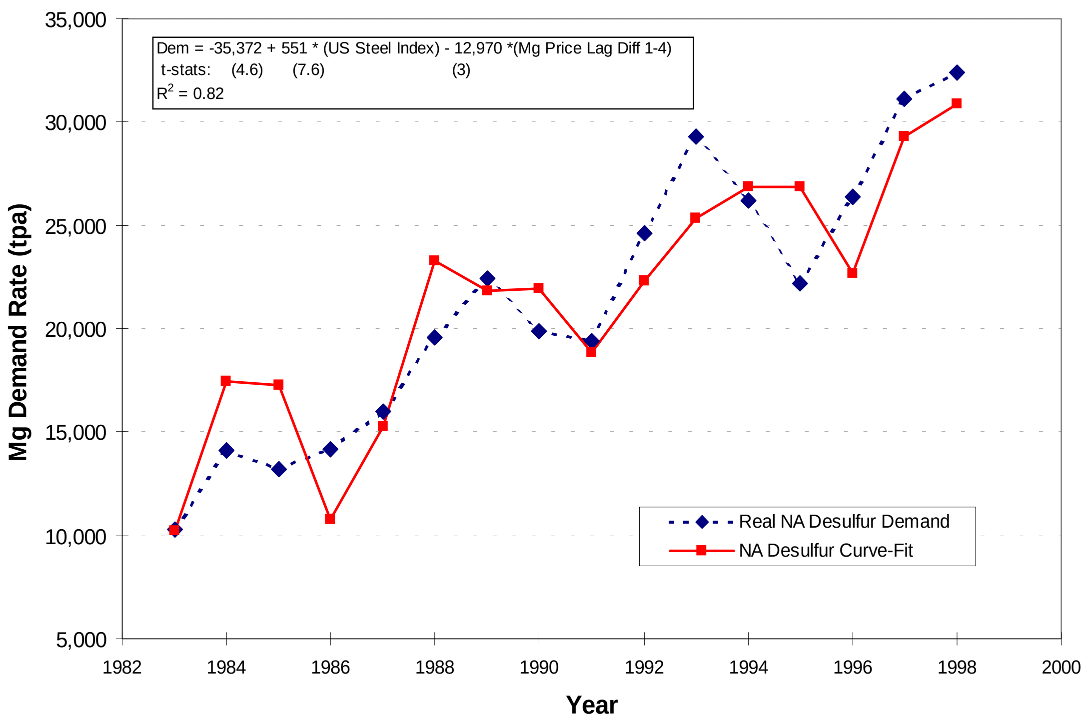

Figure A-2: North American Steel Desulfurization Mg Demand and Econometric Curve-Fit

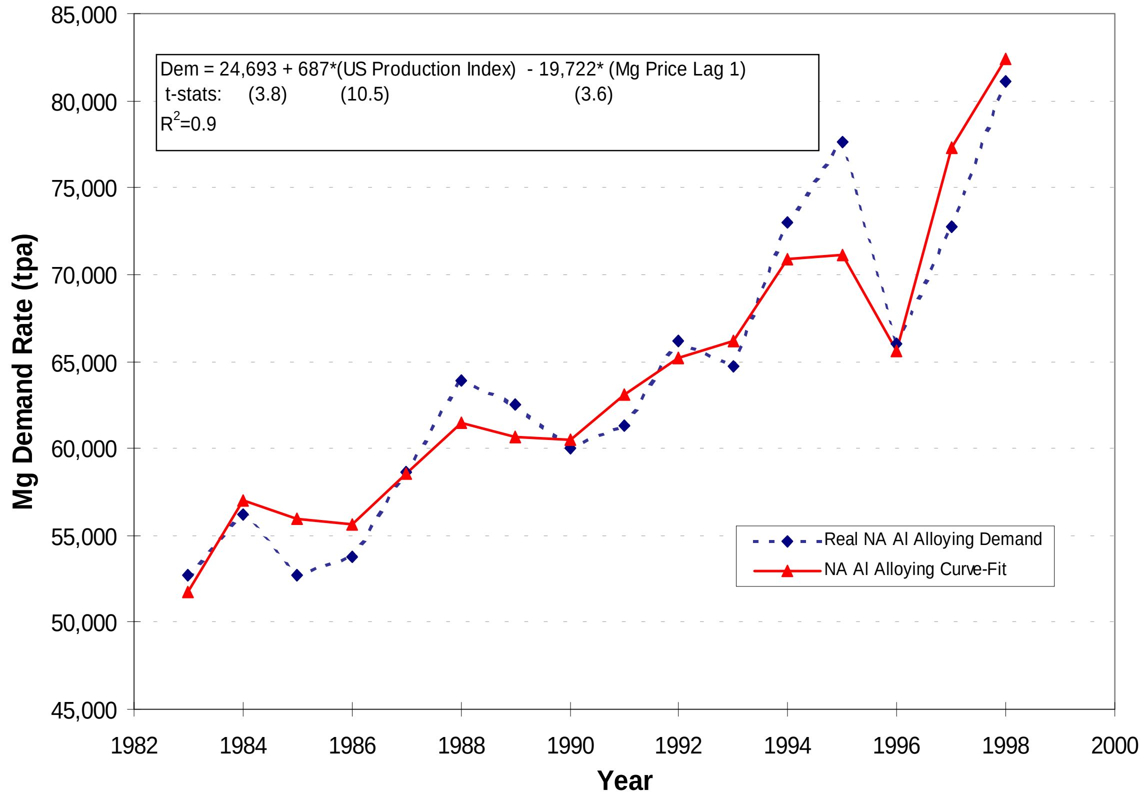

Figure A-3: North American Aluminum Alloying Mg Demand and Econometric Curve-Fit

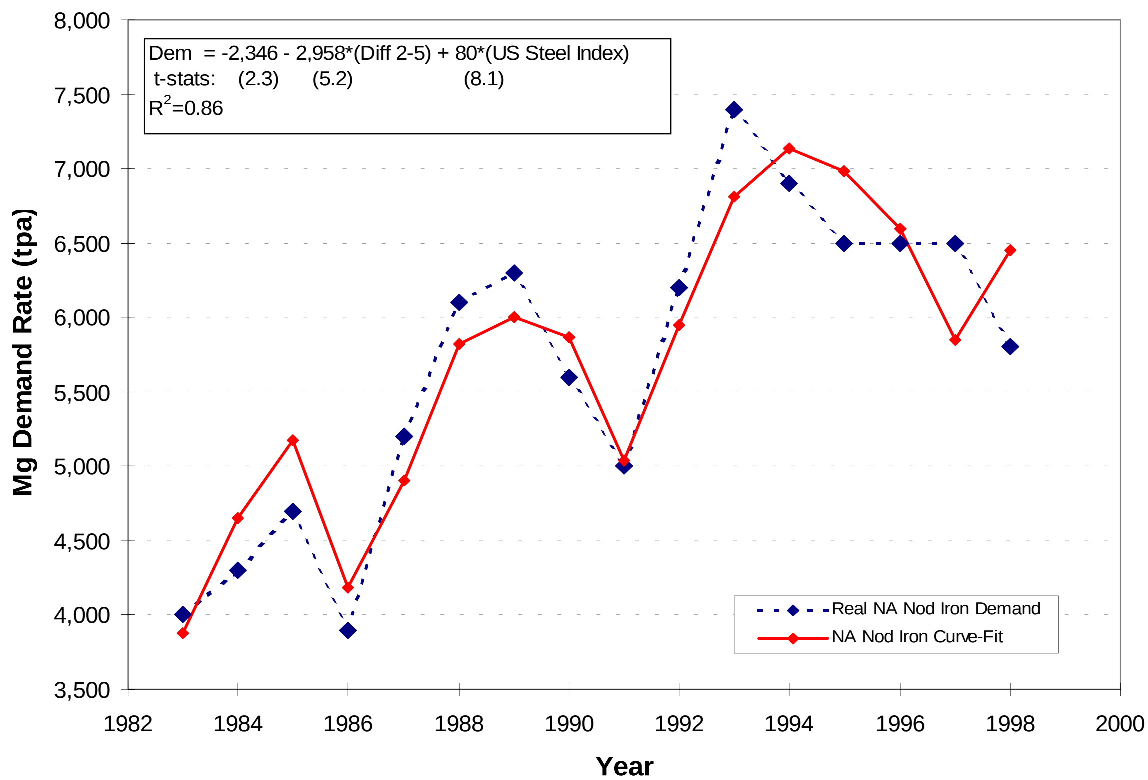

Figure A-4: North American Nodular Iron Mg Demand and Econometric Curve-Fit

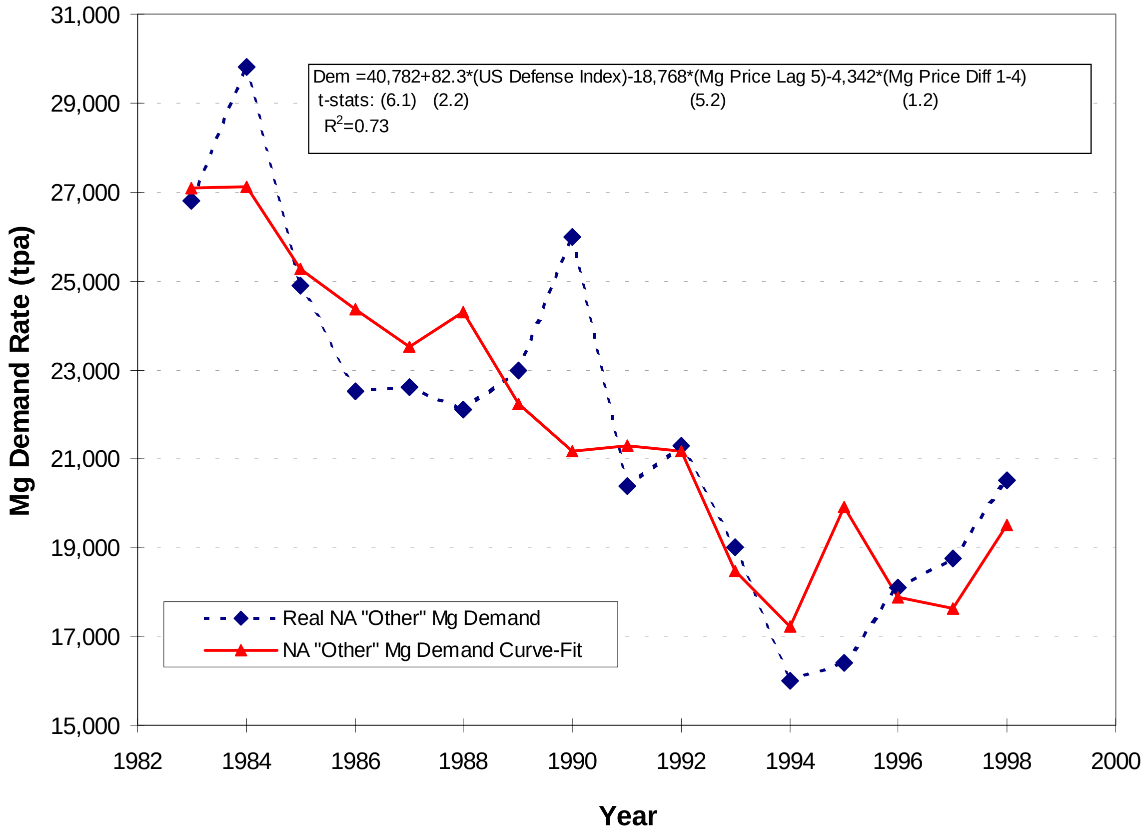

Figure A-5: North American "Other" Mg Demand and Econometric Curve-Fit

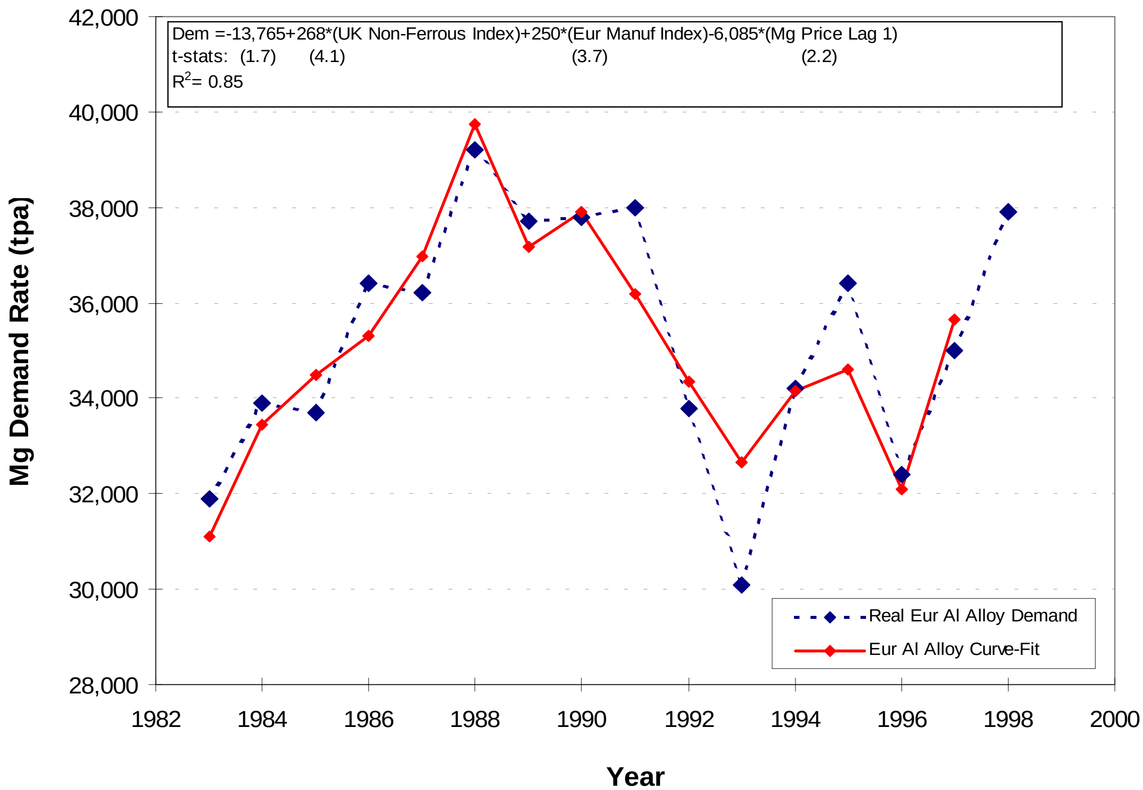

Figure A-6: European Aluminum Alloying Mg Demand and Econometric Curve-Fit

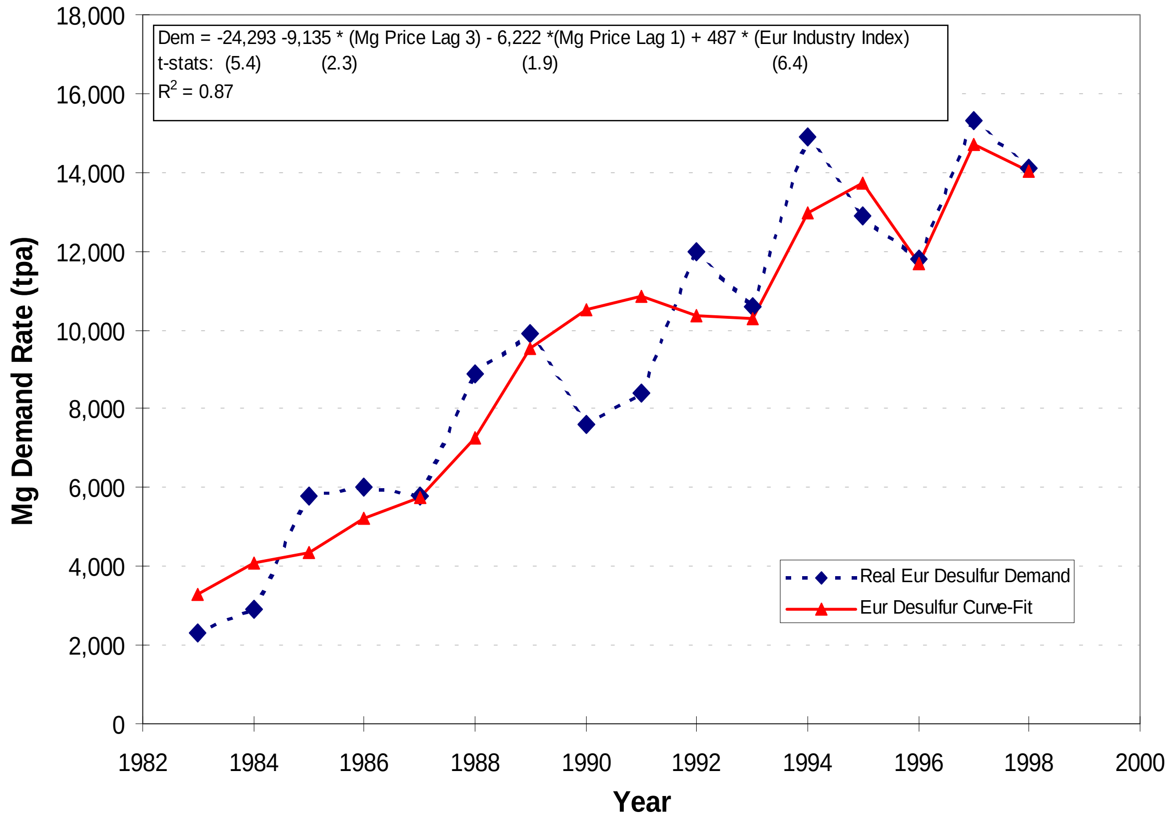

Figure A-7: European Steel Desulfurization Mg Demand and Econometric Curve-Fit

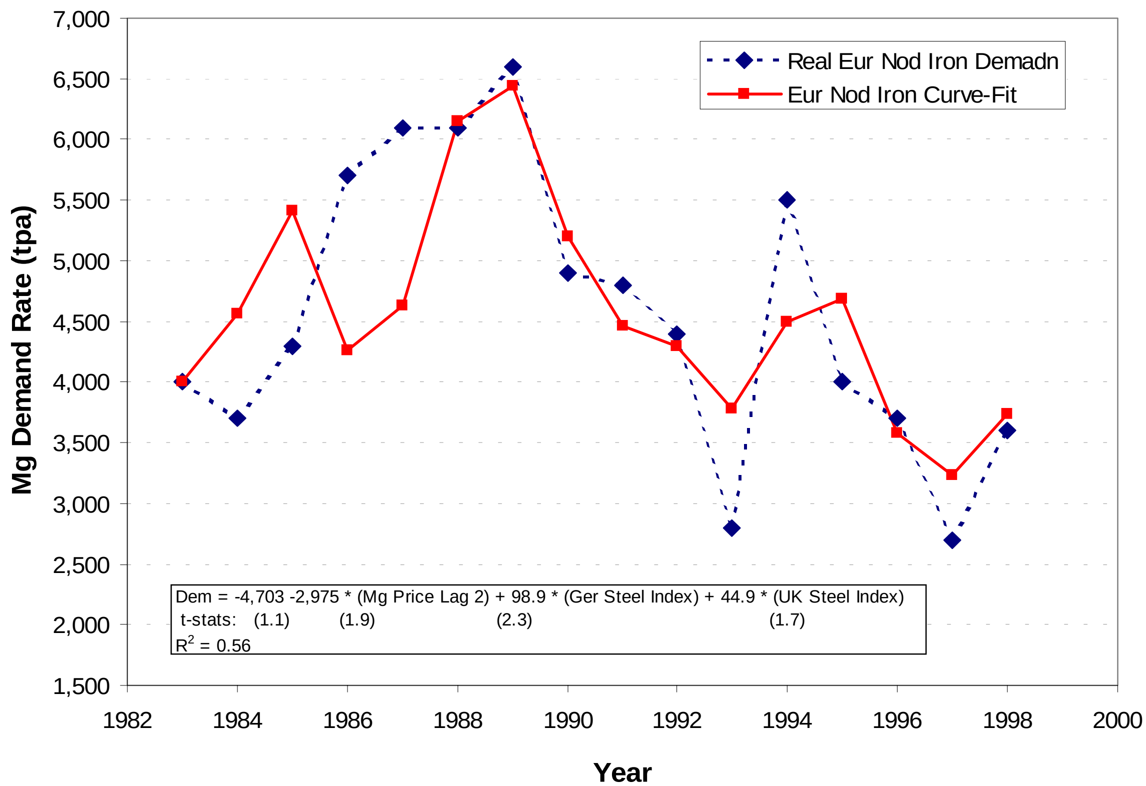

Figure A-8: European Nodular Iron Mg Demand and Econometric Curve-Fit

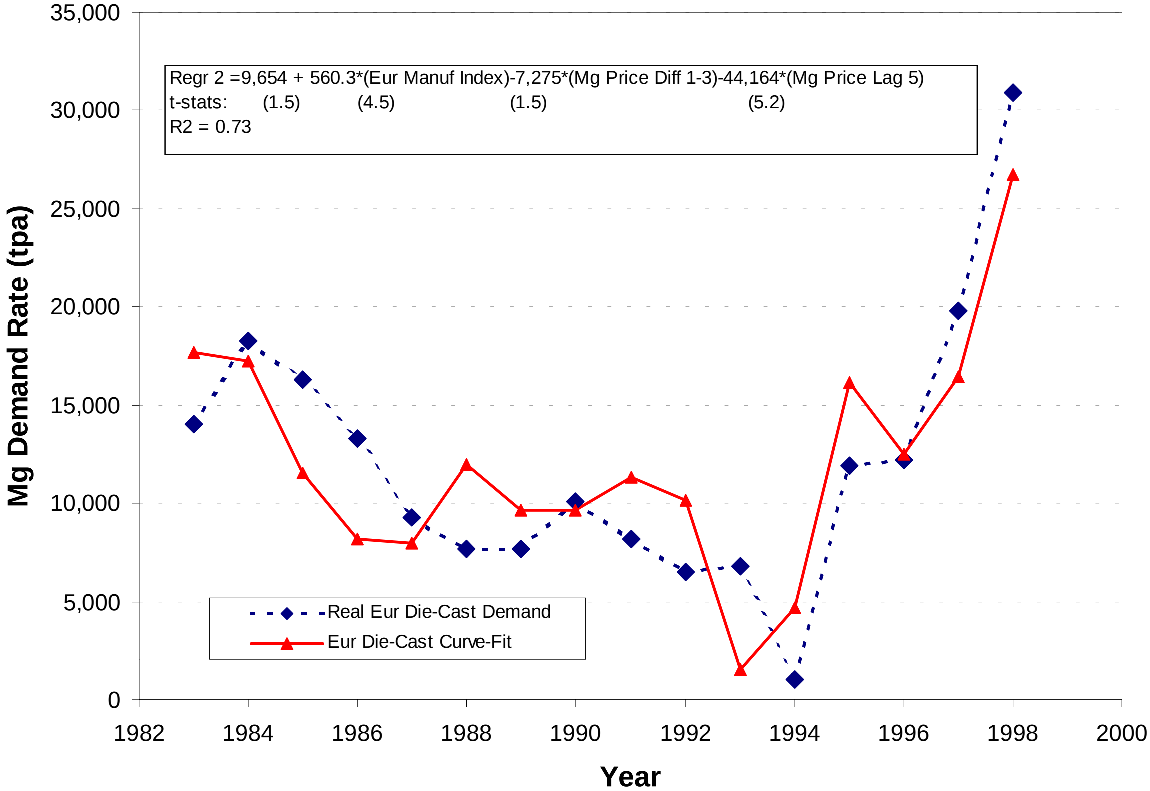

Figure A-9: European Die-Cast Mg Demand and Econometric Curve-Fit

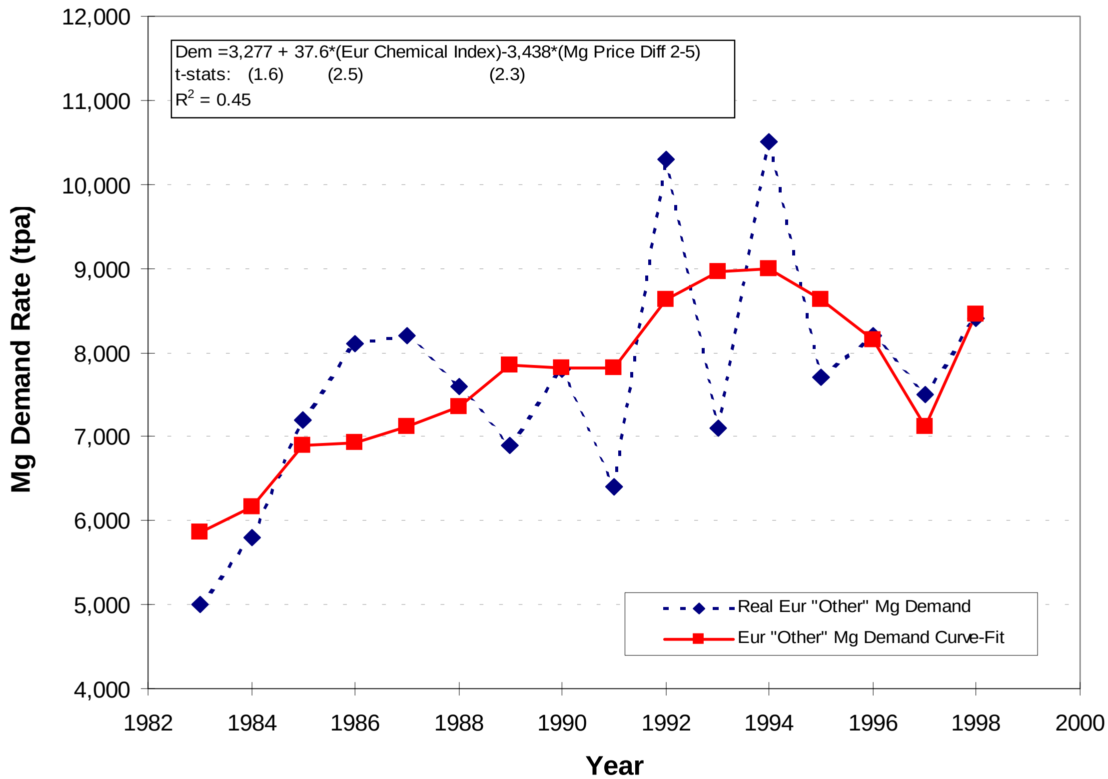

Figure A-10: European “Other” Mg Demand and Econometric Curve-Fit

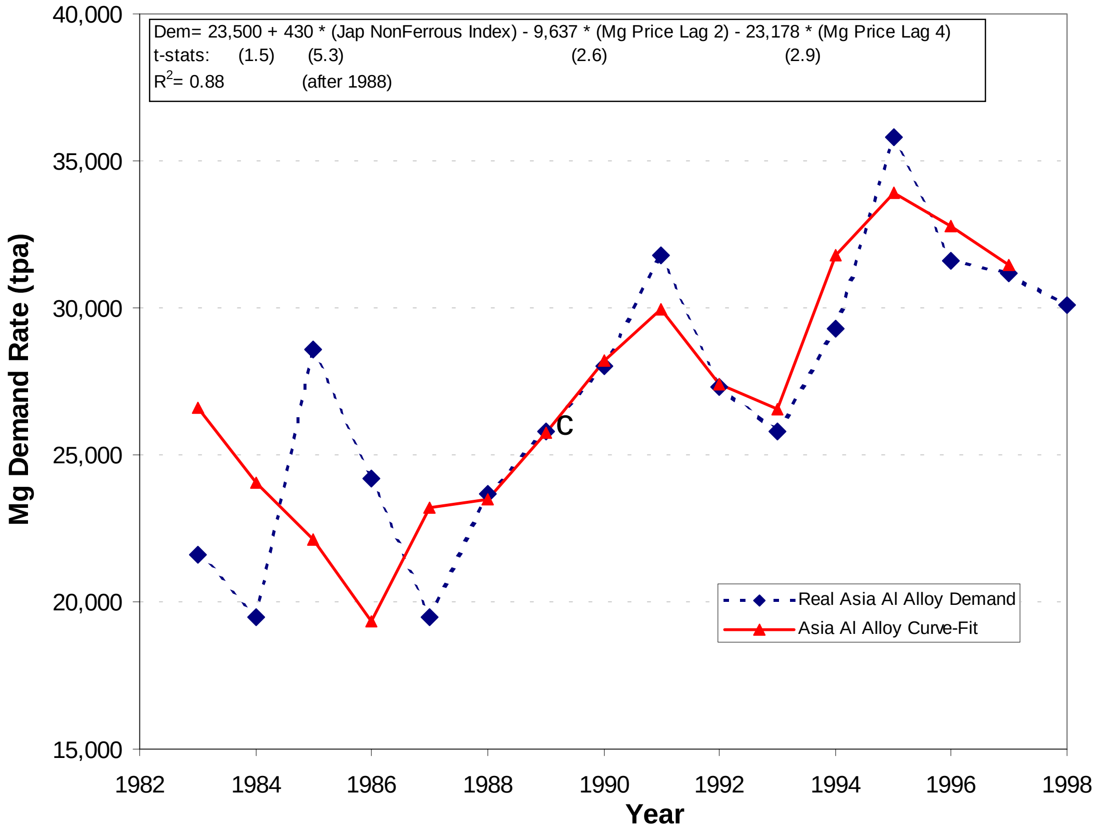

Figure A-11: Asian Aluminum Alloying Mg Demand and Econometric Curve-Fit

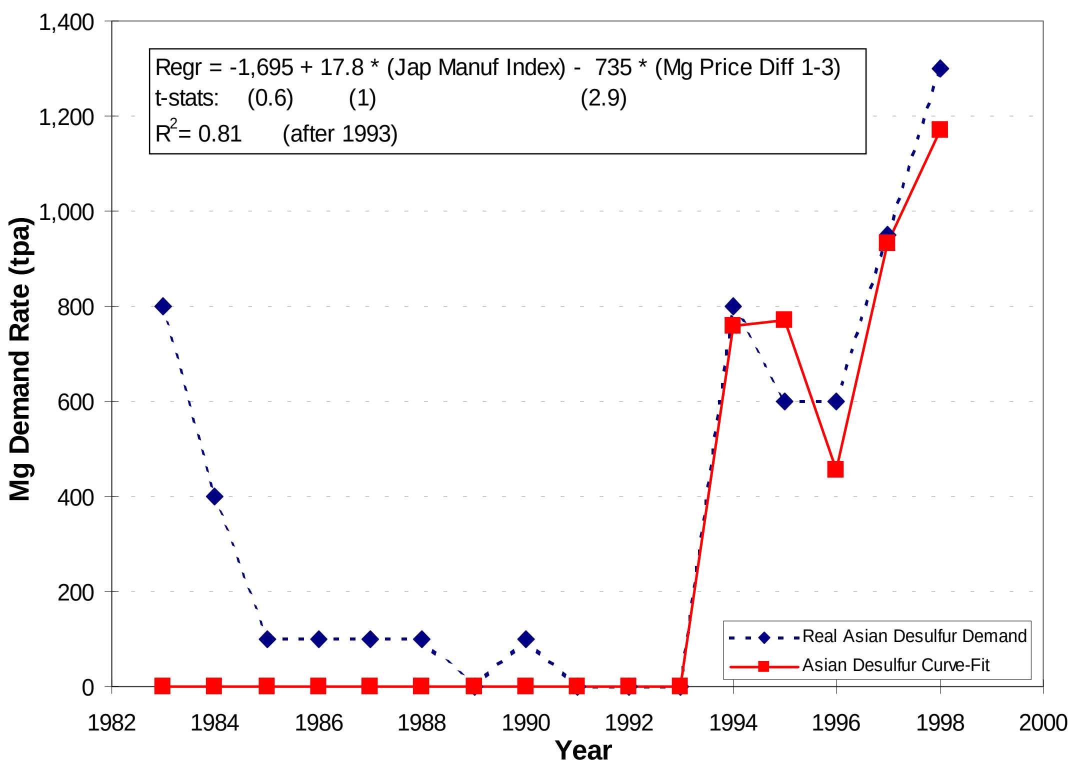

Figure A-12: Asian Aluminum Alloying Mg Demand and Econometric Curve-Fit

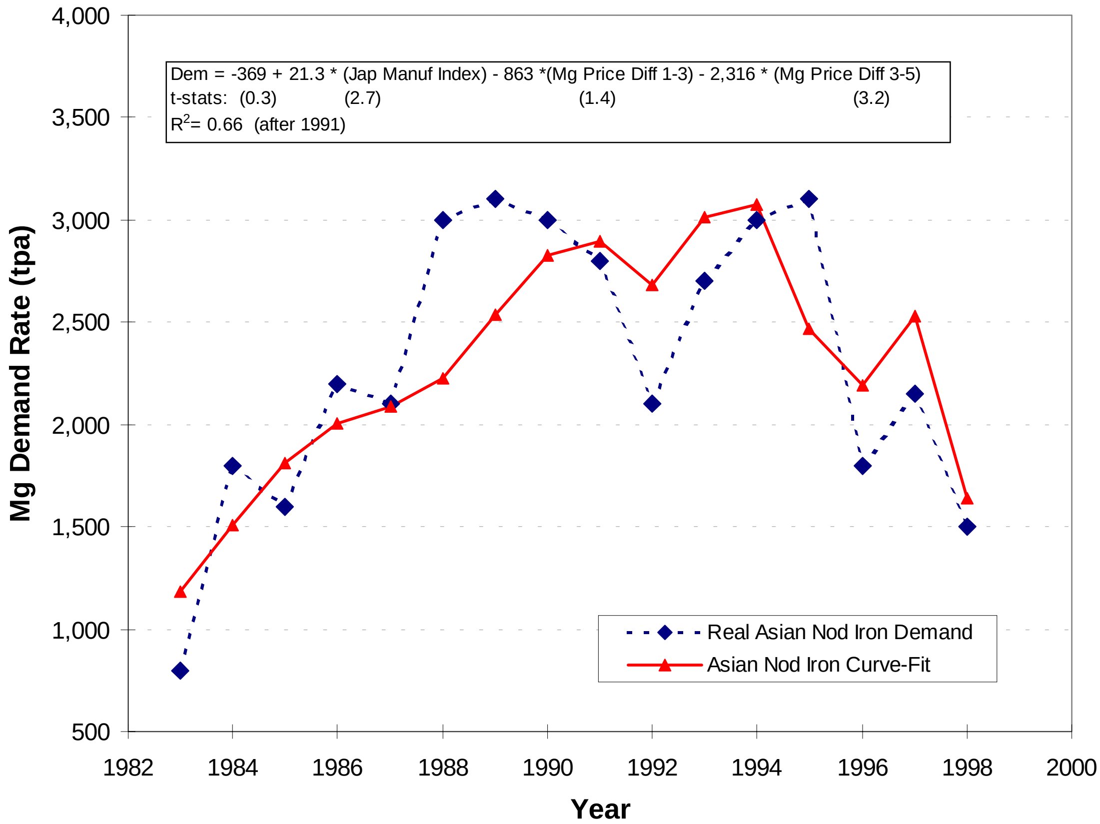

Figure A-13: Asian Nodular Iron Mg Demand and Econometric Curve-Fit

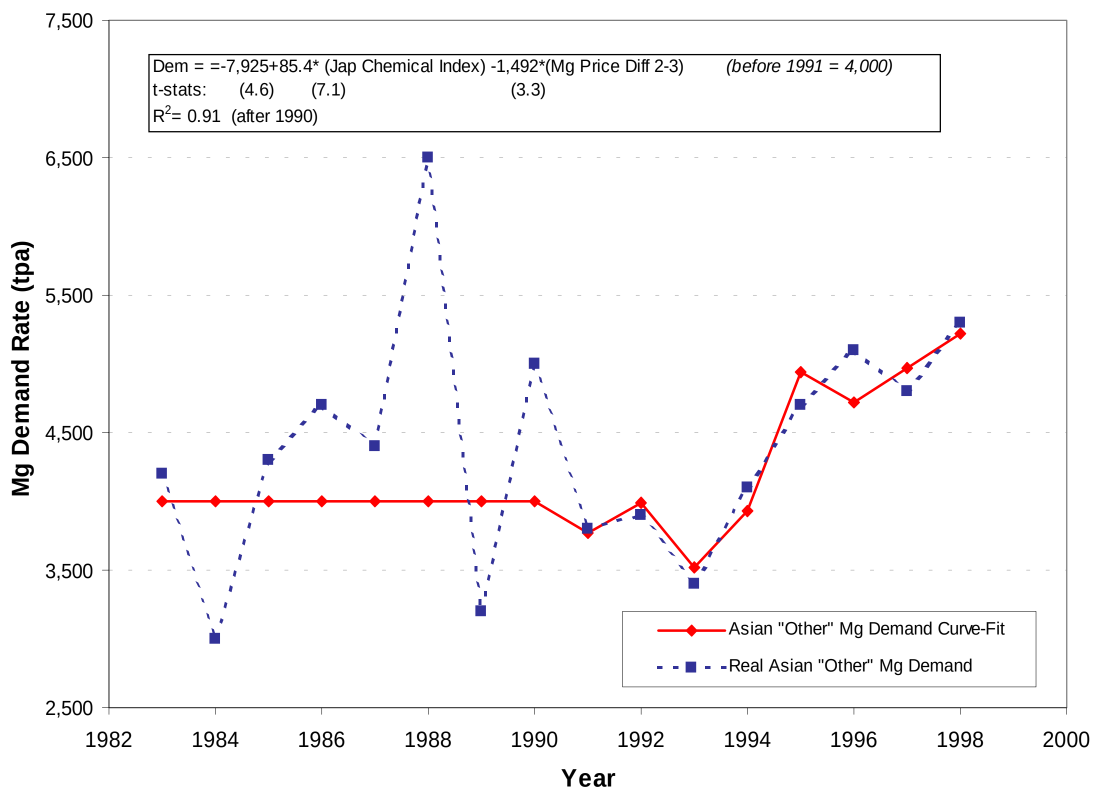

Figure A-14: Asian "Other" Mg Demand and Econometric Curve-Fit

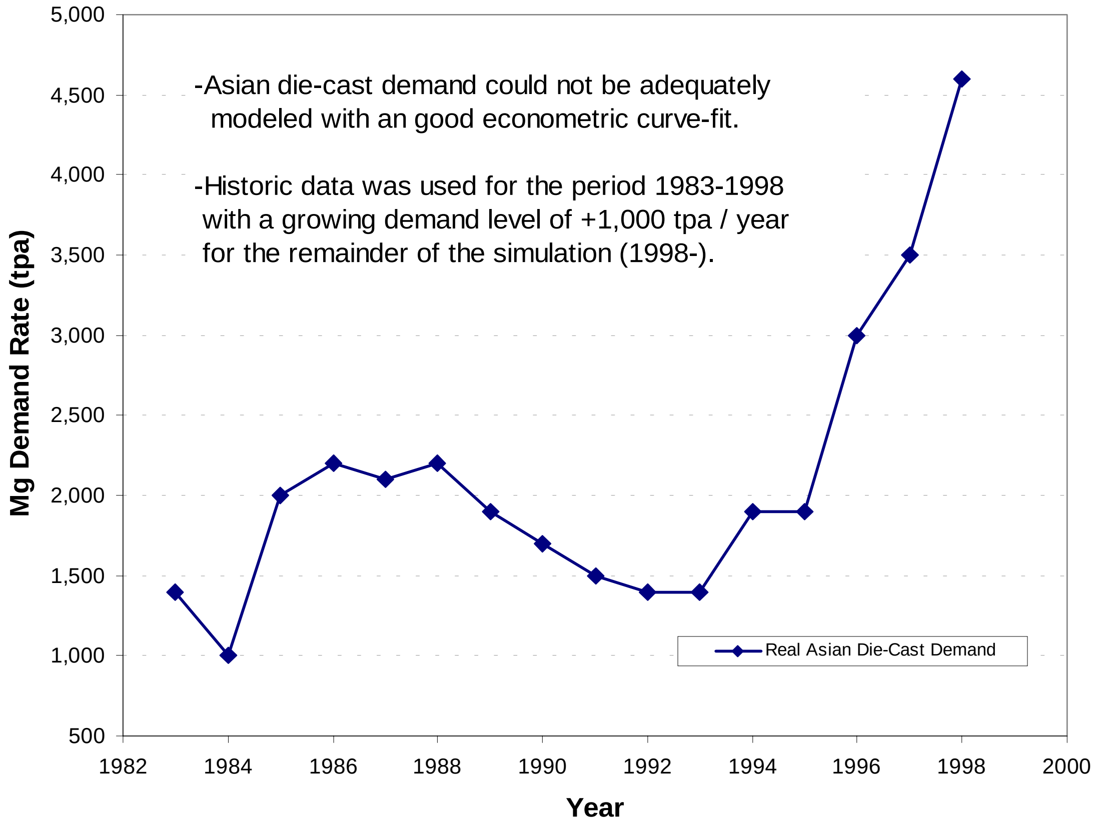

Figure A-15: Asian Die-Cast Mg Demand and Econometric Curve-Fit

APPENDIX B: Revolutionary Magnesium Demand / Automotive Demand Triggers,

Magnesium Auto Component Introduction Triggers (also including component mass assumptions)

Given Current Material Prices						
Current Mg Die Cast Alloy Price	$ 1.50	to	$ 1.60	per pound	from Norsk Hydro
Current Al Alloy Price	$ 0.80	to	$ 0.90	per pound	
Current Steel Sheet Price	$ 0.30	to	$ 0.35	per pound	
Current Nylon Price	$ 1.00	to	$ 1.40	per pound	
Current SMC	$ 0.90	to	$ 1.10	per pound	

Competing Material Color Code
Aluminum
Polymer
Iron
Steel

Mg Price to Substitute In Mg

BRACKETS (Mass ~2lb each)		Small Car	Medium Car	Large Car	Small Truck	Med Truck	Large Truck	Specialty
Alternator Bracket	Al to Mg	$ 1.35	$ 1.40	$ 1.45	$ 1.35	$ 1.40	$ 1.45	$ 1.45
Valve Cover	Poly to Mg	$ 1.35	$ 1.40	$ 1.45	$ 1.35	$ 1.40	$ 1.45	$ 1.45
Side Mirror Housing	Poly							
Seat Headrest	Steel to Mg	$ 1.35	$ 1.40	$ 1.45	$ 1.35	$ 1.40	$ 1.45	$ 1.45
Airbag Housing	Steel							
Armrest Insert	Steel	*Roughly 5 Aluminum Substitutable Brackets per Vehicle*						
Gear Shift Bracket	Steel	*Roughly 5 Polymer Substitutable Brackets per Vehicle*						
Lock Housing	Steel	*Roughly 10 Steel Substitutable Brackets per Vehicle*						
Parking Brake Handle	Steel							
Pedal Bracket	Steel							
Steering Column Braket	Steel							
Steering Pump Bracket	Steel							
Steering Wheel	Steel							

Mg Price to Substitute In Mg

Power Train			Small Car	Medium Car	Large Car	Small Truck	Med Truck	Large Truck	Specialty
auto	Auto Trans	Al to Mg	$ 1.00	$ 1.05	$ 1.10	$ 1.00	$ 1.05	$ 1.10	$ 1.15
	mg weight (lb)		45	50	50	**45**	**55**	**60**	50
manual	Man Trans	Al to Mg	$ 1.00	$ 1.05		$ 1.00	$ 1.05	$ 1.10	$ 1.15
	mg weight (lb)		20	20	**?**	**20**	**25**	**25**	21
tranfer case	Transfer Case	Al to Mg				$ 1.30	$ 1.35	$ 1.40	
	mg weight (lb)					**11**	**13**	**15**	**?**
engine block	Engine	Al to Mg	$ 1.00	$ 1.05	$ 1.10	$ 1.00	$ 1.05	$ 1.10	$ 1.15
	mg weight (lb)		**20**	**26**	**32**	**26**	**34**	**40**	**34**
intake manifold	Intake	Poly to Mg	$ 1.20	$ 1.25	$ 1.30	$ 1.20	$ 1.25	$ 1.30	$ 1.30
	mg weight (lb)		3.5	5	6	3.5	5	6	6
oil pan	Oil Pan	Al to Mg	$ 1.25	$ 1.30	$ 1.35	$ 1.25	$ 1.30	$ 1.35	$ 1.35
	mg weight (lb)		6	7	7	7	7	8	8
engine cover	Eng Cover	Al to Mg	$ 1.25	$ 1.30	$ 1.35	$ 1.25	$ 1.30	$ 1.35	$ 1.35
	mg weight (lb)		3	4	5	3	5	6	6

Wheels			Small Car	Medium Car	Large Car	Small Truck	Med Truck	Large Truck	Specialty
Road	Road Wheels	Al to Mg	$ 1.10	$ 1.15	$ 1.20	$ 1.10	$ 1.15	$ 1.20	$ 1.40
	mg weight (lb)		48	60	60	55	65	75	60
Spare	Spare	Steel to Mg	$ 1.15	$ 1.20	$ 1.25	$ 1.15	$ 1.20	$ 1.25	$ 1.40
	mg weight (lb)		10	12	12	11	13	15	13

Chasis and Susp			Small Car	Medium Car	Large Car	Small Truck	Med Truck	Large Truck	Specialty
susp arm	Suspension Arm	Iron to Mg	$ 1.05	$ 1.10	$ 1.15	$ 1.05	$ 1.10	$ 1.15	$ 1.25
	mg weight (lb)		**5**	6	7	**6**	**8**	**10**	7
			20	**24**	**28**	**24**	**32**	**20**	**28**
Steering Rack	Steering Rack	Al to Mg	$ 1.05	$ 1.10	$ 1.15	$ 1.05	$ 1.10	$ 1.15	$ 1.25
	mg weight (lb)		13	13	13	**14**	**14**	**14**	13
Engine Cradle	Eng Cradle	Steel to Mg	$ 1.05	$ 1.10	$ 1.15	$ 1.05	$ 1.10	$ 1.15	$ 1.25
	mg weight (lb)		**22**	**24**	**28**	**24**	**30**	**32**	**28**

Closures Inners			Small Car	Medium Car	Large Car	Small Truck	Med Truck	Large Truck	Specialty
Door Inner	Doors	Steel to Mg	$ 1.10	$ 1.15	$ 1.20	$ 1.10	$ 1.15	$ 1.20	$ 1.30
	mg weight (lb)		8	10	12	11	13	15	13
			32	**40**	**48**	**44**	**39**	**45**	**26**
Hood Inner	Hood	Steel to Mg	$ 1.15	$ 1.20	$ 1.25	$ 1.15	$ 1.20	$ 1.25	$ 1.30
	mg weight (lb)		**12**	**14**	**16**	**14**	**16**	**18**	**16**
Rear Inner	Rear	Steel to Mg	$ 1.10	$ 1.15	$ 1.20	$ 1.10	$ 1.15	$ 1.20	$ 1.30
	mg weight (lb)		**12**	**14**	**16**	**14**	**16**	**18**	**16**

Body Applications			Small Car	Medium Car	Large Car	Small Truck	Med Truck	Large Truck	Specialty
Front End Beam	Front End Beam	Steel to Mg	$ 1.15	$ 1.20	$ 1.25	$ 1.25	$ 1.30	$ 1.35	$ 1.40
	mg weight (lb)		10	12	14	12	14	16	14
IP Beam	IP Cross Member	Steel to Mg	$ 1.25	$ 1.45	$ 1.55	$ 1.30	$ 1.40	$ 1.50	$ 1.55
	mg weight (lb)		10	12	14	12	14	16	14
Rear Cross Member	Rear Cross Member	Steel to Mg	$ 1.20	$ 1.25	$ 1.30				$ 1.35
	mg weight (lb)		10	12	14				14
Pillars	Side Pillars	Steel to Mg	$ 1.10	$ 1.15	$ 1.20	$ 1.10	$ 1.15	$ 1.20	$ 1.20
	mg weight (lb)		**11**	**13**	**15**	**13**	**15**	**17**	**15**
Sun Roof / Targa	Sun / Targa Roof	Steel to Mg	$ 1.15	$ 1.20	$ 1.30	$ 1.15	$ 1.20	$ 1.30	$ 1.40
	mg weight (lb)		**8**	**9**	**10**	**8**	**9**	**10**	**15**

Seats			Small Car	Medium Car	Large Car	Small Truck	Med Truck	Large Truck	Specialty
Seat Base	Seat Base	Steel to Mg	$ 1.20	$ 1.25	$ 1.30	$ 1.20	$ 1.25	$ 1.30	$ 1.30
	mg weight (lb)		8	8	9	8	8	9.5	8
Seat Riser	Seat Riser	Steel to Mg	$ 1.20	$ 1.25	$ 1.30	$ 1.20	$ 1.25	$ 1.30	$ 1.30
	mg weight (lb)		7	7	7	7	7	8	7
Seat Back	Seat Back	Steel to Mg	$ 1.20	$ 1.25	$ 1.30	$ 1.20	$ 1.25	$ 1.30	$ 1.30
	mg weight (lb)		**7**	**7**	**8**	**7**	**7**	**8**	**7**

Magnesium Auto Component Removal Triggers

Given Material Prices						
Current Mg Die Cast Alloy Price	$ 1.50	to	$ 1.60	per pound	from Norsk Hydro
Current Al Alloy Price	$ 0.80	to	$ 0.90	per pound	
Current Steel Sheet Price	$ 0.30	to	$ 0.35	per pound	
Current Nylon Price	$ 1.00	to	$ 1.40	per pound	
Current SMC	$ 0.90	to	$ 1.10	per pound	

Competing Material Code Color
Aluminum
Polymer
Iron
Steel

Mg Price to Substitute OUT Mg

BRACKETS (Mass ~2lb each)		Small Car	Medium Car	Large Car	Small Truck	Med Truck	Large Truck	Specialty
Alternator Bracket	Al to Mg	$ 1.49	$ 1.54	$ 1.60	$ 1.49	$ 1.54	$ 1.60	$ 1.60
Valve Cover	Poly to Mg	$ 1.49	$ 1.54	$ 1.60	$ 1.49	$ 1.54	$ 1.60	$ 1.60
Side Mirror Housing	Poly							
Seat Headrest	Steel to Mg	$ 1.49	$ 1.54	$ 1.60	$ 1.49	$ 1.54	$ 1.60	$ 1.60
Airbag Housing	Steel							
Armrest Insert	Steel							
Gear Shift Bracket	Steel							
Lock Housing	Steel							
Parking Brake Handle	Steel							
Pedal Bracket	Steel							
Steering Column Braket	Steel							
Steering Pump Bracket	Steel							
Steering Wheel	Steel							

Mg Price to Substitute OUT Mg

Power Train			Small Car	Medium Car	Large Car	Small Truck	Med Truck	Large Truck	Specialty
auto	Auto Trans	Al	$ 1.07	$ 1.12	$ 1.18	$ 1.07	$ 1.12	$ 1.18	$ 1.23
manual	Man Trans	Al	$ 1.07	$ 1.12		$ 1.07	$ 1.12	$ 1.18	$ 1.23
tranfer case	Transfer Case	Al				$ 1.43	$ 1.49	$ 1.54	
engine block	Engine	Al	$ 1.07	$ 1.12	$ 1.18	$ 1.07	$ 1.12	$ 1.18	$ 1.23
intake manifold	Intake	Poly	$ 1.32	$ 1.38	$ 1.43	$ 1.32	$ 1.38	$ 1.43	$ 1.43
oil pan	Oil Pan	Al	$ 1.38	$ 1.43	$ 1.49	$ 1.38	$ 1.43	$ 1.49	$ 1.49
engine cover	Eng Cover	Al	$ 1.38	$ 1.43	$ 1.49	$ 1.38	$ 1.43	$ 1.49	$ 1.49

Wheels			Small Car	Medium Car	Large Car	Small Truck	Med Truck	Large Truck	Specialty
Road	Road Wheels	Al	$ 1.16	$ 1.21	$ 1.26	$ 1.16	$ 1.21	$ 1.26	$ 1.47
Spare	Spare	Steel	$ 1.21	$ 1.21	$ 1.26	$ 1.16	$ 1.21	$ 1.26	$ 1.47

Chasis and Susp		Small Car	Medium Car	Large Car	Small Truck	Med Truck	Large Truck	Specialty
Suspension Arm	Iron	$ 1.10	$ 1.16	$ 1.21	$ 1.10	$ 1.16	$ 1.21	$ 1.31
Steering Rack	Al	$ 1.10	$ 1.16	$ 1.21	$ 1.10	$ 1.16	$ 1.21	$ 1.31
Engine Cradle	Steel	$ 1.10	$ 1.16	$ 1.21	$ 1.10	$ 1.16	$ 1.21	$ 1.31

Closures Inners		Small Car	Medium Car	Large Car	Small Truck	Med Truck	Large Truck	Specialty
Doors	Steel	$ 1.16	$ 1.21	$ 1.26	$ 1.16	$ 1.21	$ 1.26	$ 1.37
Hood	Steel	$ 1.27	$ 1.32	$ 1.38	$ 1.27	$ 1.32	$ 1.38	$ 1.43
Rear	Steel	$ 1.16	$ 1.21	$ 1.26	$ 1.16	$ 1.21	$ 1.26	$ 1.37

Body Applications		Small Car	Medium Car	Large Car	Small Truck	Med Truck	Large Truck	Specialty
Front End Beam	Steel	$ 1.21	$ 1.26	$ 1.31	$ 1.31	$ 1.37	$ 1.42	$ 1.47
IP Cross Member	Steel	$ 1.38	$ 1.60	$ 1.71	$ 1.43	$ 1.54	$ 1.65	$ 1.71
Rear Cross Member	Steel	$ 1.32	$ 1.38	$ 1.43				$ 1.49
Side Pillars	Steel	$ 1.16	$ 1.21	$ 1.26	$ 1.16	$ 1.21	$ 1.26	$ 1.26
Sun / Targa Roof	Steel	$ 1.27	$ 1.32	$ 1.43	$ 1.27	$ 1.32	$ 1.43	$ 1.54

Seats			Small Car	Medium Car	Large Car	Small Truck	Med Truck	Large Truck	Specialty
	Seat Base	Steel	$ 1.32	$ 1.38	$ 1.43	$ 1.32	$ 1.38	$ 1.43	$ 1.43
	Seat Riser	Steel	$ 1.32	$ 1.38	$ 1.43	$ 1.32	$ 1.38	$ 1.43	$ 1.43
	Seat Back	Steel	$ 1.32	$ 1.38	$ 1.43	$ 1.32	$ 1.38	$ 1.43	$ 1.43

11 References

[1] Mangers, Dwain and Jo Willekens of Norsk Hydro Magnesium. “Global Outlook on the use of Magnesium Diecastings in Automotive Applications.” Presented at the International Magnesium Conference (April 1998).

[2] Corbett, Brian, Tom Murphy and Bill Visnic, “Materials Use Expected to Change Slowly in New Millennium” Ward’s Automotive Yearbook 2000. p. 50.

[3] Opec Homepage <http://www.opec.org>.

[4] Energy Policy and Conservation Act of 1975 “Public law 94-163” <http://thomas.loc.gov/cgi-bin/bdquery/z?d094:SN00622:|TOM:/bss/d094query.html|>.

[5] Davis, Stacey C. Transportation Energy Data Book (20th edition). Table 7-16 p. 7-18. <http://www-cta.ornl.gov/data/tedb20/Spreadsheets/Table7_16.xls>.

[6] Office of Transportation Technologies: Fact of the Week “US Gasoline and Oil Prices January 1998 – March 2000.”<(http://www.ott.doe.gov/facts/archives/fotw123.html>.

[7] Environmental Defense Website “Global Warming: The History of International Global Consensus.” <http://www.edf.org/pubs/FactSheets /d_GWFact.html>.

[8] Emissions of Greenhouse Gases in the United States 1999 “Carbon Dioxide Emissions.” (October 2000) p.24-40. <http://tonto.eia.doe.gov/FTPROOT/environment/057399.pdf>.

[9] Field, Frank. Coursework for MIT class ESD123 “The Effect of Vehicle Mass on Fuel Economy.” <http://msl1.mit.edu/TPP12399/vehicle_data_1.pdf>.

[10] Corbett, Brian, Tom Murphy and Bill Visnic, “Materials Use Expected to Change Slowly in New Millennium” Ward’s Automotive Yearbook 2000. p. 47.

[11] Magnesium in Automotive. Brochure from Norsk Hydro Magnesium. (August 97).

[12] Society of Automotive Engineers “Magnesium Flair” (1996).

[13] Magnesium in Automotive a Brochure from Norsk Hydro Magnesium. p. 3. (August1997).

[14] Society of Automotive Engineers “Magnesium Flair” (1996).

[15] Cole, Gerald S., et. al. The Potential For Mg in the Auto Industry. (1995).

[16] Schofield, Julie. Design News “Comfort Rules Redesign.” (May 1995). <http://www.manufacturing.net/magazine/dn/archives/1996/dn0506.96/09news.htm>.

[17] Newing, Graeme. Solomon Smith Barney Report on Australian Magnesium (October 1999) p. 93.

[18] Wrigley, Al. Automotive Industries Magazine “Consolidation Drives Magnesium Use” (October 1999) <http://www.ai-online.com/archive/ 1099material1.htm>.

[19] Kramer, Deborah A. Magnesium Yearbook: 1999 Yearly Review published by the US Geological Survey. < http://minerals.usgs.gov/minerals/pubs/commodity/magnesium/>.

[20] Newing, Graeme. Solomon Smith Barney Report on Australian Magnesium (October 1999) p. 87.

[21] Newing, Graeme. Solomon Smith Barney Report on Australian Magnesium (October 1999) p. 76.

[22] Newing, Graeme. Solomon Smith Barney Report on Australian Magnesium (October 1999) p. 78.

[23] Newing, Graeme. Solomon Smith Barney Report on Australian Magnesium (October 1999) p. 83.

[24] Newing, Graeme. Solomon Smith Barney Report on Australian Magnesium (October 1999) p. 83.

[25] Platt’s Metals Week v. 69 no.6. (February 1998) p. 14.

[26] Newing, Graeme. Solomon Smith Barney Report on Australian Magnesium (October 1999) p. 85.
[27] Flemings, Merton C., et al. An Assessment of Magnesium Primary Production Technology. (February 1981) p. 82-84.
[28] Newing, Graeme. Solomon Smith Barney Report on Australian Magnesium (October 1999) p. 87.
[29] Newing, Graeme. Solomon Smith Barney Report on Australian Magnesium (October 1999) p. 77.
[30] Magnesium in Automotive a Brochure from Norsk Hydro Magnesium. p. 12.
[31] Newing, Graeme. Solomon Smith Barney Report on Australian Magnesium (October 1999) p. 79-80.
[32] Kramer, Deborah A. Material Prices in the United Sates through 1998 “Magnesium.” p. 80. < http://minerals.usgs.gov/minerals/pubs/commodity/magnesium/400798.pdf >.
[33] Newing, Graeme. Solomon Smith Barney Report on Australian Magnesium (October 1999) p. 87.
[34] Kramer, Deborah A. Magnesium Yearbook: 1996-98 Yearly Reviews published by the US Geological Survey. <http://minerals.usgs.gov/minerals/pubs/commodity/magnesium/>.
[35] Dow Press Release. <http://www.dow.com/dow_news/prodbus/p8_1120.html> *page 30*
[36] Newing, Graeme. Solomon Smith Barney Report on Australian Magnesium (October 1999) p. 88.
[37] Busch, John, Frank Field and Joel Clark. An Engineering-Economic Simulation Model of the World Magnesium Market. (1986) p. 34.
[38] Kramer, Deborah A. Magnesium Yearbook: 1999 Yearly Review published by the US Geological Survey. < http://minerals.usgs.gov/minerals/pubs/commodity/magnesium/>.
[39] VanFleteren, Robert J. Magnesium Supply and Demand. (1999) p. 65.
[40] Schey, John A. “Manufacturing Processes and Their Selection” ASTM Handbook, Vol. 20. p. 690-691.
[41] Kramer, Deborah A. Magnesium Yearbook: 1999 Yearly Review published by the US Geological Survey. < http://minerals.usgs.gov/minerals/pubs/commodity/magnesium/>.
[42] Meridian Overview Presentation (2000)
[43] Newing, Graeme. Solomon Smith Barney Report on Australian Magnesium (October 1999) p. 90.
[44] Cole, Gerald S., et. al. The Potential For Mg in the Auto Industry. (1995).
[45] Encyclopedia Britannica Online “Steel.” <http://www.britannica.com/bcom/ eb/article/printable/ 4/0,5722,119874,00.html>.
[46] Kramer, Deborah A. Magnesium Yearbook: 1999 Yearly Review published by the US Geological Survey. < http://minerals.usgs.gov/minerals/pubs/commodity/magnesium/>.
[47] van de Velde, Cees. Nodular Cast Iron Before it Was Even Invented. (December 1999). <http://members.tripod.lycos.nl/cvdv/nodoud.html>.
[48] Gowri, S . and P. Bouchard. Ductile Iron News Issue 3. (1999). <http://www.ductile.org/ Magazine/Issue3_1999/determination.htm>.
[49] Kramer, Deborah A. Magnesium Yearbook: 1999 Yearly Review published by the US Geological Survey. < http://minerals.usgs.gov/minerals/pubs/commodity/magnesium/>.
[50] International Magnesium Association Primary Magnesium Shipment Statistics. (1999).
[51] International Magnesium Association Primary Magnesium Shipment Statistics. (1999).

[52] Carey, Francis A. Organic Chemistry “Preparation of Organomagnesium Compounds. Grignard Reagents.” (1987) p. 524-526.
[53] International Magnesium Association Primary Magnesium Shipment Statistics. (1999)
[54] International Magnesium Association Primary Magnesium Shipment Statistics. (1999)
[55] International Magnesium Association Primary Magnesium Shipment Statistics. (1999)
[56] International Magnesium Association Primary Magnesium Shipment Statistics. (1999)
[57] Kramer, Deborah A. Material Prices in the United Sates through 1998 “Magnesium.” p. 80. < http://minerals.usgs.gov/minerals/pubs/commodity/magnesium/400798.pdf >.
[58] Corbett, Brian, Tom Murphy and Bill Visnic, “Materials Use Expected to Change Slowly in New Millennium” Ward’s Automotive Yearbook 2000. p.50.
[59] International Magnesium Association Primary Magnesium Shipment Statistics. (1999).
[60] de Neufville, Richard. Applied Systems Analysis: Engineering Planning and Technology Management. p. 352-371.
[61] Davis, James. The Potential for Vehicle Weight Reduction Using Magnesium: *SAE Technical Paper #910551*. (1991).
[62] Pindyck, Robert and Daniel Rubinfeld. Microeconomics “The Short-Run Market Supply Curve.” p. 264-267.
[63] Forrester, Jay. Industrial Dynamics. (1961).
[64] Forrester, Jay. Industrial Dynamics. (1961).
[65] Sterman, John. Business Dynamics: Systems Thinking and Modeling for a Complex World. p. 791-841.
[66] Vensim Website <http://www.vensim.com>.
[67] PowerSim Website <http://www.powersim.com/default_home.asp>.
[68] Newing, Graeme. Solomon Smith Barney Report on Australian Magnesium (October 1999) p 87. and Kramer, Deborah A. Magnesium Yearbook: 1999 Yearly Review published by the US Geological Survey. <http://minerals.usgs.gov/minerals/pubs/ commodity/magnesium/>.
[69] Kramer, Deborah A. Material Commodity Summaries. Yearly summaries published by the US Geological Survey. <http://minerals.usgs.gov/minerals/pubs/commodity/magnesium/>.
[70] Newing, Graeme. Solomon Smith Barney Report on Australian Magnesium (October 1999) p. 88.
[71] Newing, Graeme. Solomon Smith Barney Report on Australian Magnesium (October 1999) p. 6.
[72] Newing, Graeme. Solomon Smith Barney Report on Australian Magnesium (October 1999) p. 90.
[73] Greene, William H. Econometric Analysis 3rd Edition. p. 250-257.
[74] Greene, William H. Econometric Analysis 3rd Edition. p. 265.
[75] Newing, Graeme. Solomon Smith Barney Report on Australian Magnesium (October 1999) p. 90.
[76] Economic Report of the President: 1999. p. 386-388. <http://w3.access.gpo.gov/usbudget/index.html>.
[77] Organization for Economic Cooperation and Development (OECD). OECD Statistics: Indicators of Industrial Activity. (1980-1999).
[78] Magnesium Component Utility Interviews with Larry Ouimet, Richard Osborne and David Barris of General Motors Corporation and Thomas Sweeder and Paul Dellock of Ford Motor Company. (December 2000-January 2001).

[79] International Magnesium Association Primary Magnesium Shipment Statistics. (1999). *p75*
[80] Automotive News: 2000 Market Data Book**.** p. 20.
[81] Motor Industry of Great Britain,1999 World Automotive Statistics. A Statistical Publication of The Society of Manufacturers and Traders, Ltd. ADS Department.
[82] Davis, James. The Potential for Vehicle Weight Reduction Using Magnesium: *SAE Technical Paper #910551*. (1991).
[83] VanFleteren, Robert J. Magnesium Supply and Demand. (1999) p. 64.
[84] Newing, Graeme. Solomon Smith Barney Report on Australian Magnesium (October 1999) p. 6.
[85] Kramer, Deborah A. Magnesium Yearbook: 1999 Yearly Review published by the US Geological Survey. < http://minerals.usgs.gov/minerals/pubs/commodity/magnesium/>.
[86] Newing, Graeme. Solomon Smith Barney Report on Australian Magnesium (October 1999) p. 1, 88.
[87] Newing, Graeme. Solomon Smith Barney Report on Australian Magnesium (October 1999) p. 1, 88. and Kramer, Deborah A. Magnesium Yearbook: 1999 Yearly Review published by the US Geological Survey. <http://minerals.usgs.gov/minerals/pubs/ commodity/magnesium/>.