MATERIALS PRODUCTION ECONOMICS: AN EXAMINATION OF THE VARIABLES AND RELATIONSHIPS THAT DRIVE MATERIALS PRODUCTION AND RECYCLING IN THE WORLD ECONOMY

By

Yao-Chung King

SUBMITTED TO
THE DEPARTMENT OF MATERIALS SCIENCE AND ENGINEERING
IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF
BACHELOR OF SCIENCE IN MATERIALS SCIENCE AND ENGINEERING

AT THE
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

JUNE 2006

© 2006 Yao-Chung King.
All rights reserved.

The author hereby grants to MIT permission to reproduce and to distribute publicly paper and electronic copies of this thesis document in whole or in part in any medium now known or hereafter created.

Signature of Author: [Signature]

Department of Materials Science and Engineering
May 26, 2006

Certified by: [Signature] Thomas W. Eagar
Professor of Materials Engineering and Engineering Systems
Thesis Supervisor

Accepted by: [Signature] Caroline A. Ross
Professor of Materials Science and Engineering
Chair, Departmental Undergraduate Committee
# Materials Production Economics:
An Examination of the Variables and Relationships that Drive Materials Production and Recycling in the World Economy

**Table of Contents**

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Introduction</td>
<td>4</td>
</tr>
<tr>
<td>Material Introduction Model</td>
<td>5</td>
</tr>
<tr>
<td>Key Features: Production</td>
<td>5</td>
</tr>
<tr>
<td>Recycling Curve</td>
<td>5</td>
</tr>
<tr>
<td>Materials Data Analysis:</td>
<td>7</td>
</tr>
<tr>
<td>Introduction through the Production of Steel</td>
<td>7</td>
</tr>
<tr>
<td>U.S. History through Steel Production in the U.S.</td>
<td>7</td>
</tr>
<tr>
<td>World Production of Steel</td>
<td>9</td>
</tr>
<tr>
<td>World Production of Structural Materials</td>
<td>11</td>
</tr>
<tr>
<td>Increase from 1945-1972</td>
<td>11</td>
</tr>
<tr>
<td>Increase from 1972 to 2002</td>
<td>11</td>
</tr>
<tr>
<td>Total Increase from 1945-2002</td>
<td>11</td>
</tr>
<tr>
<td>Trend Discussion</td>
<td>11</td>
</tr>
<tr>
<td>World Material Production and Population Growth</td>
<td>12</td>
</tr>
<tr>
<td>Production Growth and Population Growth</td>
<td>12</td>
</tr>
<tr>
<td>Variations in Developmental Group Population Growth as a Function of Materials Production</td>
<td>13</td>
</tr>
<tr>
<td>Steel and Cement: Economic Factors in Less Developed Regions</td>
<td>13</td>
</tr>
<tr>
<td>World Materials Production During the Introductory Phase</td>
<td>15</td>
</tr>
<tr>
<td>World Materials Pricing During Its Modern Lifetime</td>
<td>16</td>
</tr>
<tr>
<td>Material Price vs. Time</td>
<td>16</td>
</tr>
<tr>
<td>Material Production vs. Material Price</td>
<td>17</td>
</tr>
<tr>
<td>Material Price vs. Energy Price</td>
<td>18</td>
</tr>
<tr>
<td>U.S. Recycling Trends within the Steel and Aluminum Industry</td>
<td>19</td>
</tr>
<tr>
<td>Historic Recycling Percentage in the U.S.</td>
<td>19</td>
</tr>
<tr>
<td>Aluminum Recycling Rate Deviation</td>
<td>19</td>
</tr>
<tr>
<td>Recycling Rate as a Function of Primary Product Price</td>
<td>20</td>
</tr>
<tr>
<td>Growth Analysis to Determine Market Critical Point: Four Proposed Methods</td>
<td>21</td>
</tr>
<tr>
<td>Growth Curves</td>
<td>21</td>
</tr>
<tr>
<td>Growth (Absolute Value) Curves</td>
<td>21</td>
</tr>
<tr>
<td>Growth 5-point Traveling Standard Deviation Curves</td>
<td>22</td>
</tr>
<tr>
<td>Growth 5-point Traveling Variance Curves</td>
<td>23</td>
</tr>
<tr>
<td>Conclusion</td>
<td>24</td>
</tr>
<tr>
<td>Next Steps</td>
<td>25</td>
</tr>
<tr>
<td>References</td>
<td>26</td>
</tr>
<tr>
<td>Footnotes</td>
<td>27</td>
</tr>
</tbody>
</table>
Introduction

New materials are being developing each year that could revolutionize the world. However, while development of novel materials in the lab brings us one step closer to next latest-and-greatest innovation, the following and perhaps similarly difficult step requires bringing these materials to the world market. Indeed, “although U.S. firms have invested the majority of materials introduced over the past half-century, they have failed to commercialize many of these innovations” (Eagar, 98). For a material introduction to be successful, it will be useful to understand the trends involved within the market for such an introduction and for continuing survival.

This study lays the groundwork for understanding world demand by using primary source data to analyze market forces that have affected the world production of materials in the past. Because this study targets variables that do and do not affect materials production, the potential future developments from this study will be useful not only for materials introductions but also to new materials that are already to the marketplace, to people who produce those materials, and to people who recycle those materials. Indeed, the ability to forecast future material production needs will increase worldwide economic efficiency. This study focuses on structural materials, specifically, steel, aluminum, cobalt, and cement.

Because there is a sizeable history of materials production for structural staples like steel and aluminum, the data can be used to determine patterns in materials usage from introduction to market acceptance to common usage. This study begins by introducing a model for materials introductions and their respective recycling curves. It continues by analyzing the production curve for steel in the U.S., explaining the seemingly unpredictable variations from a historical perspective. The study continues by analyzing influences that have affected the world production of materials in the past, and then works to decipher to world material production curves. Because major world events occur continually, understanding which of those events will likely affect future materials production through an analysis of the past will aid the industry in operating efficiently.

This study also analyzes population growth with respect to material production, as well as suggesting one way in which asymmetries in More Developed Region growth and
Less Developed Region growth can affect the mix of materials used per capita worldwide. Material price is also analyzed.

Additionally, recycling data has been drawn to develop a relationship between materials usage and recycling volume. This relation will be useful, not just for anticipatory uses, such as for a recycler to begin setting up a plant in anticipation for the need, but also for the industry to determine the amount of material that is currently going to waste in landfills vs. materials that are still in use.

One of the key features of the proposed model is the Market Critical Point (MCP), the point in which material production begins exponential growth. This study proposes four methods to objectively determine the MCP.

Understanding market trends and the variables that affect the future of materials production will be invaluable in making the world economy more efficient. For example, market indications may determine that the MCP has just passed, implying fast, exponential market growth in the future years. Given this knowledge, mining facilities may begin to expand operations ahead of time, distributors may obtain new warehouses early, and manufacturers may purchase more equipment to prepare for the oncoming influx of demand. An investor may decide to invest, giving the industry a boost that allows the industry to be better equipped to handle the oncoming sharp increase in demand, leading to more efficient production of material applications and less market lag time response.
Material Introduction Model

Because of the many factors that will affect the amount of material produced across different industries, it will be difficult to extract reliably a clearly defined graph from historical data. Therefore, this thesis begins by introducing a basic economic model (Figure 1) that makes intuitive sense and then will match this model to historical data, with explanations for any deviations noted.

*Key Features: Production*

**Introduction:** When a new material is introduced into the market, there will be an introductory phase during which the material develops credibility within the market. This phase is characterized by timidity and uses are likely experimental and low risk applications. This stage is the so called “dating stage” because the market is timid, but curious about the new material. This stage decides where a healthy relationship will bloom between the market and the material.

**Market Acceptance and Growth:** Following the slow growth introductory stage is the fast growth “market acceptance” stage. This stage represents the period when the material has proven its reliability, and projects to exploit the material’s advantages become full scale, prompting larger demand from both the pioneering early users and others in their industry. Other applications may materialize, user industries expand, and a host of other causes may lead to the fast growth that characterizes this period. This period is the so called “engagement stage” because the market, now assured of its assessment, becomes committed to the new material. This fast and exciting stage also determines whether the material producers can keep up with the diverse needs of the users to continue to maintain interest in the market.

**Market Saturation:** This stage represents the maturation of the market for the material. Most uses for the material have been explored and demand remains constant. Production slowly increases to fill demand and growth is slow.

*Recycling Curve*

The recycling curve is similar in shape to the production curve but sits below the curve and delayed in time. While the material may have production capacity for virgin product, it is unlikely that recycling technology can be implemented immediately for several reasons:
• Recycling Technology Development
  o While the technology is available to produce the material, there may be a delay in developing the technology to efficiently recycle the material. This effect causes a lateral shift in the recycling curve.
  o This barrier will largely impact the recycling start date.
• Questionable Necessity
  o Because of the size of the initial investment for research and facilities, the implementation of recycling must be delayed until product acceptance is assured.
  o The faster the growth of production (i.e. the steeper the slope of the production curve), the more certain the necessity.
• Reservoir Accumulation and Product Aging
  o Materials must accumulate in the recycling “reservoir” so that there will be large amounts of material to be continuously recycled
    ▪ Reservoir: Material that is neither in production nor characterized as waste, the reservoir is the amount of material that is currently “in use.” The steel reservoir, for example, consists in part of steel beams that are currently holding up buildings, steel rails of railways, and steel auto bodies. These components are still in useful service but have the possibility of being recycled in the future.
  o If the product in which the material is used is still in useful service, that product must age past its useful life before the material is recycled. In the steel example, the car owner must dispose of the car before that steel can be recycled.
• Waste Loss
  o As with most processes, recycling is not 100% efficient. It can always be expected that some of the material will end up in land fills instead of recycled.
  o The recycling curve will likely stay below the production curve, barring extreme situations.
    ▪ One such situation would be a bankruptcy of most major companies in an industry. Production will drop precipitously, but the amount of material that is aged in the reservoir and available for recycling may be more than that year’s production.
Materials Data Analysis:
Introduction through the Production of Steel

Steel-making dates back millennia as a high skilled art, but modern steel making, efficient bulk production, and widespread use began in 1855 with the introduction of the Bessemer process, which opened the doors for bulk steel production during the industrial revolution. Steel has since found widespread use in the auto industry, in construction, and in railways, and is produced in a variety of ways. World production continues at a rapid pace as world populations develop lifestyles inclusive of products that require steel.

Steel production in the U.S. (Figure 2) will be more sensitive to events on a smaller scale than those that can affect the world production of steel. This sensitivity, evidenced in the many precipitous rises and falls found in Figure 2, will make it difficult to fit the U.S. production to the proposed model. However, reviewing the significance of U.S. policies and world events relative to the steel industry will be a useful exercise for the drawing of trends and predictions of fluctuations.

U.S. History through Steel Production in the U.S.

The many large deviations in steel production in the U.S. can be explained through world and domestic events. Removing these effects would likely produce a much smoother production curve that is closer in shape to that of World Production (Figure 5). For our purposes, a simplified analysis is sufficient to capture the essence of our method and is useful for the determination of significant relationships between world/national events and production.

1855: The Bessemer process make processed steel abundant. Demand steadily increases.
1914: World War I begins. Demand for steel increases more than normal as wartime plants produce steel for use in combat vehicles and other wartime products.
1919, June 28: Treaty of Versailles. Ceasing hostilities and decreased need for wartime goods causes production to drop off precipitously.
1929: The Great Depression extinguishes both steel demand and the ability to produce steel in the U.S.
1939: World War II begins, hastening the steel industry’s recovery.  
1939-1945 Demand remains strong throughout the war.  
1946 Demand drops after war’s end.  
1946-1956: United Steelworkers Union strikes five times within this period, causing delays in production that hurt many domestic steel companies. These turbulent events can account for the wide fluctuations and unpredictability seen in U.S. steel production during these years.  
1959: Great Steel Strike of 1959 keeps production suppressed. Buyers begin to turn to foreign producers.  
1971- U.S. devalues the U.S. dollar. Apparent domestic prices decrease relative to imported products. This effect includes a beneficial effect for steel producers in the U.S.  
1975- Japan passes US in steel/worker hour productivity.  
1979-1982 The Paul Volcker Depression decreases inflation. Foreign steel becomes more attractive as the U.S. Dollar increases in value relative to foreign currencies, causing less demand for domestic steel and more imports. At the same time, the third world obtains its own steel mills, decreasing U.S. exports.  
1980: Import quotas on specialty steel (stainless steel and alloy tool steels) were eliminated on February 13, 1980. U.S Steel files antidumping petitions against foreign steel companies.  
1982: The impact of foreign steel is nearly immediate. Imports gain a larger share of the U.S. steel market.  
1985: U.S. enacts Voluntary Restraint Agreements to aid the struggling domestic steel industry by restricting imports. Domestic steel industry starts to regain ground.

1 "Since the beginning of the war in 1939 expanding war-industries needs have been responsible for a continued stimulus in the production of steel ingots and castings; consequently, a new record has been established each year.” (Carmony, Minerals Yearbook 1943, 525)  
2 “The United Steelworkers Union was founded in violence in 1942 and hostility remained its trademark. There were steel strikes in 1946, 1948, 1952, 1955 and 1956. Some lasted a few days. Some a few months. At least three involved full-scaled confrontations with governments. Harry Truman even seized the mills in 1952, forcing strikers back to work.” (Strohmeyer 1)  
3 “The Iron and steel industry experienced the longest steel strike in its history. Although consumers anticipated the strike and built up large stocks of steel, the 116-day work stoppage caused shortages in many industries. Workers were idled in the automotive, railroad, construction, and other fields, curtailing the output of many finished products.” (Harris, James C.O, Minerals Yearbook 1959, 571)  
4 “[I]n 1975 Japan passed the United States in productivity. The U.S. Bureau of Labor Statistics reported that the Japanese worker needed only 9.2 hours to produce a ton of steel—a spectacular improvement from their 25.2 man-hours in 1964. U.S. steelworkers required 10.9 man-hours, only a modest improvement over the 13.1 hours required in 1964.” (Strohmeyer 1)  
5 “Production of pig iron and raw steel and shipments of steel mill products declined in 1980 because of lower demand from most major markets…. [The International Trade Commission] determined that a U.S. industry was being materially injured by imports of subsidized pig iron from Brazil.” (D.H. Desy, Iron and Steel 1980, 438)  
6 Eagar, Thomas. Verbal correspondence. May 22, 2006  
7 These quotas were instituted on June 14, 1976. (D.H. Desy, Iron and Steel 1980, 437)  
8 “On March 21, United States Steel Corp. filed antidumping petitions pertaining to five basic steel mill products exported variously by Belgium, France, the Federal Republic of Germany, Italy, Luxembourg, the Netherlands, and the United Kingdom.” (D.H. Desy, Iron and Steel 1980, 438.)  
9 “Imports dropped less sharply than domestic shipments and gained a larger of the U.S. Steel market. (Schottman, Frederick J. Iron and Steel 1982, 461)
World Production of Steel

As we have seen, international and local events can have an immediate and dramatic impact on the U.S. production curve for steel. However, the world production curve for steel lacks such a high sensitivity. This insensitivity becomes apparent when viewing the world production of steel graph (figure 3) where, as expected, there are fewer and less extreme increases and decreases. The overall trend for worldwide production shows a consistent upward growth, with the possibility of market saturation in the 1970's and 1980's. However, the continuing upward growth in recent years indicates the possibility of continued “Market Acceptance” type growth in world steel production. Currently, the largest producers of steel are China, Japan, and the United States.

The curve begins, almost immediately, by dipping down after the resolution of WWII. Thereafter, rapid exponential growth takes hold until the 1970s. The curve appears to plateau starting in 1972, about the time when the change from ingot casting to continuous casting increased yield from raw steel by about 23%\(^\text{10}\). The extremeness of this plateau is due partly to the type of data used to measure world steel production. The values for “Steel Produced” in Figure 3 are represented by the sum amount of raw steel produced across most steel making countries. Therefore, the values represent the amount of raw steel entering the casting process, not the amount of finished steel product.\(^\text{11}\)

Given this sudden increase in yield and therefore, increase in finished steel produced per unit raw steel, the steel industry could choose to maintain current mining levels, leading to a sudden 23% jump in finished product, or decrease mining levels by 18.7%\(^\text{12}\) to maintain production at the same level. Extrapolating the production curve from 1972 to an extrapolated period of 1975 (extrapolated to about 700 million tons) to 1979 shows about a 10% decrease.

However, it cannot be safely assumed that the increase in yield was immediate, but rather that the steel mills gradually converted their casting equipment over a long period of time. A simplifying assumption would be the incremental and linear increase of technological replacement starting in 1970 (with 0% additional yield) and ending in

\(^{10}\) Eagar, Thomas W. Verbal Correspondence, May 30, 2006

\(^{11}\) The term raw steel, as used by the American Iron and Steel Institute, includes ingots, steel castings, and continuously cast steel. It corresponds to the term crude steel as used by the United Nations. For UN definition of “crude steel,” see endnote iii.

\(^{12}\) A 23% yield increase from 81.3% will bring production back to 100% target production.
1990 (with 23% additional yield.\textsuperscript{13}) Figure 4 show the results of that adjustment. Continuous casting’s additional yield accounts for only part of the drop in crude steel production. However, this adjustment does allow the 1972-1990 period to fall better in line with the previous curve.

The period in the 1980s and 1990s was tense for the steel industry. The steel industry has been sensitized to overproducing, and limits and quotas were common worldwide for steel production and importing/exporting operations. Developing countries began opening their own steel plants, vastly oversupplying the market to suppress demand. A poor steel market and claims of dumping and unfair subsidies caused European countries and the U.S. to enforce quotas to keep their own companies profitable, which led to the suppression of production during this time.

\textsuperscript{13} It should be noted that neither ingot nor continuous casting account for all crude steel production. In the U.S. in 1991, continuous casting continued to make headway as the share of steel produced through that method increased to 75.8\% (Houck, Iron and Steel 1991, 797)
World Production of Structural Materials

*Increase from 1945 to 1972*  
The production of steel, cement, cobalt, and aluminum exhibited a sizable World War II production increase and a post-WWII production drop, from which production has increased at a steady pace. 1945 (after the inflated war-time demand) shows a return to normal market demand levels and will be a useful baseline from which to measure growth. Further, the period from 1945 to 1972 shows consistent growth with minimal fluctuations in all industries.

During this period, steel shows a 6.2 fold increase from that baseline to 1972. Aluminum shows 12.6 fold, cobalt 5.3 fold, and cement 13.3 fold.

*Increase from 1972 to 2002*  
The slowdown in the steel industry’s growth is noticeable in its increase from 1972-2002, a 1.4 fold increase, compared to 2.4 for Aluminum, 1.9 for Cobalt, and 2.7 for cement.

*Total Increase from 1945 to 2002*  
Increase in production during this period were 8.9 fold for Steel, 29.9 fold for Aluminum, 10.1 fold for Cobalt, and 36.4 fold for Cement.

*Trend Discussion*  
Qualitatively, aluminum production shows more stability than steel production, while cement shows the least sensitivity to world events. Cobalt, on the other hand, exhibits high fluctuations in worldwide production. This high sensitivity results from the fact that most of the world’s cobalt is produced in politically unstable areas. Cobalt production is dominated by the Congo and Zambia, which combine to produce...
48.1% of the world’s cobalt in 2003, and 49.6% in 2004. Therefore, the high sensitivity and fluctuations exhibited in cobalt result both from the fact that the production is dominated by a few small countries and that those countries’ political conditions have been historically unstable.

Cement production, while comparable to steel in growth from 1945-1972, has fast outpaced the steel industry (Figure 5e.) In 1974, cement producers generated 702 billion metric tons of cement, nearly matching steel producers’ 708 billion that same year. In the next 28 years, cement producers would outpace steel makers, finally producing 1.8 trillion tons of cement in 2002, double the amount of steel’s 898 billion tons that same year.

World Material Production and Population Growth

Production Growth and Population Growth

The world population continues to grow each year, increasing the world demand for resources. The world population crossed the 3 billion mark in 1960 and doubled to 6 billion by 1999. During the same period, steel production increased by a factor of 2.26, aluminum by 5.26, cobalt by 2.22, and cement by 5.05.

Assuming equal distribution of usage across the world population\(^{14}\), the per person usage from 1960-1999 for steel increased by 14.7%, aluminum by 166.1%, cobalt by 12.7%, and cement by 156.9% (Figure 6b.) Therefore, material production growth cannot be fully accounted for by simple world population growth\(^{15}\).

\(^{14}\)This assumption is made only for quantitative purposes to show that materials usage is outpacing world population growth.

\(^{15}\)However, an in-depth analysis of materials usage by country, scaled by the growth of the country’s population, plotted against the growth of the industry may reveal that the growth of certain resource-use intensive societies may be driving the industry growth. The above statement does not preclude this possibility.
Variations in Development Group
Population Growth as a Function of Materials Production

In the past century, the population growth of "lesser developed regions" has quickly outpaced that of "more developed regions" (The terms to designate the development groups "lesser developed regions" (LDRs) and "more developed regions" (MDRs) are used as defined by the United Nations.) Currently, the world population grows at a rate of 1.2% yearly, resulting in an annual additional of 77 million people. However, a breakout of population growth by development group shows that MDR populations grow by 0.25% annually while LDR populations rise almost six times as fast, at 1.46%. (Figure 6c.)

Steel and Cement: Economic Factors in Less Developed Regions

While it may be argued that MDRs consume more resources per capita, the dominating proportion of the world population and of world population growth arising from LDRs result in high resource demands. The specific resources demanded will depend on the economic standing of the growing nations, in this case, that of LDRs.

As the lesser developed region (LDR) population grows, those regions will require construction materials to construct...
require construction materials to construct buildings and other structures. Our material usage analysis shows a shifting of demand from steel to concrete, and this growth from LDRs may be able to account for the continuing speedy production growth of cement compared to steel.

There are several reasons these regions will prefer cement over steel. A large incentive is price; steel costs about 7.5 as much as cement. To produce steel entails building blast furnaces and steel mills. Steel mill construction requires considerably more initial investment and entails higher operational costs than constructing cement plants. Cement plants request less than 1/10th of the capital cost of a steel mill. Mining capabilities further impede the LDRs ability to undertake steel production, as limestone can more easily and cheaply extracted and converted to concrete. These cost differences mean that, for LDR’s, steel production would be difficult and expensive, implying steel would likely need to be imported if it were chosen. Cement, on the other hand, can more easily be produced locally at dramatically smaller expense.

The main appeal in the use of the stronger steel instead of cement is vertical capabilities. However, while the ability to construct skyscrapers is valued in densely populated and economically developed areas, tall buildings are not a requirement for many LDRs.

Overall material use per capita is increasing across all industries analyzed. However, as can be seen in Figure 6e, the mix of materials that people use is changing. The shift in favor from steel to cement is likely the effect of increasing demand from the growing and disproportionately large LDRs in the world population.
World Material Production During the Introductory Phase

Because the nature of long scale representations prevents the observation of the early, short term trends, figures 7a-c show a smaller, scaled view of production from 1900-1945. These views were scaled to allow for the peak that occurred in all industries during WWII. While zooming into this period has shown fluctuations not apparent in Figures 5a-e, the investigations into the introductory phase show few useful or useable trends.

It is interesting to note that aluminum production, despite the decreased scale in figures 7c and 7d, still shows a remarkable amount of stability relative to the behavior of cobalt or cement production.

![Cobalt Production](image1)

**Historic Cobalt Production (Worldwide to 1946)**

- Figure 7a. Cobalt Production (Worldwide). Because of the small scale and few major producers, the cobalt production curve in the introductory stage varies unpredictably.

![Cement Production](image2)

**Historical Cement Production (World Wide to 1946)**

- Figure 7b. Cement Production (Worldwide) Cement shows a widely varying trend from 1925-1945.

![Aluminum Production](image3)

**Historical Aluminum Production (Worldwide to 1946)**

- Figure 7c. Aluminum Production Scaled to 2,500,000 tons. This production curve, despite the small scale, shows a smoother and more predictable curve than cobalt or cement.

![Aluminum Production](image4)

**Historical Aluminum Production (Worldwide to 1946)**

- Figure 7d. Aluminum Production Scaled to 300,000 tons. Despite scaling the data down below the peak WWII production, the curve continues to show smooth fluctuations.
World Material Pricing During Its Modern Lifetime

*Material Price vs. Time:*

Figure 8a-d shows that materials price is generally positively correlated with time, but with little predictability with respect to time. It is interesting to note that all graphs exhibit about a three fold jump starting from the early 1970's, indicating an event or influence common to all four industries. As energy use is common to all material producing industries, it is likely that the 1973 energy crisis is the cause of this increase in price.

![Cobalt Price vs. Time](image)

**Figure 8a Cobalt Price Since 1900**

![Steel Price vs. Time](image)

**Figure 8b Steel Price Since 1900**

![Aluminum Price vs. Year](image)

**Figure 8c Aluminum Price Since 1900**

![Cement Price vs. Time](image)

**Figure 8d Cement Price Since 1900**

It should be noted that gas and oil prices (figure 9a-b) markedly increased on October 17, 1973 when OPEC announced its embargo. (Oil prices jumped from $.738/million BTU in December 1973, to $1.91/million BTUs in January, 1974. Gas Prices starting at $.294 in December 1974 increased to $.568 in December of 76.) Energy price changes before 1973 appear to be gradual and in-line with the previous trend. At the same time, major price changes across the four studied industries increased by about a factor of three from 1973-1980. Steel's price peaks in 1984, while the price peaks for Aluminum, Cobalt, and Cement peak on or near 1980. Oil prices peak on July 1, 1980, while gas prices continue to rise, peaking in 1984. This correlation would suggest that the price of steel is tied more closely to the price of natural gas, while the price of aluminum, cobalt, and cement are better related to the price of oil.
Figure 9a Gas prices starting in 1930 ($/million BTU)
Gas Prices starting at $.294 in December 1974
increased to $.568 in December of 76. Another peak

Figure 9b Oil Prices Starting in 1946 ($/million BTU)
Oil prices jumped from $.738/million BTU in
December 1973, to $1.91/million BTUs in January,
1974

Material Production vs. Material Price:

Figures 10a-d show production as a function of price. While for some materials, there is a positive correlation, this correlation is weak at best. There is little evidence to show that the amount of material produced to meet demand is inversely related to price. The positive correlation seen is likely correlation, not causation.
Material Price vs. Energy Price:

All materials except cobalt showed a moderate to strong correlation with energy prices. The R² values to a logarithmic fit²⁰ for cobalt, aluminum, steel, and cement with respect to oil prices are, respectively, 0.5868, 0.7757, 0.9092, and 0.868. The R² values to a logarithmic fit²¹ for cobalt, aluminum, steel, and cement with respect to natural gas prices are, respectively, 0.6391, 0.8335, 0.9712, and 0.9484. The logarithmic fit for all materials shows higher correlations, without exception, with natural gas prices than with oil prices. Based on this evidence, it is likely that energy prices, especially that of natural gas, plays a dominant role in determining the price of steel and cement, and possibly aluminum.

²⁰ A linear fit was also applied. The R² values for a least squares regression linear fit for cement, aluminum, cobalt, and steel prices with respect to oil prices are, respectively, 0.7506, 0.6459, 0.5398, 0.7932. The R² values for cement, aluminum, cobalt, and steel prices with respect to natural gas prices are, respectively, 0.8857, 0.7341, 0.5899, 0.8985. The correlations between material price and energy price are higher across the board for natural gas instead of oil using a linear fit. However, the logarithmic fit showed higher correlations without exception for both oil and natural gas prices.
U.S. Recycling Trends within the Steel and Aluminum Industry

*Trends with Primary Production and Recycling*

Recycling trends will be useful in determining future recycling needs. Though recycling takes place in most developed nations, this analysis will shed light on U.S. recycling trends. As can be seen from Figure 13a-b, steel recycling in the U.S. seems to follow directly with production. Most fluctuations observed in steel production are seen immediately in recycling. Aluminum shows a loose correlation between production and recycling.

*Historic Recycling Percentage in the U.S.*

Figure 14a-b shows the historic recycling percentage in the U.S for steel and aluminum. Steel shows a consistently high recycling rate of about 70% that has stayed consistent since 1950. Aluminum shows the beginning of consistency starting in 1960 and then begins to increase starting in 1970, passing the 50% mark in 2001. This increase in rate can be rationalized from a historical perspective.

*Aluminum Recycling Rate Deviation*

Despite being the most abundant metallic element in the earth’s crust (between 7.6-8%), aluminum is one of the most difficult metals to refine because it quickly forms a stable oxide that resists flaking. Interestingly, the property that makes aluminum desirable for many applications also makes its production very difficult and energy intensive. Recycling aluminum, in contrast, consumes only about 5% of the energy required to produce the
virgin product. The 1973 energy crisis made the aluminum situation in the U.S. very difficult, and among the U.S. responses was to enact bottle deposit laws\(^\text{22}\) to encourage aluminum production by recapturing aluminum from the recycling reservoir. This government incentive in the face of the energy crisis explains the rise in % recycled beginning in 1973.

Figure 14b. Historic Aluminum Recycling Percentage in the U.S. Recycling begins haphazard and stabilizes beginning the in 1950's and 1960's. The eventually rise in recycling percentage begins in the 1970s, when the 1973 energy crisis prompts enactment of bottle deposit laws.

Recycling Rate as a Function of Primary Product Price

As has been shown in the previous section, materials prices show high dependence on energy costs. Given that recycling often results in energy savings that translates into less expensive secondary product, the relationship between recycling percentage and the price of primary product was explored. Interestingly, percentage recycled and price shows a high degree of inelasticity in the case of steel. Aluminum shows a weakly positive correlation because percent recycled and price of the primary product.

Recycling vs. Steel Price

Recycling and Price show a high degree of inelasticity.

Steel Recycling vs. Steel Price

Recycling and Price show a high degree of inelasticity.

Aluminum Recycling vs. Aluminum Price

No trend is immediately obvious, though recycling and price show a weak positive correlation.

\(^{22}\) Aluminum cans manufacturers are the second highest users of aluminum, next to the transportation industry. The bottle deposit laws began with Oregon in 1972, and then continued in 1973 with Vermont, and in 1978 with Maine and Michigan. Today, the U.S. Census bureau states 30% of the US Population resides in states with container deposit laws.
Growth Analysis to Determine Market Critical Point:
Four Proposed Methods

The ability to determine the end of the introductory phase and the beginning of
the market acceptance/fast growth phase (the market critical point) will be invaluable in
predicting the need for future plant and mine construction. Below are four proposed
methods to aid in determining the MCP. While the MCP becomes more easily
identifiable in these figures, one must keep in mind that these convergence points are
only identifiable because of the context in which they are viewed. It is the benefit of
hindsight and the ability to see the entire history that allows identification in these cases.
However, there is hope that these methods may be able to aid in predicting the MCP out
of context to predict the beginning of the exponential growth associated with the Market
Acceptance/Growth Period.

_Growth Curves_

Upon analysis of industry production growth curves (Figure 16a-d), it is apparent
that the early stages (the introductory stage) exhibits high variation that collapses into a
much tighter formation of growth points. Comparisons between this “collapsing” points
and historic production curves (Figures 5a-d) shows that these points seem to initiate the
beginning of the Market Acceptance/Fast Growth stage of a material’s introduction.

![Steel Production Growth](image1)

![Aluminum Production Growth](image2)

![Cobalt Production Growth](image3)

![Cement Production Growth](image4)
**Growth (Absolute Value) Curves**

The data points graphed (Figure 17a-d) are the absolute values of the points in the previous method. The idea is to obtain high variation in the introductory stage that will collapse at the MCP.

**Growth 5-point Traveling Standard Deviation Curves**

To utilize the difference in spread in the introductory stage vs. the market growth stage, the standard deviation is obtained for the set of data points containing that year and the four previous years. These standard deviations are graphed below (Figure 18a-d).
Growth 5-point Traveling Variance Curves

These curves (Figures 19a-d) take advantage of the same spread difference, but also magnifies the difference between low spread and high spread time periods.
Conclusions

Several key observations and questions are drawn from this study. These observations merit further study, and the implications from potential future work may lead to aiding the efficiency of the world economy.

Based on the steel industry study, the slow down in steel production can be explained by the dual influences of rapid increase in finished steel as a result of the continuous casting technique and the further construction of large steel mills in developing countries. This increase in competition and yield flooded the market with steel, and lead to a slow down in world production for more than a decade. This effect can be used in an anticipatory fashion when further technological develops increase the yield for other industries.

Aluminum and cement show strong promise to continue their rapid growth. Based on the data available, it seems likely that steel will overcome the slowdown in the 1970s as the growing world population and increasing per capita material use begins to make up for the excess steel production.

Based on the World Product of Structural Materials data, the growing world population cannot fully account for the increase in materials production. Taking the world as a whole, the per capita use for materials is growing in all industries analyzed.

This data also makes it clear that concrete is the fastest growing structural material analyzed. While cement has outshone the steel market, this study also suggests a steel resurgence within the next decade and further as the large populations in a LDR develop into a steel using MDR. LDRs have an anticipated growth rate of 1.46%, while MDRs are anticipated to grow at .25%. These growth projections have implications for the future of worldwide cement and steel productions.

This study failed to identify useful trends in the introductory phase of materials. Based on the World Materials Pricing data, it was determined that material production has a loosely correlated effect on price. The most significantly correlated variable is the price of energy. The price of energy shows a moderate to strong logarithmic relationship with material price, and in this study, the price of natural gas had a stronger correlation than oil for all materials studied.

Based on the U.S. Recycling Trends data, the U.S. recycling rate for steel counterintuitively appears to have no relation to steel price. The recycling rate for aluminum is loosely positively correlated with price.

Finally, methods to determine the MCP have been suggested.
Next Steps

One of the key next steps is to substantiate the above conclusions with additional data analysis from other industries and further in depth analysis of the four industries studied. More information must also be collected to determine the causes of the existence or lack of certain relationships. Many of the above conclusions need further verification and exploration:

While it is useful to understand that per capital materials use is increasing, explorations are need to determine whether that statement holds true for other materials. A country by country analysis will be helpful to determine whether the growth of certain countries are driving the increase or decrease of materials use, as suggested by the MDR-LDR relation with cement and steel. This study has pointed out the correlation and a rationale, but has not verified causation to a high degree of certainty.

Further study into the rate of conversion from LDR-MDR will help determine the future changes in steel and concrete usage per capital.

Analysis of more industries may be helpful in identifying useful trends in the introductory phase of materials.

Further study into the variables affecting materials price is needed. The current relationship between price of energy and price of material shows high correlation, but without proof of causation. It is possible that the same factors that affect energy price also highly affect materials price.

Recycling trends seem to hold at steady levels except through large scale intervention. In aluminum’s case, the government gave an incentive to recycle. Hypotheses to be explored include whether steel recycling is constant because all recycling rates tend to stay constant (as seems to be true for aluminum before the bottle deposit laws) or because there exists a definable gradient as a barrier to increasing the recycling rate.

Steel’s recycling rate is notably high. Further study into the source of steel that is recycled may shed light onto why that industry has such a high recycling rate.

Finally, methods to determine the MCP have been suggested that can help objective identify the MCP in hindsight. More analysis should be done to identify the MCP within the first several years of its passing. Additionally, it should be noted that the MCP for all industries analyzed occur within a small range. While this study took high variance in production as an indication of the introductory phase, high variance in production may simply be a characteristic of that time period. Similarly, low variance in production may also be an artifact of a certain time period. Study outside of the realm of materials (such as the introduction of a new product) may aid in understanding the variance phenomenon on a smaller time scale.
References

Note: Most sources have been referenced in the Footnotes Section. It should be noted that the data for the amount of materials produced world wide was obtained from the United States Geological Survey and the U.S. Bureau of Mines through their Minerals Yearbooks and previous incarnations of the same publication. Data for the spot price of oil and natural gas was obtained from Dow Jones and Company. World population data, including the proportion of LDRs and MDRs was obtained from the United Nations and the U.S. Census Bureau.


During the first half of 1939 the rate of consumption was fairly stable and approximated the levels established in the last quarter of 1938, but with the outbreak of war in Europe demand improved as steel production soared to record proportions in the closing months of the year. The consumption of scrap probably reached an all-time peak in November 1939." (503)

Exports of ferrous scrap from the United States in 1940 declined 21 percent from 1939 mainly because exports to several countries that were involved in the European War were eliminated and because exports to countries other than the United Kingdom and the Western Hemisphere were restricted beginning in October. ... Immediately after war broke out in September 1939 the International Scrap Convention- a centralized buying agency for European consumers- suspended operations." (500)

Under the impetus of greatly increased activity in war industries steel-ingot production in 1941 surged to unprecedented heights, creating the greatest demand for iron and steel scrap ever known. The production of steel ingots in 1941 increased 24 percent over that in 1940.... During the first 6 months of 1941, scrap consumption was fairly stable, but with the accelerated rate of war-materials manufacture, demand improved as steel production soared to record proportions in the closing months of a year (517)
“The supply of iron and steel scrap in the United States was critically short throughout 1945. Except for a small increase in consumers’ stocks in the Southeastern district, all districts reported declines from the previous year, indicating that suppliers were unable to meet the demand, even though requirements decreased considerably during the year.” (522)

“Battlefield scrap has been considered a means for bolstering the dwindling supply of purchased scrap in the United States, but full utilization has not yet been deemed advisable because of the high alloy content and the presence of contaminating elements normally undesirable in steel compositions. These elements are copper, tin, cadmium, zinc, lead, and some boron and arsenic from enemy sources. Arsenic which is not removed in the melting process and is present in some German steels has a detrimental effect on the toughness of steel and its response to heat treatment. Therefore, it is felt that before battlefield scrap can be successfully used in making American steels it must be properly segregated. Dealers were not able to segregate this scrap properly due to the labor shortage, but since hostilities have ceased abroad it is expected that the battlefield scrap will be returned to the United States, properly segregated and will eventually flow into commercial channels.” (523)

“At the end of 1959 blast- and steel-furnace capacities reached new peaks of 96.5 million and 148.6 million tons. Steelmaking capacity increased 0.9 million tons, compared with 6.9 million in 1958, and blast-furnace capacity increased 1.9 million tons, compared with 3.6 million in 1958. New steelmaking capacities, by type of process and gain or loss during 1959, in million tons, were: Open hearth, 126.6 (plus 0.1); electric, 14.4 (plus 0.9); oxygen, 4.2 (plus 0.1); and Bessemer, 3.4 (minus 0.2). Advances in technology included increased unit blast-furnace output through the improved preparation of raw materials and the use of natural gas in the blast furnace. Algoma Steel Corp., Ltd., used iron-ore agglomerates to replace over 50 percent of the scrap used in its basic oxygen converters, without any apparent loss in metallic yield. At an experimental oxygen converter installation in Donawitz, Austria, the scrap charge was increased from 30 to 50 percent.”

Then came the strike of 1959. Steel production had fallen off the year before in a brief recession to 85 million tons, the lowest since 1947. Profits were down, costs were getting out of line and the industry decided it was time to challenge the union not only on wages but also on padded work crews and inflexible work rules.
The strike started in the middle of July, and ... many steel customers were less confident and turned to markets abroad. That was the year steel buyers discovered that other nations also sold steel. At first they dealt with the Europeans and then the Japanese came on fast.

Imports jumped from 2 million tons in 1958 to 5 million tons in 1959. They were never again to return to the 1958 level.

Tom Crowley, a Yale graduate who became general manager of Bethlehem's Johnstown, Pa., plant, recounts the subtle market changes after the strike.

"The big customers came back," he said, "but we began to lose the by-products—nails, field fence and barbed wire. It was nickel and dime impact at first but it started to affect the cost structure because we were now selling a smaller piece of the product."

"And soon we were competing with a market we could not match. Belgian barbed wire was being delivered on the docks at Baltimore at less money than it cost us to make it."

"They should have learned several lessons after the 1959 strike," says Don Swan, who is now a securities broker in New York. "First, if there is cheap steel out there—even if it is only 5 percent of the market—it is going to impact on the price of the other 95 percent. Second, the strike showed there was a group of steel users looking to up their profit margins and this type of user discovered the cost benefits of foreign steel."

The UN defines:

iron, pig iron and crude steel [code 82]

**Long name**

iron, iron ore, pig iron and crude steel

Various mineral aggregates from which iron metal is obtained by the conversion of various iron ores by reduction either into pig iron, in blast furnaces or electric furnaces, or into a spongy form (sponge iron) or into lumps by various direct reduction processes. Iron ore is measured by the weight of the ore and may contain varying concentrations of metal. (11) CPC Vers. 1: Iron ores and concentrates, other than roasted iron pyrites (Group 141). Basic iron and steel (group 411).

United Nations, Statistics Division
