Improving steel demand modeling in Integrated Assessment Models

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Abstract

Steel production emits a large share of a country's greenhouse gas emissions. Therefore it is important that the steel production is accurately modeled in Integrated Assessment Models (IAMs). This thesis focusses on using physical drivers, rather than GDP, in a method to model steel demand. These drivers are based on the two largest steel consuming end-use sectors: construction and automotive. Within those sectors, 9 drivers for steel demand were identified. After statistical analysis, only population, new dwellings constructed, total floor area and motor vehicles produced showed strong correlations with their sectors' steel consumption. These four drivers were then used to model the steel demand for the entire end-use sector. The method used for modeling is a bottom-up model based on population size and historical trends of steel intensity and product intensity.

Acknowledgement

I would like to thank everyone who supported me while writing this thesis. Special thanks are for my supervisors Katerina Kermeli and Wina Graus. Katerina, thank you for making me enthusiastic for this project and your always insightful feedback. Wina, thank you for your patience, supportive words, and helping me straighten out my thoughts. You both really helped me improve my work.

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1. Introduction

Steel plays a large role in modern day life. It is used in buildings, vehicles, every day appliances, etc. With an increasing world population and increasing demand of steel containing products, it is not surprising that steel demand continues to rise. Between 1999 and 2013 the worldwide crude steel production more than doubled (World Steel Association, 2005, 2014a). Since the world population is still increasing, and the economies of China and India are developing at a rapid pace, steel demand will likely increase even further.

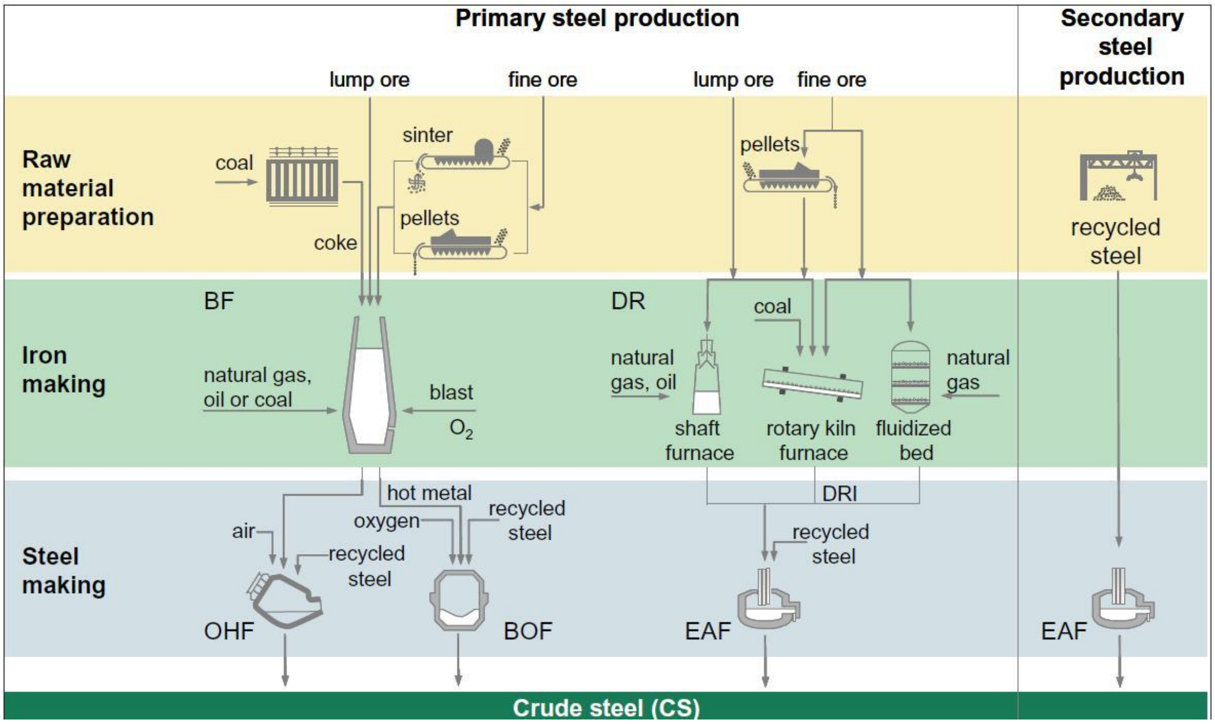

Figure 1: The steel making process (World Steel Association, 2008)

There are two routes for making steel: primary steel production and secondary steel production. The three main methods of steel production are shown in Figure 1, two of which are primary and one that is secondary. The first method shown is primary steel making when using a Blast Furnace (BF). Coke (a coal product), and iron ore (in the form of sinter or pellets) are added to a BF. The burning of coke in combination with hot blasts of air in the furnace heat up the iron to 1530° Celsius, which is the temperature steel becomes liquid. This allows chemical reactions to take place and remove impurities (Worrell, Blinde, & Neelis, 2010). The molten iron is then transferred to a Basic Oxygen Furnace (BOF) where pure oxygen is added to reduce the carbon content of the iron to create steel. The steel is then cast into a final shape or a slab (Worrell et al., 2010).

The second method in the figure is when making Direct Reduced Iron (DRI) through Direct Reduction (DR). This process was designed to cut out the need for coke plants, sinter plants, blast furnaces and basic oxygen furnaces to save energy. Instead, lump ore or pellets are gasified with natural gas to remove the impurities and melt it after which an Electric Arc Furnace (EAF) is used to make steel out of the metal by using an electric current (Battle et al., 2014).

The third method is the secondary steel production which uses scrap/recycled steel directly in an EAF to make it liquid so it can be cast and re-used (Worrell et al., 2010).

Primary steel making, the blast furnace specifically, requires large amounts of energy. This makes the iron and steel industry the second largest industrial energy consumer worldwide (IEA, 2014). As a result the steel industry had greenhouse gas emission in 2005 totaling up to 2165 Mt CO_2eq (IEA, 2007).Through its large energy consumption and high greenhouse gas emissions, the steel industry is a large contributor to anthropogenic climate change. Therefore the steel industry is often included in models which try to predict future greenhouse gas emissions. One type of model that often tries to predict greenhouse gas emissions is Integrated Assessment models (IAMs). IAMs combine information from different fields of study such as social, economic and energy sciences in order to predict future greenhouse gas emissions and other environmental effects caused by human activities (Dowlatabadi, 1995).

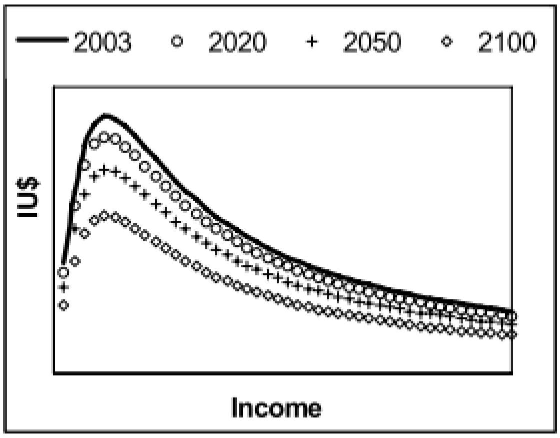

Figure 2: Schematic picture of intensity of use (Neelis & Patel, 2006)

Since the energy demand is different for every process and every plant, the average energy intensity per tonne of steel is often used in models (Neelis & Patel, 2006). This leads to the need of modeling future steel demand in order to know the energy demand and calculate greenhouse gas emissions. Almost every model bases their steel demand forecasts on a combination of population growth and Gross Domestic Product (GDP) growth (Aden, 2010; Akashi, Hanaoka, Matsuoka, & Kainuma, 2011; Dutta & Mukherjee, 2010; Groenenberg, Blok, & Van Der Sluijs, 2005; Neelis & Patel, 2006). These models mainly analyze the Intensity of Use ($IU_\$$), which can be described as the material consumption per unit of GDP (Neelis & Patel, 2006). When plotting the $IU_\$$ for steel demand based on GDP/capita, it shows an inverse u shape curve as can been seen in Figure 2. The shape of the curve is often explained by the development of the country. As a country develops, and GDP grows, a shift to less material-intensive products takes place, materials are used more efficiently and old lower quality materials are replaced by new higher quality ones (Neelis & Patel, 2006). This implies a decoupling between material use and GDP at high GDP levels. When using the IU method the focus is only on material flow and the service providing stock is neglected. Furthermore, the IU is an abstract ratio between two fluctuating variables, which makes it a weak method for estimating future trends (Müller, Wang, & Duval, 2011). Therefore the idea is proposed to instead of GDP physical indicators can be used for modeling demand (Pauliuk, 2013). Nevertheless, there seems to be very few non-monetary indicators available for modeling steel demand in IAMs.

The aim of this research is to improve steel demand modeling in IAMs by using physical drivers. This will be done by answering the research question:

How can steel demand modeling in IAMs be improved through looking at physical drivers of end-use of steel?

The answer can provide a method to improve steel demand modeling in IAM's. The identification of physical drivers and a method to model steel demand with physical drivers would be good addition to the existing literature on modeling steel demand, since only very limited research into physical steel demand drivers has been performed. Furthermore, the identification of these drivers and method might influence how IAMs model steel demand. This new method might lead to better information on future emission caused by the steel industry. Considering that IAMs are often used by policy makers, a new way of modeling may indirectly contribute to better emission reduction policies.

Based on the conceptual model in Figure 3, three sub questions have been formulated to better guide the research. The sub questions are:

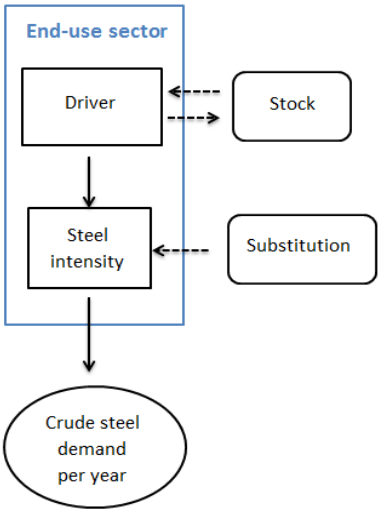

Figure 3: Conceptual framework

1. **What are the main end-use sectors for steel demand and what does their steel consumption look like?**

When the IU method is used for modeling steel demand, an assumption on the state of the economy is made. As an alternative future steel demand could be based on the services that steel products provide. This sub-question contributes to the identification of steel services. Since there are many individual products that use steel, looking at the sector rather than individual products allows identification of the general purpose of large quantities of steel. Furthermore, identifying the uses of steel contributes to the identification of drivers for that sector.

2. **What are usable physical drivers for steel demand within the identified end-use sectors?**

After the identification of the main uses of steel and the size of their consumption, the next step is to identify what causes the consumption of these products to grow or decline. This will be done through identifying the drivers, which are a key aspect that influence the growth/decline of steel demand. The identified drivers are then tested on their usability for modeling steel demand.

3. **How can the identified drivers be used to model steel demand?**

After the drivers have been identified, they have to be converted into a form that allows modeling steel demand. A method that allows the modeling of steel demand using the identified drivers will be proposed. Steel intensity will be included in this method.

Within the conceptual framework of Figure 3 stock and substitution are also incorporated. These factors will come back throughout the research and don't have individual research questions.

The next section of this thesis is the methodology, where the methods used to answer the sub-questions will be discussed. This will be followed by three chapters, where the results will be discussed and the sub questions will be answered. In chapter 3 end-use sectors of steel will be identified. The fourth chapter will focus on the identification of usable drivers for steel demand. The fifth chapter is about the proposed method to use the identified drivers to model steel demand. This is followed by a discussion sector where limitations of the used methodology will be discussed and recommendations for future research will be made. The final part of this thesis in the conclusion where the main research question will be answered.

2. Methodology

To find a way to improve modeling in IAMs, first research had to be conducted on end-use sectors of steel, physical drivers and methods of modeling steel demand. In this chapter the methods used for conducting the research and modeling demand are discussed. This will be done per chapter, each representing one sub-question.

Chapter 3: Identifying end-use sectors and their steel consumption

The first step of this research was to gather data on the steel consumption of different end-use sectors for different countries and regions. The choice to focus on countries and regions rather than the world was made to be able to account for the regional differences in development and practices. Since modeling future projections was not an aim of this thesis, only data up to the year 2014 was collected. Most of this data came from the World Steel Association as well as other national and regional steel associations. The data that was gathered consisted of the sectorial division of steel use within the country or region in percentages of total steel consumption. Based on the global data the four largest steel end-use sectors were identified. After the largest end-use sectors were determined, literature research was performed to describe the functions of steel within these end-use sectors. A comparison between the identified national and regional data was used to identify the two largest end-use sectors that would be used in the other chapters of this paper.

Chapter 4: Identifying usable physical drivers for steel demand

Before identifying drivers, the term driver first needed to be defined. The definition of a driver as given by the oxford dictionary is: “*A factor which causes a particular phenomenon to happen or develop*” (Oxford Dictionaries, n.d.). For statistics a driver could be defined as causality. The combination of these two definitions led to the definition used in this thesis: *a factor that shows a causal connection to the increase or decrease of steel production and steel consumption*.
However, since proving causal connections is outside the scope of this thesis, some of the proposed drivers might be factors that show strong correlations instead.
A physical driver within this thesis is defined as: a physically existing factor that shows a causal connection to the increase or decrease of steel demand and steel consumption. Physical is something that you can touch, measure with a tape, weight, etc., which distinguishes it from non-physical drivers like monetary drivers, legislation, competitiveness of other material sectors, etc.
Steel production is the amount of steel that is produced by the entire steel industry of a country, region or the world. The steel consumption is the amount of steel that is used by an end-use sector when creating their products. Within this thesis steel demand is the amount of steel that is either expected in the future or the amount of steel that is modeled. These are examples of material flows, which are inputs and outputs of the system. The material already in the system is called stock.

Initially, an investigation on how steel demand was currently modeled in IAMs a literature study was performed. Most of the information came from scientific literature and some of it came from a confidential source.
The next step was to perform a scientific literature study to identify existing physical drivers for steel demand in the main end-use sectors, and modeling methods that incorporate them. Then physical drivers that could possibly represent sectorial steel demand were chosen. These drivers were either

chosen from literature or determined by looking at the forms of sectorial steel use identified in chapter 3. Historical data of the chosen drivers was gathered from a combination of online databases and relevant associations.

The historical data on the drivers was then tested against historical steel consumption of the relevant sector by determining the coefficient of determination. This was done to determine their usability for the next chapter. In some cases, data for the year 2009 or 2009 onwards, were marked as outliers and excluded to limit the influence of the financial crisis on the correlation. The coefficient of determination method was chosen because it identifies the statistical correlation between the change in driver and (sectorial) steel demand. Drivers with higher statistical correlation were identified as most usable for modeling in the next chapter. Therefore, usability of the drivers is defined as: *a positive statistical correlation with an R^2 of 0.5 or higher*. The value of 0.5 for R^2 was chosen based on Table 1, where it is the minimum value for a strong correlation. The choice for a positive correlation was made since it is expected that the demand of steel goes up as the driver increases. A negative correlation is when the linear trend has a downwards direction and indicates additional circumstantial factors which could be hard to explain, and therefore difficult to incorporate in a model. Consequently negative correlations were identified as not usable.

Table 1: Values for the coefficient of determination and their strength (University of Strathclyde, n.d.)

Value of the Correlation Co-Efficient (R^2)	Strength of the Correlation
1	Perfect
0.8 - 0.9	Very Strong
0.5 - 0.8	Strong
0.3 - 0.5	Moderate
0.1 - 0.3	Modest
> 0.1	Weak
0	Zero

Chapter 5: Using physical drivers to model steel demand

The modeling methods that were identified in chapter 4 were adjusted to allow for modeling the chosen usable drivers. How the adjusted method works is further explained in chapter 5. It contains 3 variables, population, steel intensity and product intensity. Steel intensity is the mass of steel required per steel “product’ produced. The product intensity is the physical driver per capita. The term product comes from the fact that all physical drivers can be linked to physical products. For example, for the automotive industry steel can be linked to motor vehicles, which are products this sector produces.

Since all drivers were chosen to represent an entire end-use sector, no individual data collection of steel intensity per different steel driver has taken place. In this thesis the steel intensity is defined as the amount of steel consumed in the sector divided by the historical data on sectorial steel production by the historical data of the driver. For example, the total amount of steel consumed in the automotive industry divided by the number of motor vehicles produced. The product intensity was determined by dividing the historical data of the driver by the historical data on population size. The change in product and steel intensity were plotted over time and a historical trend was determined. Based on the historical trend of intensity change over time, equations were created with time as its independent variable. These equations allow for a method of forecasting the product and steel intensities. These intensities were then used in combination with the modeling method to check if they show the same growth and decline as historical steel consumption data. The data of the steel intensity, product intensity and modeled steel demand are displayed in a number of graphs and tables. The equations for intensity change over time can be found in.

3. Identifying end-use sectors and their steel consumption

The first step to answering the research question is identifying the end-use sectors of steel consumption and the applications of steel within these sectors. When looking at worldwide steel consumption in Figure 4, the construction sector can be identified as the largest consuming sector. It consumes over 51% of all steel produced worldwide in the year 2013 (World Steel Association, n.d.). The other three fairly large steel consuming sectors that can be identified are mechanical machinery with a share of 14.5%, metal products with a share of 12.5% and automotive with a share of 12% in 2013 (see Figure 4). Together these four sectors are responsible for over 90% of worldwide steel consumption. The applications of steel will now be discussed individually for each of these four sectors.

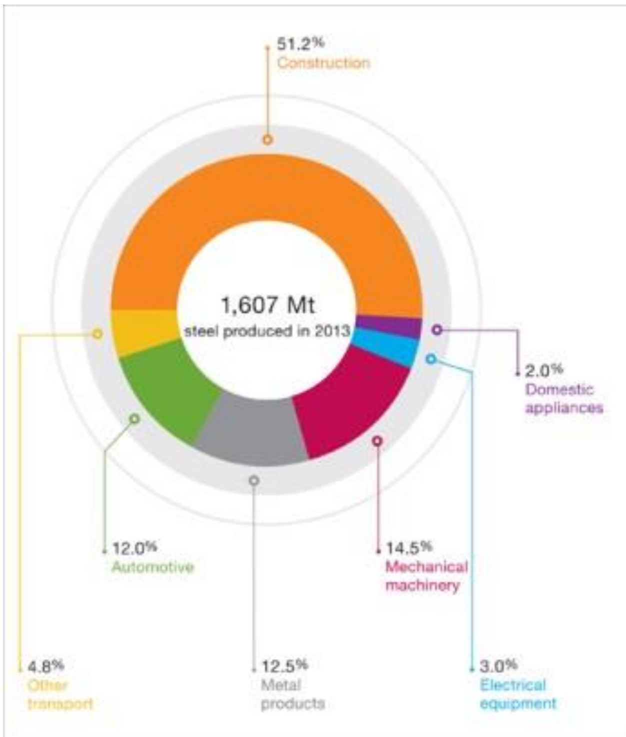

Figure 4: World steel consumption by sector

Construction sector

Within the construction sector two types of construction can be identified. The first is infrastructure construction, which consumes 26% of all steel used in construction worldwide for 2008 (Allwood, Cullen, & Carruth, 2012). A study by Moynihan and Allwood (2012) identified four infrastructure construction sub sectors for the UK: Utilities, Rail, Bridges and other. The second type of construction is building construction which consumes 74% of all steel used in construction worldwide(Allwood et al., 2012). For the building sector in the UK Moynihan and Allwood (2012) identified the following 6 sub-sectors: industrial, commercial, offices, public, residential and other. The definition of these sub-sectors can be found in

Table 2 and will be adopted for this study.

Table 2: Construction sector definitions used in Moynihan and Allwood (2012)

Sector	Definition
Buildings	
Industrial	Factories and warehouses
Commercial	Retail and leisure facilities
Offices	All office workspaces, including in mixed-use
Public	Education, health and administration
Residential	Houses and apartments
Other	Stadia, agricultural & miscellaneous
Infrastructure	
Utilities	Energy, water and waste generation, processing, distribution and collection networks and plants
Rail	Tracks and sleepers
Bridges	Road and rail bridges
Other	Airports, harbors & miscellaneous

A few key applications of steel can be identified within the different construction sub-sectors. Worldwide, the largest share of steel used within both the infrastructure and buildings sector is reinforcing bars with 54% and 44% respectively. Reinforcing bars are added to concrete to give the structure more strength and stiffness. Since steel is relatively inexpensive, binds well to concrete and has a similar expansion coefficient, it is an often used option (Allwood et al., 2012). This translates into a worldwide production of concrete reinforcing bars that consists of 16% of the total world steel production (World Steel Association, 2014b). The other large applications of steel within the infrastructure sector are structural sections, hot rolled train rails and pipelines with a share of 24%, 6% and 16% respectively. For the buildings sector, the other main applications are structural section consisting of hot rolled sections, and welded plates and sheet products with 25% and 31% respectively (Allwood et al., 2012).

Mechanical machinery sector

No exact description of the mechanical machinery sector was found. However, following the description by the European commission, (mechanical) machinery can be defined as: "*an assembly, fitted with or intended to be fitted with a drive system other than directly applied human or animal effort, consisting of linked parts or components, at least one of which moves, and which are joined together for a specific application*" (European Comission, 2014).
Allwood et al. discusses the sector mechanical equipment which covers large industrial robotic-machinery and rolling mills to small workshop tools (Allwood et al., 2012). Since they both share a similar size in world steel consumption with 14.5% for mechanical machinery in 2013 and 13% for mechanical equipment in 2005, the assumption is made that this is the same sector. The steel consumption of this sector consists of 40% plate and hot rolled bar, 22% tubes, 22% hot and coiled rolled coils and 6% of cast product and wire rod (Allwood et al., 2012).

Metal products sector

Under the North American industry classification system, the fabricated metal product manufacturing sub-sector is defined as: "[comprising of] establishments primarily engaged in forging, stamping, forming, turning and joining processes to produce ferrous and non-ferrous metal products, such as cutlery and hand tools, architectural and structural metal products, boilers, tanks and shipping containers, hardware, spring and wire products, turned products, and bolts, nuts and screws." (Industry Canada, 2015). Within this definition a lot of different end products are created within this sector.
Allwood et al., divide the metal products sector into three sub-sectors: metal goods, consumer packaging and domestic appliances (Allwood et al., 2012). Metal goods have a worldwide share of 78% in the metal products sector and produce many different goods such as filing cabinets, bathtubs, barbed wire, etc. Their steel consumption consists of 30% hot rolled coil and 20% hot rolled bar. The remainder is plate, narrow strip and cast iron (Allwood et al., 2012). Consumer packaging has a share of 5% and consists of food cans and aerosol containers. The multitude of steel consumed within this sector is tin-plated rolled steel. Finally, domestic appliances accounts for 17% steel consumption in the metal products sector. Up to 70% of this sector consists of white goods with a main steel use of cold rolled coil (Allwood et al., 2012).

Automotive sector

In the automotive sector steel is used for fabricating components of cars, light trucks and trucks. In cars, for example, steel is used to create the chassis, roofs, door beams and body panels as well as in other places through the car body (George, 2009). Cold rolled sheets, which consist of 34% of steel use in this industry, are used to produce the body of the car. Cast iron is often used for the engine block and carbon steel for gears. Together they account for 23% of steel use. The other 43% is for the suspension, gas tank, steering and braking systems, etc. (Allwood et al., 2012).

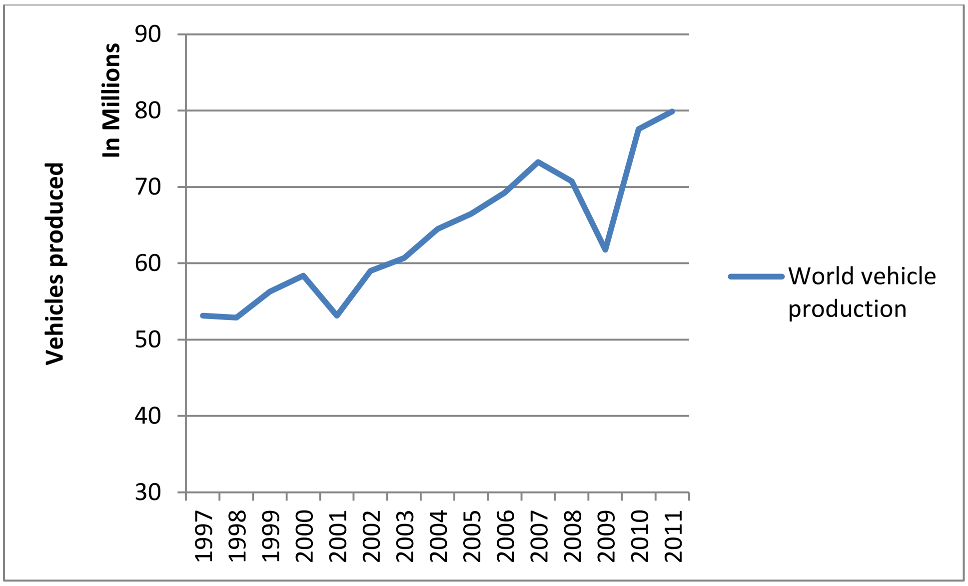

Figure 5: World vehicle production (OICA, 2015a).

Sectorial steel consumption

Since this research will mostly be conducted on a regional and national level, it is relevant to know the sectorial steel consumption at these levels as well. This data for multiple years could only be found for the EU27, USA and Japan. For the EU27 (which will also be referred to as EU and Europe),

the largest steel consuming sector in 2013 was construction. In Figure 6 it can be observed that it increased from 14% in 1999 to over 30% in 2013. In turn structural steel work and first processing were the sectors to decrease in size until they are almost non-existent in 2013. The other sectors stayed relatively stable. Automotive grew from 13% in 1999 to 18% in 2013, making it the second largest sector. Mechanical engineering and metalware have a shared 3rd place with both 14% of steel consumption in 2013.
For Japan only data for 8 years was available. When looking at Figure 7, the two largest sectors are easy to identify. Both construction and automobiles hover around an average of 35% sector share. The other sectors are much smaller, with only an average of 11% share for shipbuilding and 5% share for electrical machinery.
The USA is the only one of the included countries and regions where the construction and automotive sector are not the largest sectors (See Figure 8). Over time no large variation in sector size can be observed and the proportions stayed about the same. The largest share of steel consumption is in service centers and distributors. This basically consists of middlemen who buy steel in bulk from the producers and sell it in small quantities to their customers. They also often have the tools to shape the steel in the form their client desires (United States International Trade Commission, 1982). It is unclear which end-sector the steel consumed by this sector falls into.
The construction sector is the second largest sector with an average of 21% of total steel demand. The third largest sector is the automotive industry with an average consumption of 14%.
In Table 3 some sectorial steel shares of other countries for individual years can be observed. Construction is the largest sector for all of these countries, while automotive is a smaller sector in comparison. This could be due to the state of development of the country. If they are still developing, and their infrastructure is not yet complete, a large share for the construction sector is to be expected. Since there is not enough data for these countries to observe a development over time, these countries will not be included further on in this thesis.

Worldwide, the construction sector and automotive sector are two of the largest steel consuming sector with a total share of over 60%. Furthermore, these sectors are also the largest steel consuming sectors for the EU and Japan. For the USA they are the second and third largest sector with a combined share of 35%. Therefore these two sectors have been selected to be used as the end-use sectors for the rest of this thesis.

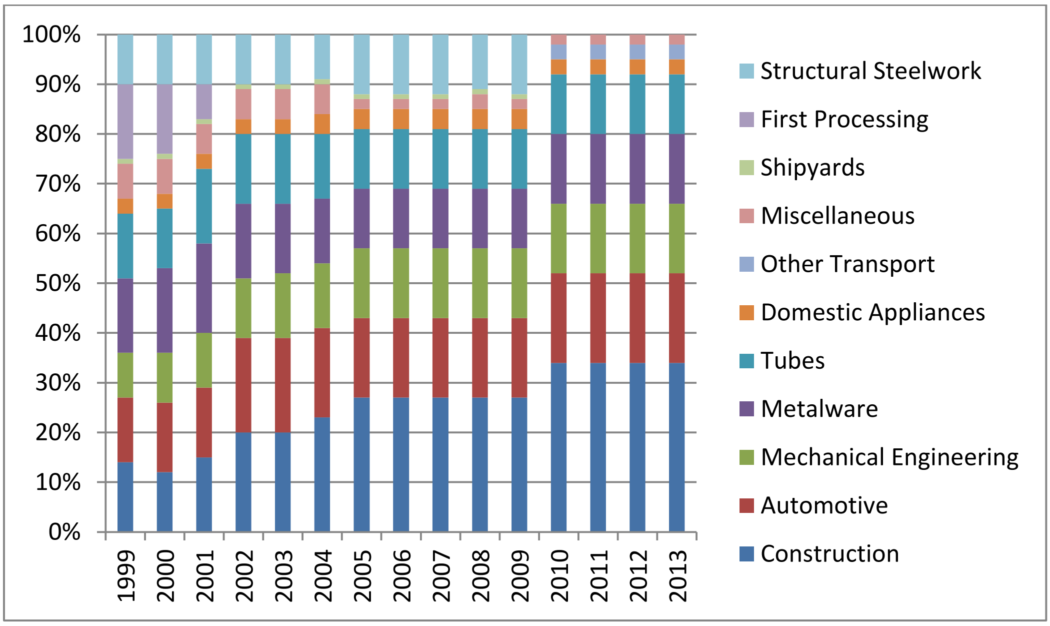

Figure 6: Sectorial steel use EU27 (Eurofer, 1999, 2000, 2001, 2002, 2003, 2004, 2009, 2010, 2014)

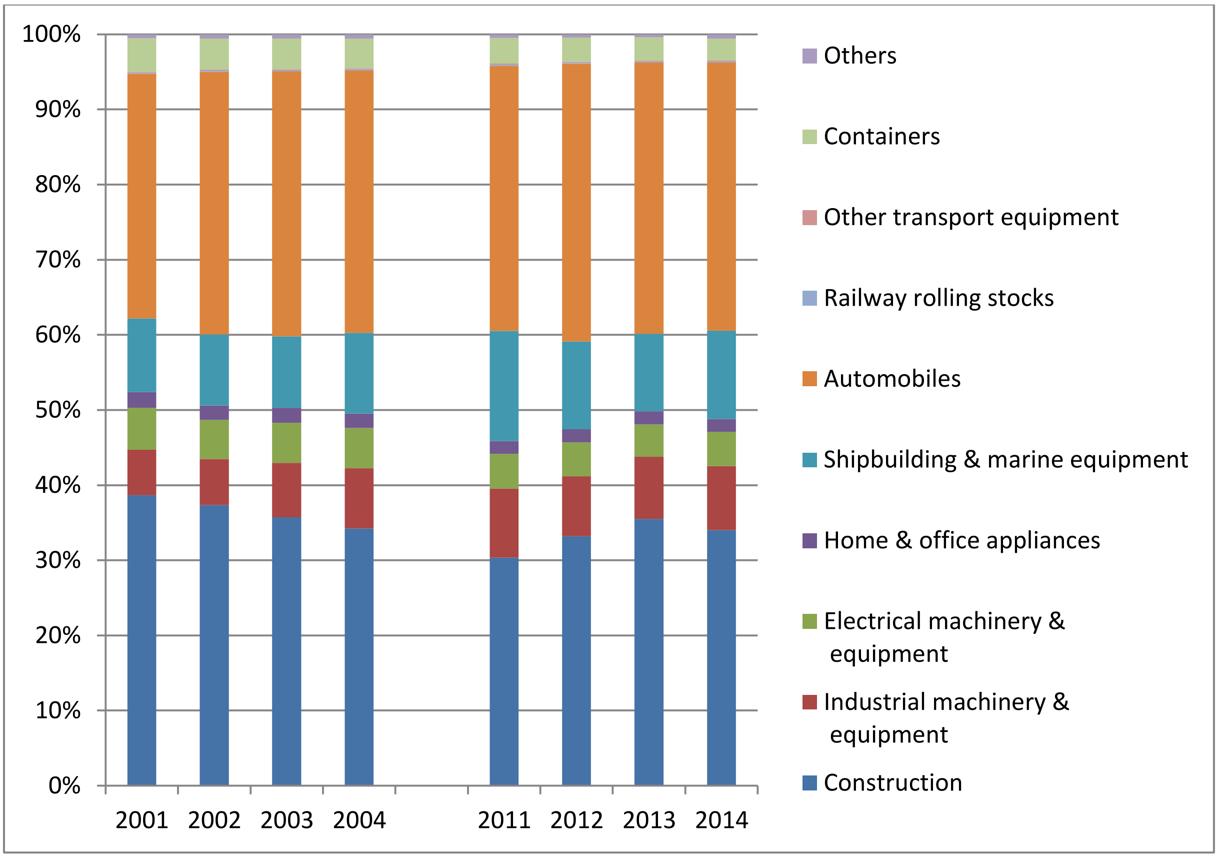

Figure 7: Sectorial steel use in Japan (The Japan Iron and Steel Federation, 2005, 2015)

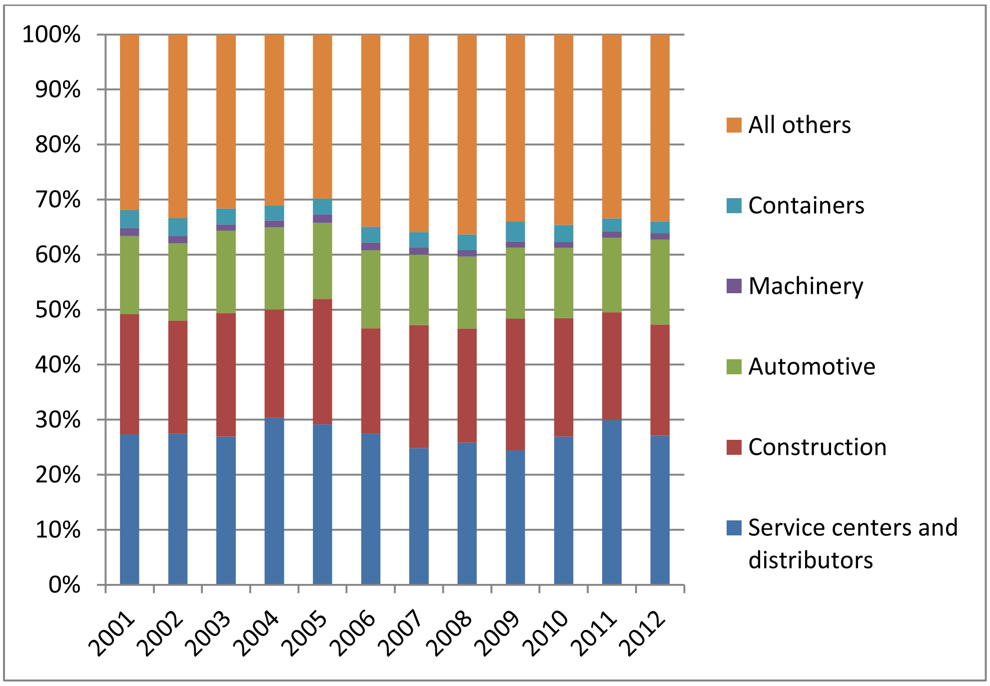

Figure 8: Sectorial steel use in the United states of America (USGS, 2002, 2003, 2012, 2004, 2005, 2006, 2007, 2008, 2009, 2010, 2011)

Table 3: Sectorial steel use of different countries and regions (Investment Support and Promotion Agency of Turkey, 2013; Metallurgical Industrial Planning and Research Institute of China, 2015; OECD Steel Committee, 2014)

	Year	Construction	Machinery	Automotive	Shipbuilding	Other
BRIC[1]	?	49%	17%	7%		27%
China	2011	48%	17%	6%	3%	26%
China	2012	48%	18%	6%	3%	26%
Russia	?	68%	8%	2%		22%
Turkey	2013	40%				60%

[1] BRIC is the abreviation for Brazil, Russia, India and China.

4. Identifying usable physical drivers for steel demand

The focus of this chapter is on identifying drivers that can be used to model future steel demand on. Since monetary drivers have been used in the past and a decoupling of GDP as driver for steel has been observed, the focus the focus of this chapter will be on physical drivers. For a driver to be considered usable, a positive statistical correlation with an R^2 of 0.5 or higher is required (Table 1).

In the first part of this chapter the method that is currently used in IAMs to model steel demand is discussed. This is followed by the identification of physical drivers within literature. Then the statistical results of the different drivers are shown and their usability is discussed. The chapter concludes with the identification of drivers that will be used in chapter 5.

How is steel demand in IAM's modeled

Integrated assessment models generally have a goal of predicting future greenhouse gas emissions based on socio-economic circumstances (Dowlatabadi, 1995). For some models this is done by making general assumptions on future emissions, while other models look at the changes within disaggregated sectors. Since the iron and steel industry is such a large energy consumer and therefore greenhouse gas emitter, it is often modeled individually as a disaggregated sector. The emissions of this sector are based on the energy intensity of the different steel manufacturing processes and the amount of steel they manufacture. To know how much steel is manufactured, the future steel demand needs to be determined first (Confidential source). The most common way to model steel demand is to use the Intensity of Use (IU). In this method the demand of steel gets coupled to driving socio-economic values like a countries national income (Neelis & Patel, 2006; Wårell & Olsson, 2009). Research has shown that the IU can often be described as a function of per capita income (Roorda, n.d.; Confidential source):

Equation 1

$$IU_{\$} = \frac{C}{GDP} = \frac{\alpha * e^{\frac{-\beta}{GDP_{cap}}}}{GDPcap}$$

Where
C = Steel consumption
GDP = GDP
GDP_{cap} = GDP per capita
α=Maximum total consumption per capita
β= GDP per capita level with the maximum IU

When GDP/capita and IU are plotted against each other, the Intensity of Use curve becomes visible (Figure 9) (Van Vuuren, Strengers, & De Vries, 1999). The theory behind the shape is that as income increases, a country's development matures. Infrastructure gets built and completed, the country's economy changes from agricultural to industrial and eventually towards a more service based one. The demand will start to decrease when steel is replaced by other, perhaps cheaper materials. Furthermore, technological development can lead to a better raw materials use. Eventually this process results in a decrease of steel demand as the GDP per capita increases (Van Vuuren et al., 1999).

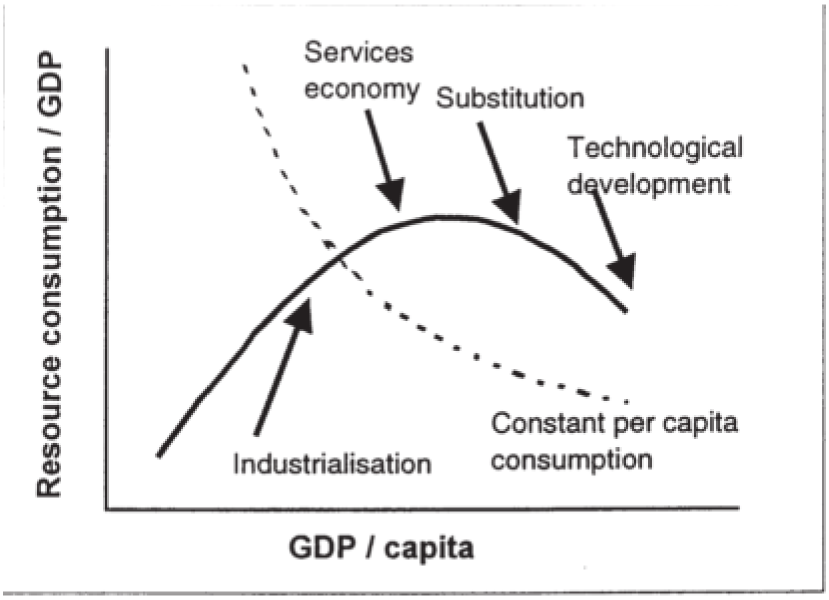

Figure 9 Intensity of use curve (Van Vuuren et al., 1999)

Using the per capita income and the intensity of use, the per capita consumption of steel can be determined (Roorda, n.d.):

Equation 2

$$PCC = IU_{\$} * GDP_{cap}$$

Where
PCC = Per capita consumption of steel
$IU_{\$}$ = The intensity of use (Kg/$)
GDP_{cap} = GDP per capita

Projections on future population and GDP levels, based on different future scenarios, are often incorporated in IAMs. That still leaves both PCC and $IU_{\$}$ as unknowns. Therefore within the model the per person consumption is modeled using the following equation:

Equation 3

$$PCC = \alpha * e^{\frac{-\beta}{GDP_{cap}}}$$

Where
PCC = Per capita consumption of steel
GDP_{cap} = GDP per capita
α=Maximum total consumption per capita
β= GDP per capita level with the maximum IU

The value of α and β are determined by performing a regression analysis on historical data (Confidential source). This can be done for a global curve, but also for individual large steel consuming regions. In essence this method is therefore based on a statistical connection between resource consumption per GDP and GDP per capita. It does not incorporate the use of steel in any way and is therefore a top-down method of modeling.

Drivers in literature

A physical driver that is named often in literature is population size (Aden, 2010; Akashi et al., 2011; Dutta & Mukherjee, 2010; Groenenberg et al., 2005; Neelis & Patel, 2006). Besides being used for the intensity of use curve, population can also play a part in combination with a different physical driver since the size of the population will most likely influence the size of product consumption.

Daniel Müller proposes to use the stock dynamics approach to forecast materials demand and waste generation as an alternative to the IU method (Muller, 2006). It is a method based on physical accounting that looks at the service provided by the stock of products in use rather than demand as an end in itself like the IU method does. The drivers and determinants of the model are:

- Population
- Service stock per capita
- Lifetime distribution
- Material intensity per service unit

The method was applied to concrete in the Dutch dwelling stock. The service stock per capita was expressed as useful floor area per capita, and the material intensity as concrete use per square meter of useful floor area.
Literature research also revealed a study by Hu, et al. (2010) who applied the stock dynamic approach on iron and steel use in residential buildings in China. A dynamic material flow analysis was used to identify steel demand and scrap availability based on the parameters:

- National total population
- Urbanization rate
- Per capita floor area
- Lifetime distribution housing
- Material intensity per unit floor area

The material flow analysis was also applied to Norway's dwelling stock to see the results of the population's demand of housing on the stocks and flows of floor area and material demand (Bergsdal, Brattebø, Bohne, & Müller, 2007). An important factor of their research is that the effects of renovation cannot be linked to floor area in the dynamic material flow analysis. For renovation the floor area of dwellings is often unchanged, but renovation does require construction and therefore has material demand (Bergsdal et al., 2007). To include renovation in a dynamic material flow analysis it has to be either linked to an individual dwelling or link it to the turnover of material through including material stock exposed to renovation and the lifetime of material stock exposed to renovation.

From the above parameters, determinants and drivers, two possible drivers for steel demand can be identified: total population and per capita floor area which represents service stock per capita. The per capita floor area is considered a driver since its decrease or increase would translate into an in- or decrease in steel demand. Lifetime distribution of housing indirectly affects steel demand through its influence on per capita floor area. When dwellings are demolished and replaced by a new dwelling with the exact same floor area, the total net floor area does not change while materials are used to construct the new dwelling. Therefore, lifetime distribution of housing should be used when looking at the change in service stock, like the change in floor area, but it is not a driver on its own. The material intensity per service unit is a measure to calculate the steel demand. Since a different method of modeling was chosen, material intensity per service unit will not be used in this thesis. The urbanization rate is also a measure, one that influences steel intensity based on the either urban or rural location. Since no region smaller than a country is included within this research, the urbanization rate will only indirectly be incorporated. Due to data limitations the effects of renovation will not be taken into account.

Literature research did not lead to any possible drivers for the automotive industry. However, the method proposed by Müller (2006) could also be applied to a service stock representing the automotive industry.

Considered drivers

In Table 4 an overview of physical drivers considered for modeling can be found. The first, Population, is based on drivers already used in IAM's. Per capita floor area as a driver is taken from Müller (2006) and Hu et al. (2010). Concrete reinforcing bars is a product that the World Steel Association (WSA) publishes numbers on, and can be completely and directly attributed to the construction sector. The WSA also publishes information on train track material, for which rail length is a driver. The other considered drivers cannot be directly linked to steel demand, but can be linked to the use of steel end products. Motor vehicles for example are clearly products that contain steel and are the main influencer for steel demand within the automotive sector. Cars per capita is an example of service stock per capita as suggested by Müller (2006).

Table 4: Considered physical drivers

Driver	Construction sector	Automotive sector
Population	x	x
Building floor area	x	
Per capita floor area (building)	x	
New Buildings	x	
Concrete reinforcing bars	x	
Total rail length	X	
Total road length		X
Number of motor vehicles produced		X
Cars/capita		X

All drivers with the exception of total rail length will be representing the entire sector rather than steel demand for their own product only. This is due to limitations of data availability for both material intensity per service unit and material intensity of new products. If the chosen drivers can represent an entire sector, a method using one physical driver can be created to model the steel demand for the entire sector.

Population

World

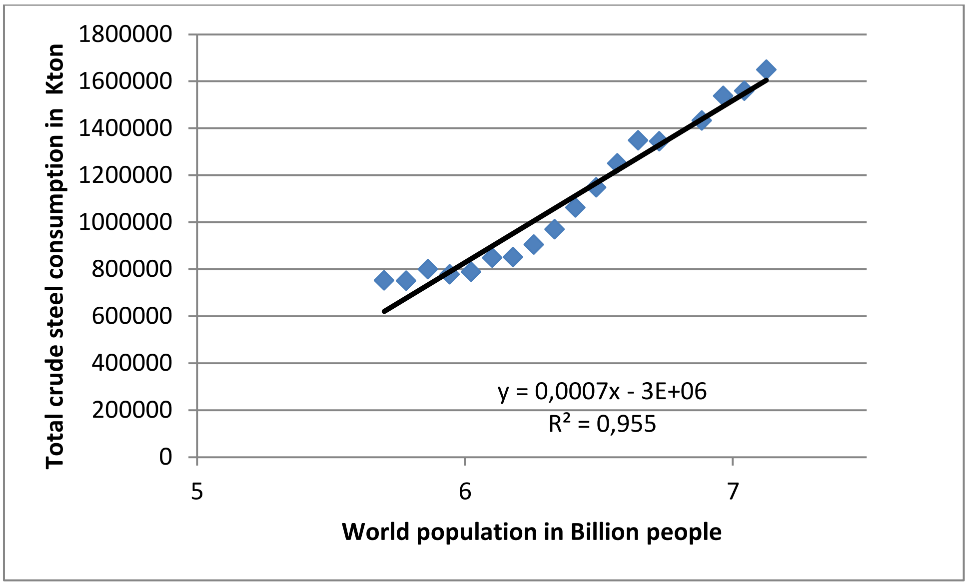

Figure 10: World steel consumption plotted against world population for 1995-2013 (The World Bank, 2015; World Steel Association, 2005, 2014b)

Population is a driver for steel demand since the human population is the one creating and using steel products.
When looking at the world crude steel consumption and world population a very clear relationship can be found. The R^2 indicates that statistically almost the complete increase in crude steel production can be explained by the increase in population. This very strong statistical relationship makes the world's population as a driver very usable for modeling steel demand.

EU

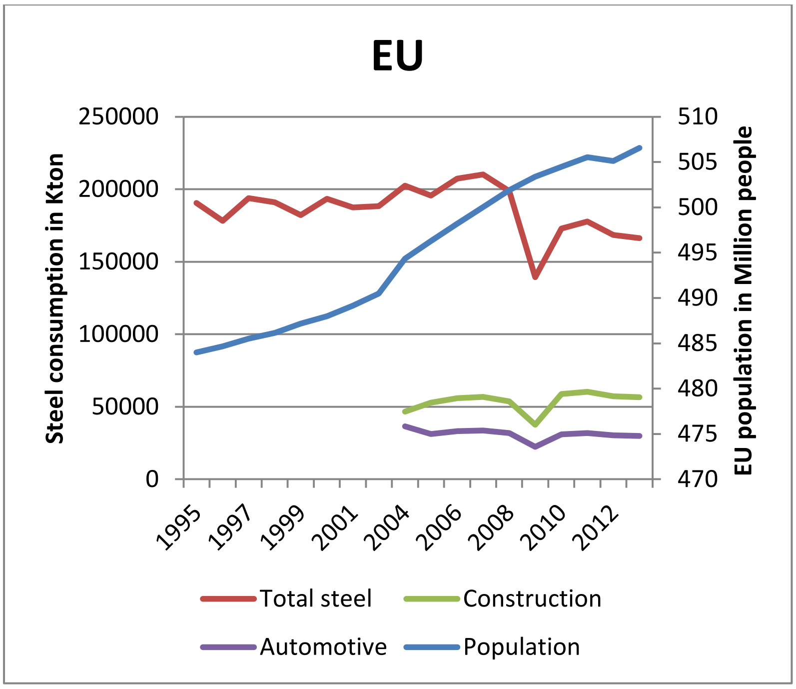

Figure 11: EU population and total, construction and automotive steel consumption plotted over time (Eurofer, 1999, 2000, 2001, 2002, 2003, 2004, 2009, 2010, 2014; The World Bank, 2015; World Steel Association, 2005, 2014b)

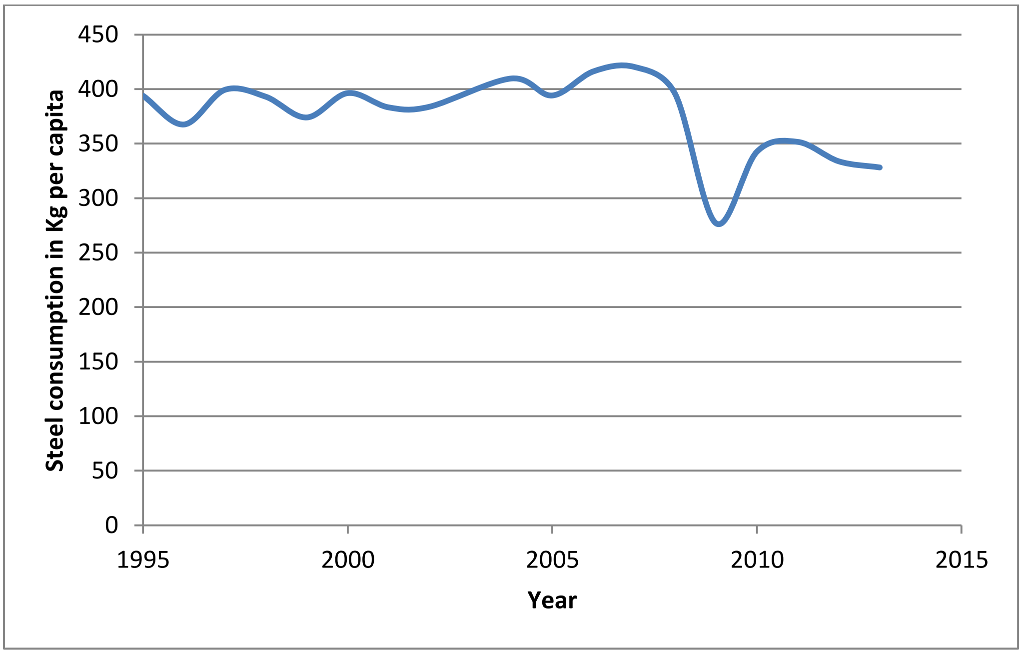

Figure 12: EU steel consumption per capita plotted over time (The World Bank, 2015; World Steel Association, 2005, 2014b)

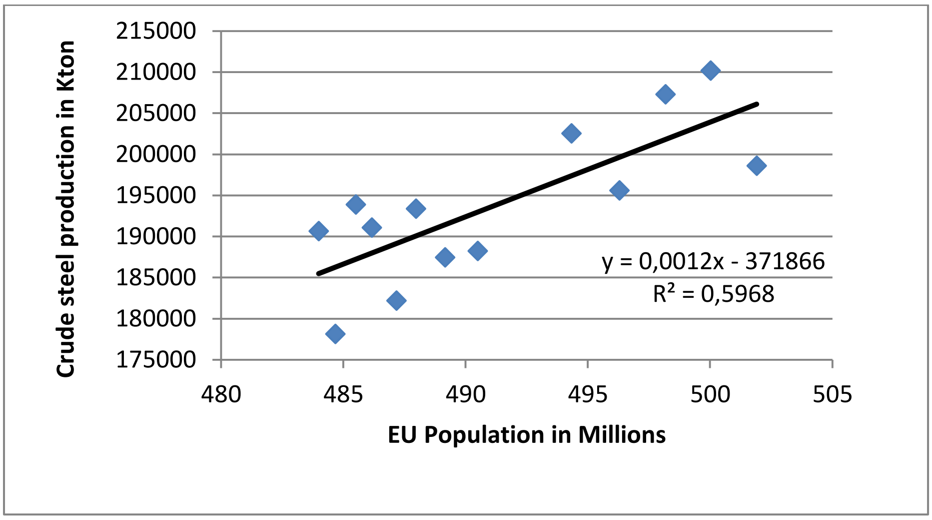

Figure 13: EU total crude steel production plotted against population size for 1995-2008 (The World Bank, 2015; World Steel Association, 2005, 2014b)

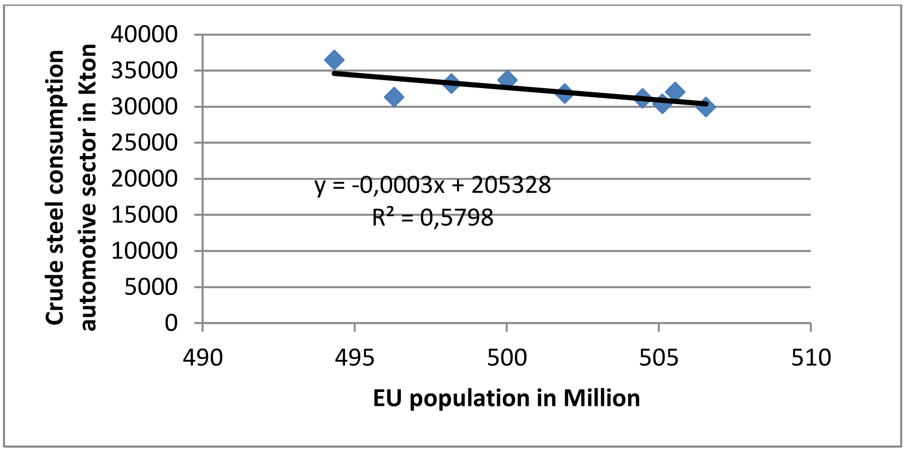

Figure 14: EU automotive sector steel consumption plotted against population size for 2004-2008 and 2010-2013 (Eurofer, 2004-2014; The World Bank, 2015; World Steel Association, 2005, 2014)

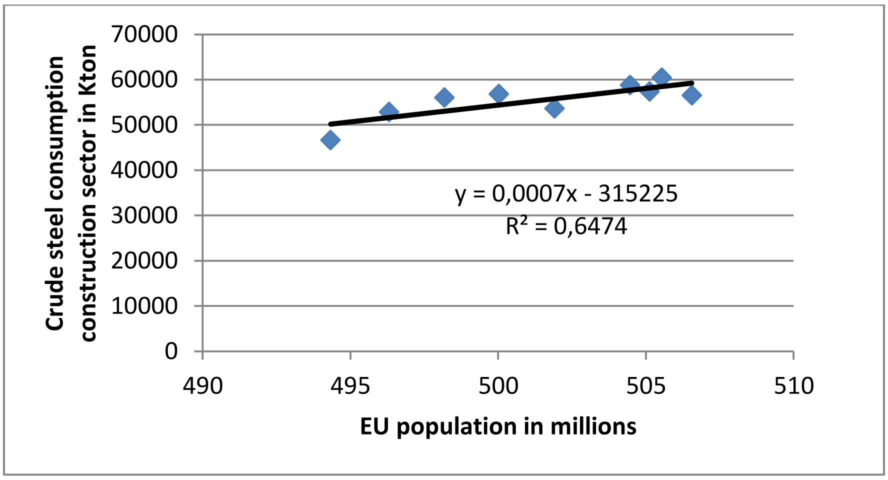

Figure 15: EU construction sector steel consumption plotted against population size for 2004-2008 and 2010-2013 (Eurofer, 2004-2014; The World Bank, 2015; World Steel Association, 2005, 2014)

When comparing the steel production and population for the EU27, the relationship between the size of the population and crude steel production is not as well established. Steel consumption per capita however seems to have stabilized prior to 2009 as can be seen in Figure 12. The population in the EU is still increasing, whereas the production of crude steel seems to have stabilized (Figure 11). When the steel production decreases in 2009 due to the financial crisis, the population increase is unchanged. A strong statistical correlation between population and total crude steel is visible for Europe from 1999 to 2008. A strong correlation also exists when comparing population to the share of crude steel production for the construction and automotive industry with 2009 data excluded. The correlation between the population and steel in the automotive sector is however a negative correlation. This is caused by the fact that steel consumption in the automotive sector stayed relatively stable while population increased. It seems unlikely that population size would not influence the automotive sector, therefore the most likely explanation is that vehicles became less steel intensive which allowed steel consumption to stay stable. The decrease in steel intensity could have been caused by more efficient use of steel or substitution with other materials like aluminum.

USA

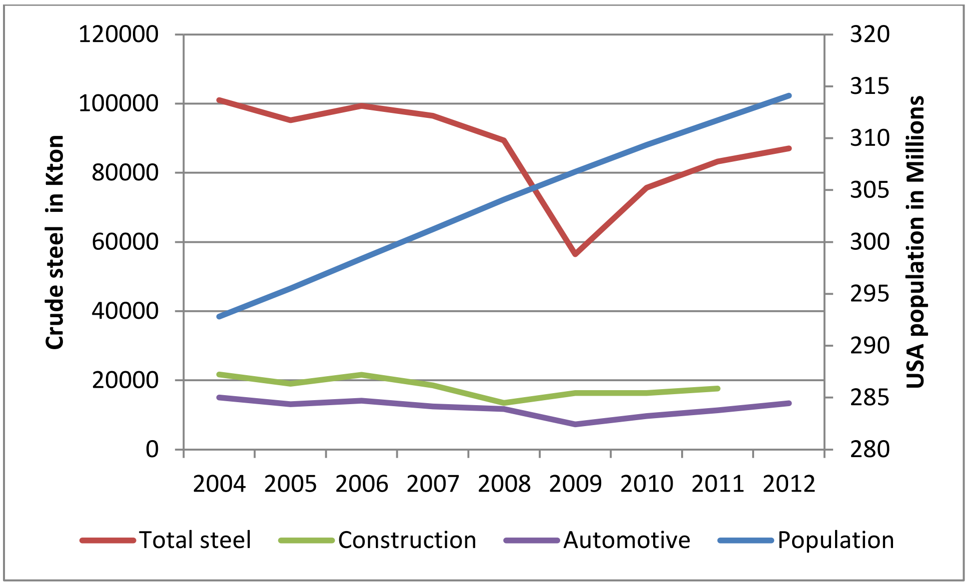

Figure 16: USA population size, total, construction and automotive steel demand plotted over time (The World Bank, 2015; USGS, 2002-2012; World Steel Association, 2005, 2014)

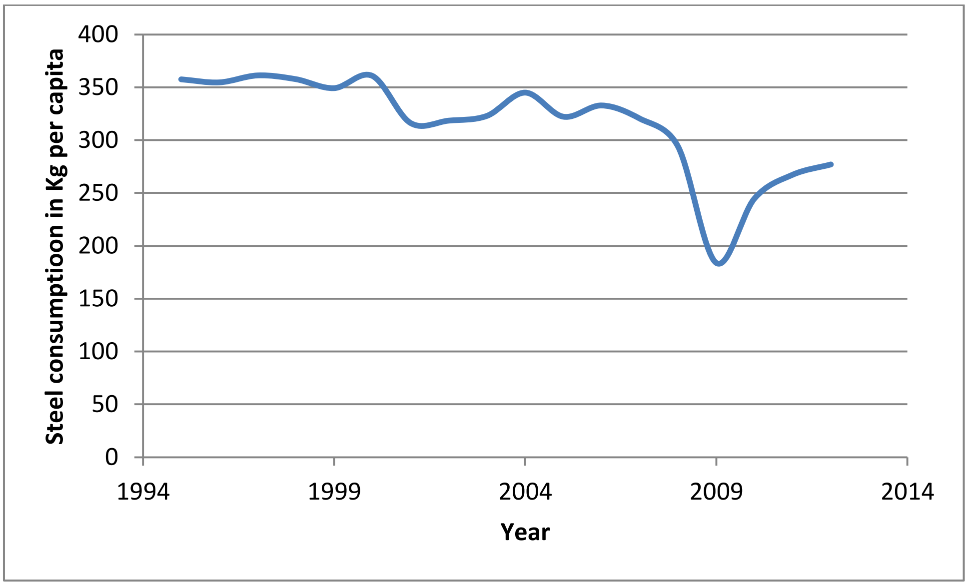

Figure 17: USA steel consumption per capita plotted over time (The World Bank, 2015; World Steel Association, 2005, 2014b)

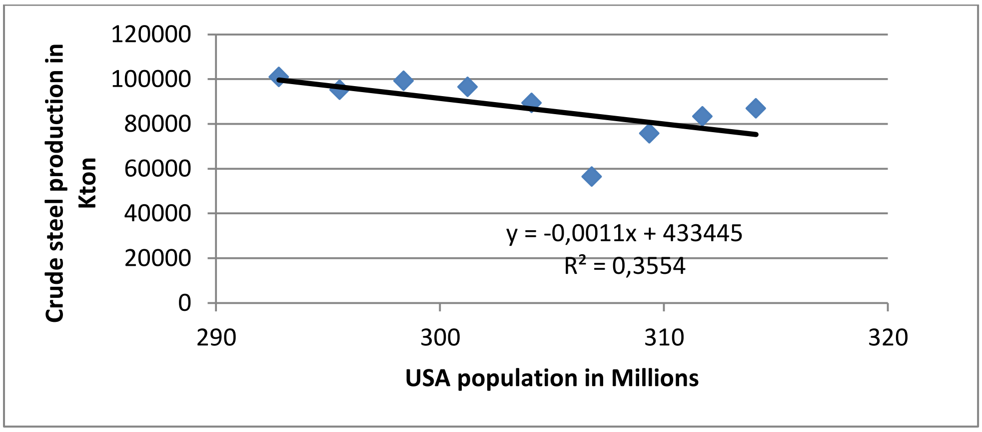

Figure 18: USA total crude steel production plotted against population size for 1995-2008 (The World Bank, 2015; USGS, 2002-2012)

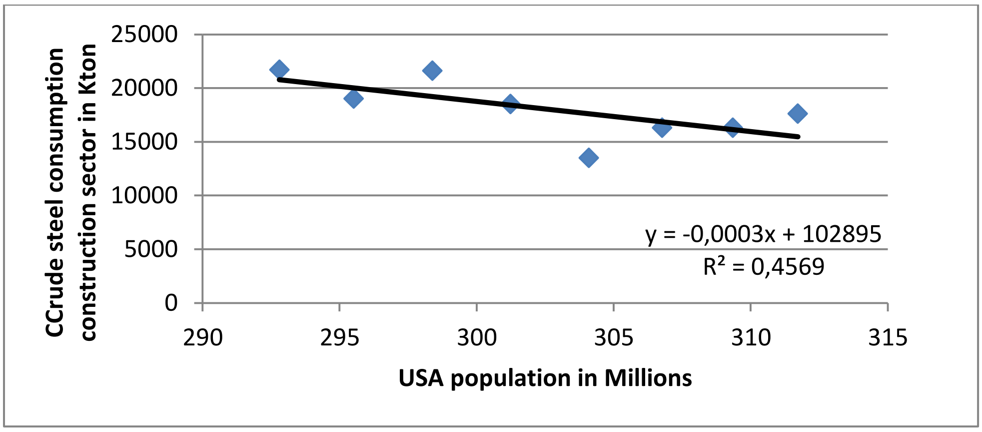

Figure 19: USA construction steel consumption plotted against population size for 2004-2011 (The World Bank, 2015; USGS, 2002-2012)

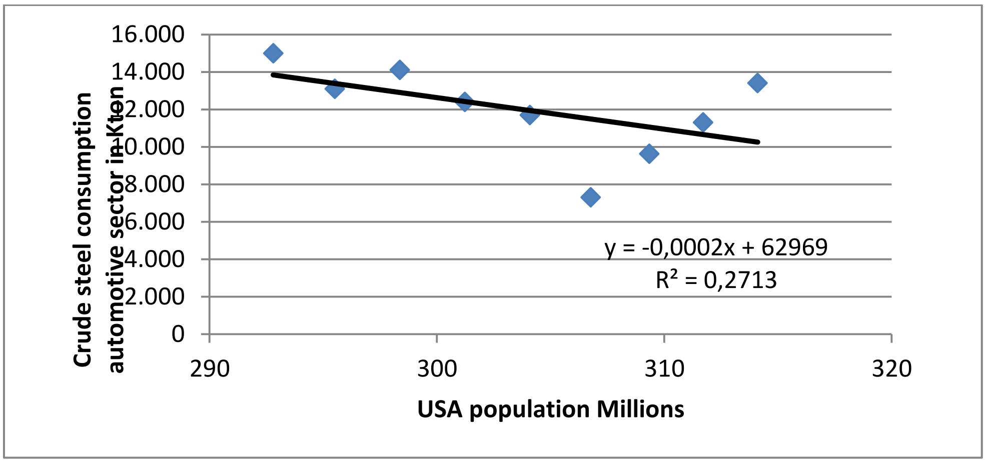

Figure 20: USA automotive steel consumption plotted against population size for 2004-2012 (The World Bank, 2015; USGS, 2002-2012)

For the United States the population shows a linear increase over time. The crude steel production however hovered around an average 96 million tons a year up until 2009 (Figure 16). While steel production increased again after the decrease in 2008, the steel production has not yet reached pre-crisis levels in 2012. Since the crude steel production did not show any increase before the crisis, while the population continued to increase, the statistical correlation between the steel production and population from 2004 to 2013 is moderate and negative (Figure 18). If only the pre-crisis years would be considered, the correlation is weak. While the population increased, steel production remained at the same level, resulting in a smaller steel production per capita each year as can be seen in Figure 17. Therefore, it appears that the size of the population does not influence the crude steel production in the USA. If the population size would influence steel production one would expect the steel produced per person to stay the same or increase which would result in an increase in steel production. Both the construction and automotive sector show negative correlations, a moderate one for construction and a modest one for automotive (Figure 19 & Figure 20).
With 3 negative correlations between population and steel consumption, population does not appear to be a usable driver to model steel demand when it comes to the United States.

Japan

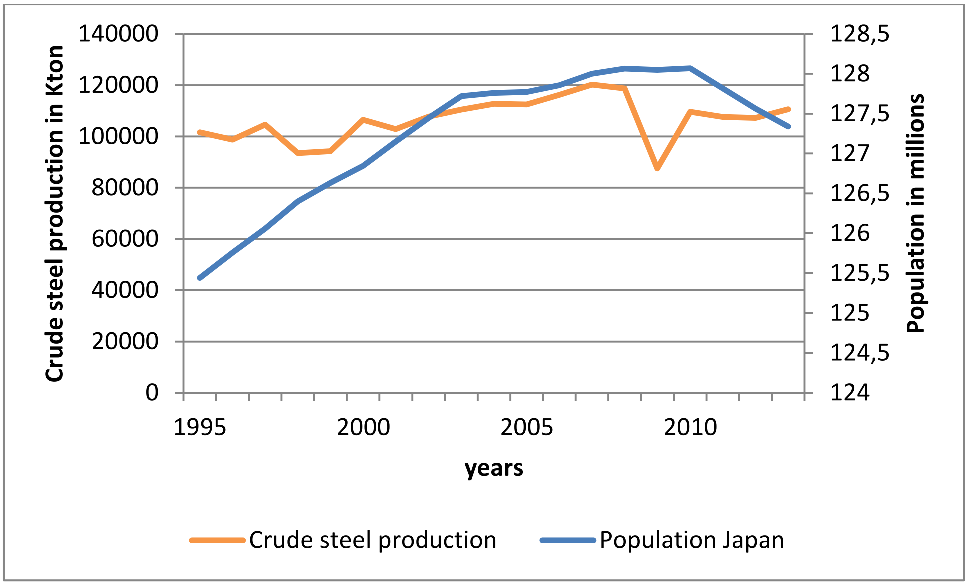

Figure 21: Japan population size and crude steel production plotted over time (The World Bank, 2015; World Steel Association, 2005, 2014b)

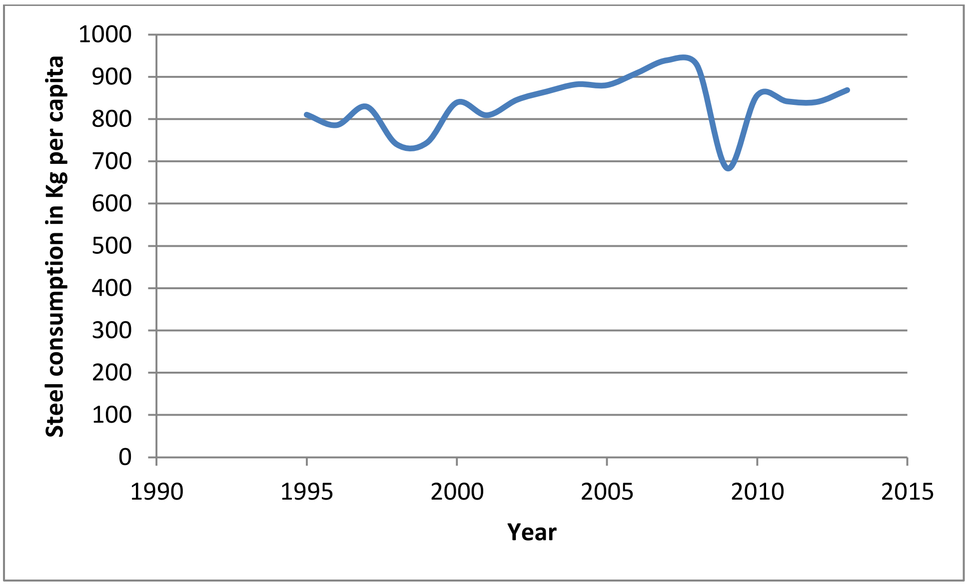

Figure 22: Japan steel consumption per capita plotted over time (The World Bank, 2015; World Steel Association, 2005, 2014b)

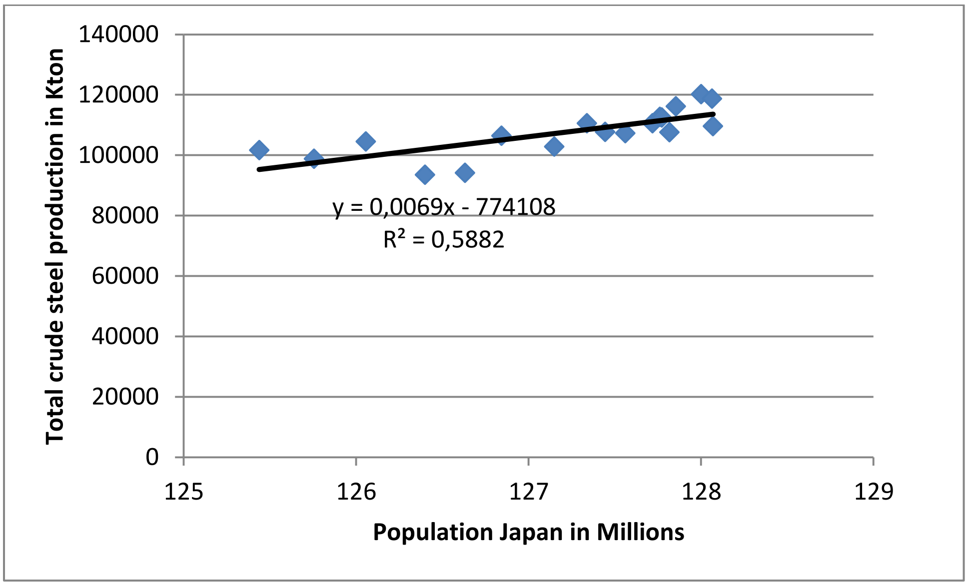

Figure 23: Japan total crude steel production plotted against population size for 1995-2008 and 2010-2013 (The World Bank, 2015; World Steel Association, 2005, 2014b)

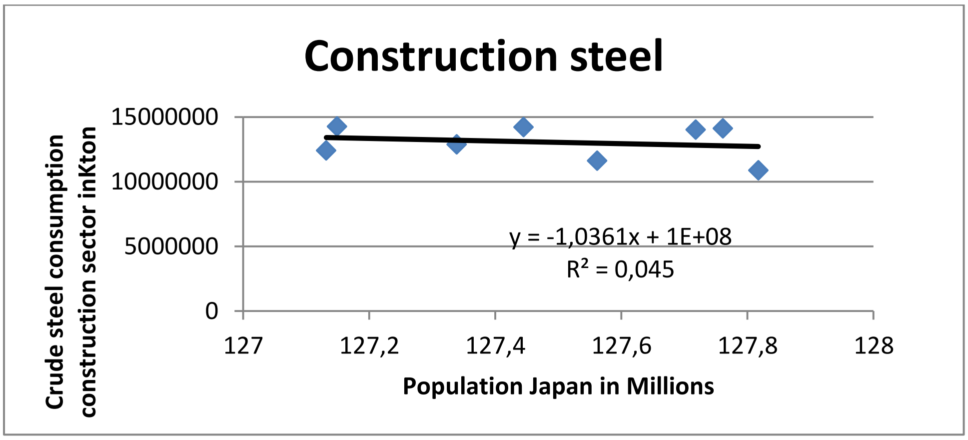

Figure 24: : Japan total crude steel production plotted against population size for 2001-2004 and 2011-2014 (The Japan Iron and Steel Federation, 2005, 2015; The World Bank, 2015; World Steel Association, 2005, 2014b)

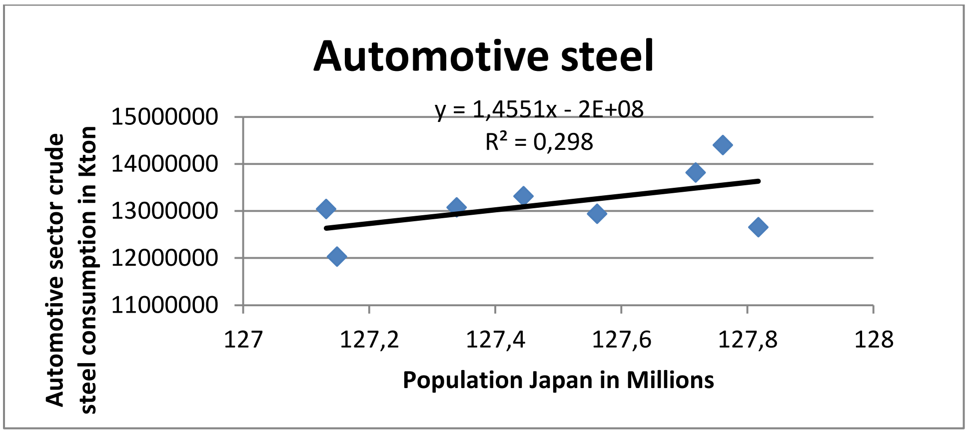

Figure 25: : Japan total crude steel production plotted against population size 2001-2004 and 2011-2014 (The Japan Iron and Steel Federation, 2005, 2015; The World Bank, 2015; World Steel Association, 2005, 2014b)

Unlike Europe and the USA, the Japanese population started decreasing after 2010 (Figure 21). The crude steel production was steadily increasing before the financial crisis, and again shows an increase after 2009. When looking at the population and total steel production in Japan, with 2009 removed as outlier, a strong statistical correlation is visible. The decrease in population does not yet seem to influence the correlation, as the steel production after 2010 is still lower than it was before 2009. As a result the steel consumption per capita is not higher after the population started decreasing (Figure 22). If the population would continue to decrease, but the crude steel production would continue to increase, the correlation between total steel and population size could become weaker. Therefore the effectiveness of population as driver for steel demand in Japan should be analyzed again in a few years to see if the trend of population decline continues. The share of steel in construction shows only a weak connection to population size. There is only a modest correlation between steel in the automotive sector and the population of Japan. This could possibly be explained by the fact that many cars produced in Japan are for export (Japan Automobile Manufacturers Association Inc., 2015).

The financial crisis has had a large impact on steel production in the above discussed countries and regions, making it necessary to exclude data in some cases. It is however very clear that the world population is a usable driver for the total crude steel production. Both Europe and Japan showed a strong and positive statistical correlation between crude steel production and population size, qualifying population size as a usable driver for these regions also. With a negative and moderate statistical correlation between total crude steel production and population size for the United States, population size does not appear to be a usable driver for the United States.
With the exception of crude steel construction in Europe, population size does not appear to be a usable driver for the construction and automotive sector due to either its negative or too low correlation.

Building floor area

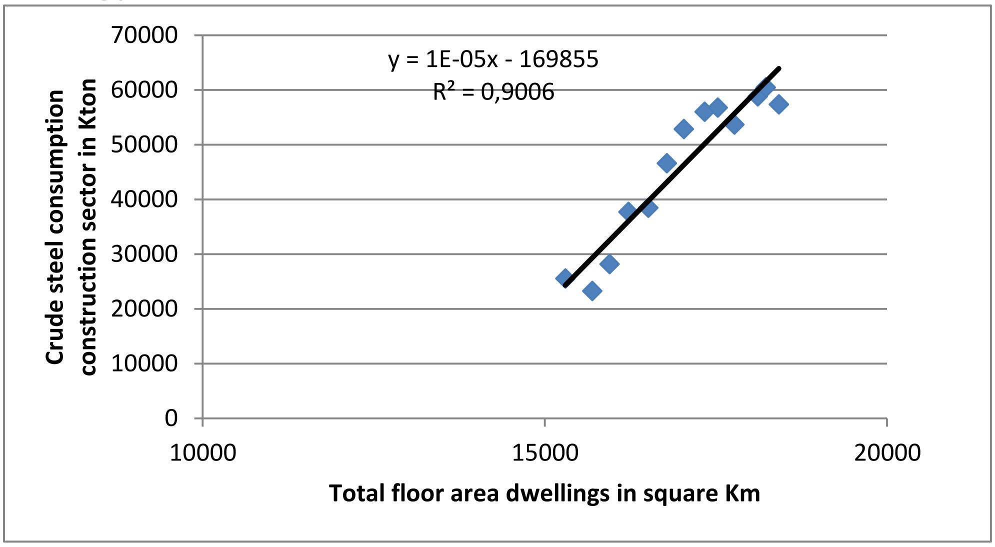

Figure 26: EU steel consumption construction sector plotted against total floor area of dwellings for 1999-2008 and 2009-2012(Enerdata, 2015; Eurofer, 1999-2014; World Steel Association, 2005, 2014)

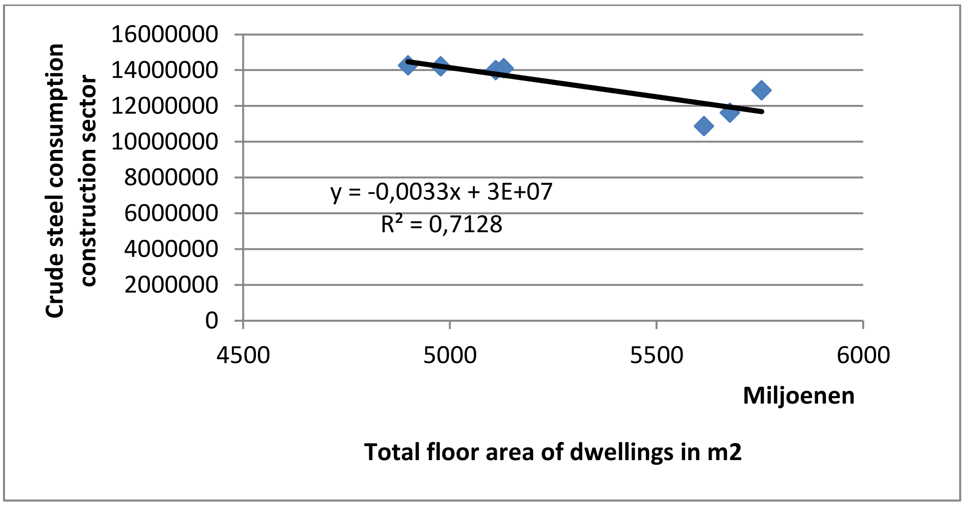

Figure 27: Japan steel consumption construction sector plotted against total floor area of dwellings for2001-2004 and 2011-2013 (Statistics bureau Japan, n.d.; The Japan Iron and Steel Federation, 2005, 2015; World Steel Association, 2005, 2014b)

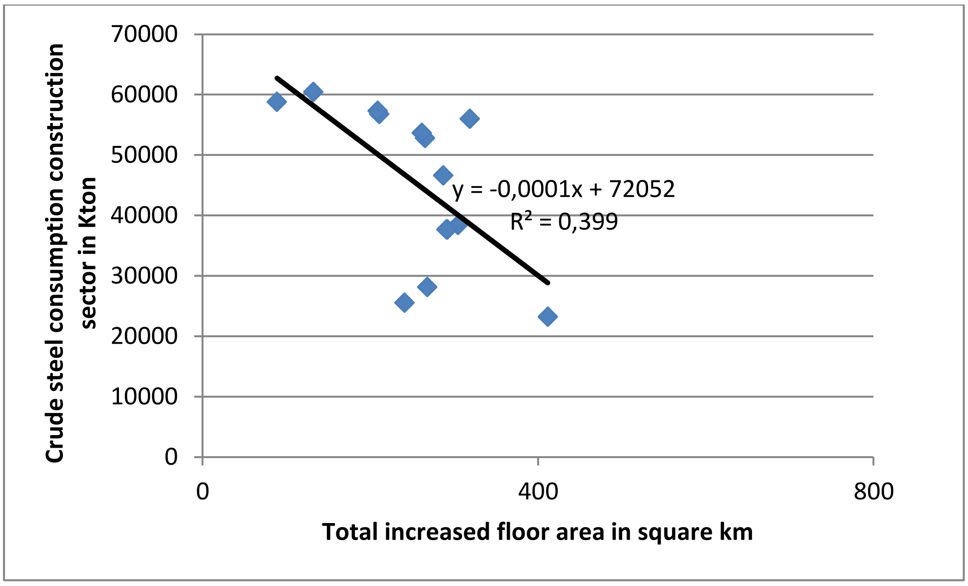

Figure 28: EU steel consumption construction sector plotted against total increased floor area of dwellings from 1999-2012 (Enerdata, 2015; Eurofer, 1999-2014; World Steel Association, 2005, 2014)

Building floor area is a direct result of building construction and therefore influences the steel consumption of the construction sector. Rather than service stock per capita it represents the entire service stock. Due to data availability the building floor area is of all existing dwellings only. Dwellings fall under residential construction based on (Table 2). Regardless of the fact that infrastructure also influences the total steel consumption of the construction sector, building floor area was considered as driver for the entire construction sector.

When looking at the total floor area of dwellings as driver for construction steel consumption in Figure 26, a very strong statistical correlation is visible for the EU. The larger the total dwelling floor area in the EU becomes, the more steel is consumed in the construction sector. This however does not seem to hold true for Japan. A strong statistical negative correlation is visible in Figure 27, indicating that steel consumption decreases as floor area increases. Therefore only building floor area in Europe is a usable driver for construction steel demand.

Extra care has been taken when looking at the increase in floor area because it is the increase of stock size rather than the total stock size that creates demand. Since buildings get demolished at the end of their lifetime, while simultaneous new buildings are being built, the increase in total floor area is a net increase. To find the actual increase in building floor area, this stock turnover of buildings needs to be taken into account (Yashiro, 2009). It was assumed that the all demolished dwellings were replaced by new dwellings. For Europe a stock turnover rate of 0,1% was chosen based on Thompsen & van der Flier (2006). The stock turnover rate was multiplied by the total floor area of the previous year, and added to the difference in floor area between the previous and current year to find the total increased floor area.
When looking at the increase in dwelling floor area for the EU, a moderate negative statistical correlation is visible in Figure 28. This indicates that the amount of dwelling floor area built is not a usable driver for modeling construction steel demand.

In Japan after the 1990s more than 60% of the increase in building stock could be attributed to the replacing of old dwellings (Yashiro, 2009). However, more recently it seems that rather than demolishing old dwellings they are abandoned while new dwellings are still built (Otake, 2014). Because of these recent changes no demolition rate or stock turnover rate could be identified for Japan. Therefore the increase in floor area for Japan is not included.

Per capita floor area

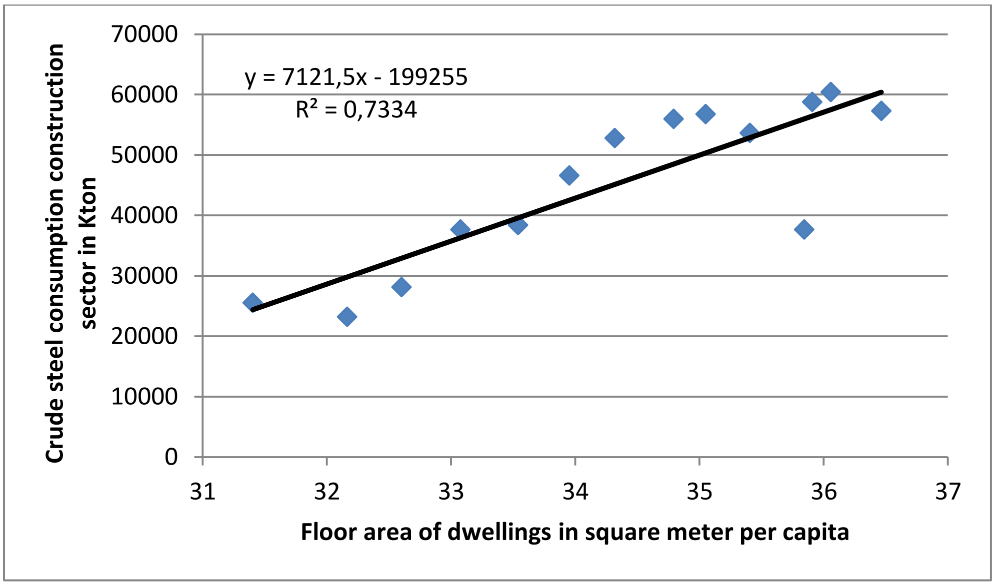

Figure 29: EU construction steel consumption plotted against floor area per capita for 1999-2012 (Enerdata, 2015; Eurofer, 1999-2014; The World Bank, 2015; World Steel Association, 2005, 2014)

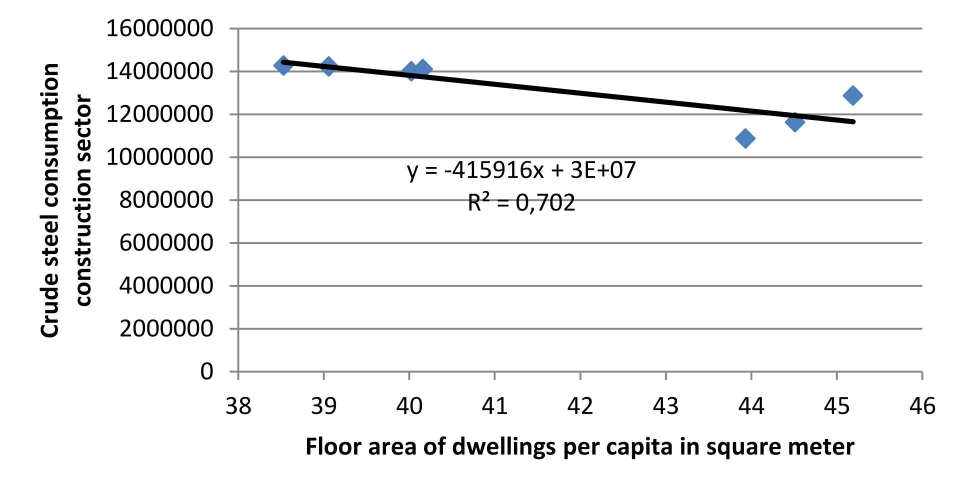

Figure 30: Japan construction steel plotted against floor area per capita (Statistics bureau Japan, n.d.; The Japan Iron and Steel Federation, 2005, 2015; The World Bank, 2015; World Steel Association, 2005, 2014b)

The choice of including this driver was based on drivers indicated in literature, as it is represents service stock per capita. It differs from total floor area by including population size.
Europe shows strong statistical correlation between construction steel consumption and the per capita floor area in Figure 29. Japan also has a strong statistical correlation, but just like for total floor area, the correlation is a negative one (Figure 30). Therefore floor area per capita is a usable driver for the EU but not for Japan.
Noteworthy is the difference in per capita floor area between Europe and Japan. Possibly the average floor area per dwelling is higher than Europe, or Japan has more smaller dwellings with smaller household sizes than Europe. Another possible explanation is a combination of the decreasing population size and the increase in number of abandoned dwellings which increase the average.

New Dwellings

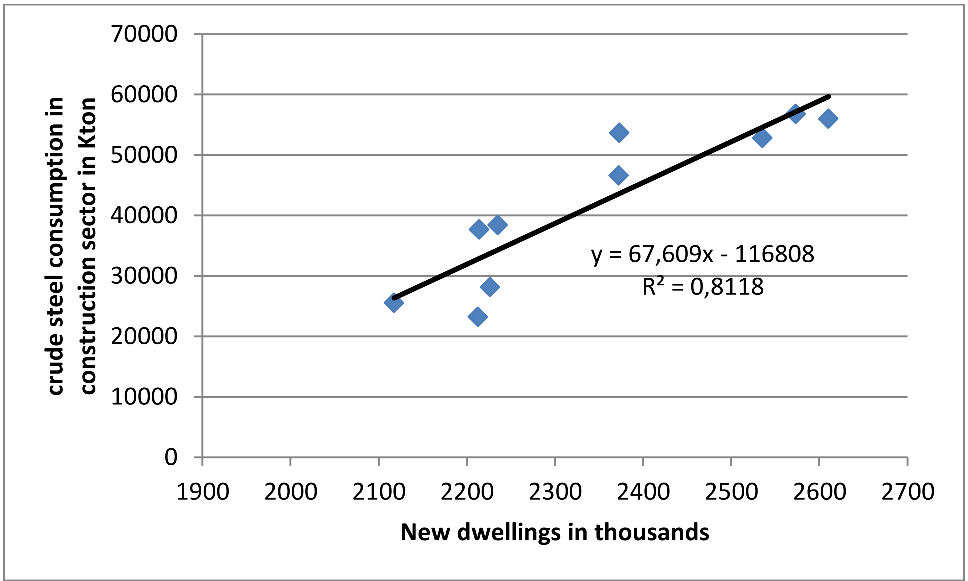

Figure 31: EU construction steel consumption plotted against new dwellings (Enerdata, 2015; Eurofer, 1999-2014; World Steel Association, 2005, 2014)

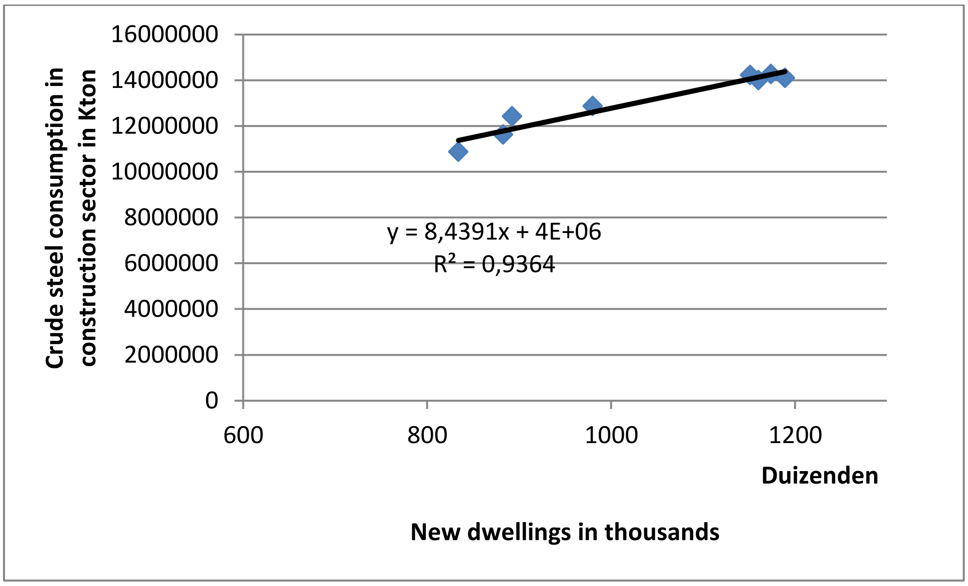

Figure 32: Japan construction steel consumption plotted against new dwellings for2001-2004 and 2011-2013 (Statistics bureau Japan, n.d.; The Japan Iron and Steel Federation, 2005, 2015; World Steel Association, 2005, 2014b)

Besides increasing the floor area, a result of construction is also the creation of new dwellings. Unlike building floor area (per capita) it does not look at stock size but rather the flow that increases stock size. Dwellings, which are building constructions, only hold a share of the entire construction sector. However, as can be observed for Japan in Figure 32 there is a very strong statistical correlation between the number of new dwellings and the crude steel consumption of the entire construction sector. This includes the years before and after the financial crisis. The EU also shows a very strong correlation when looking at the years before the financial crisis (Figure 31). This makes new dwellings a usable driver for modeling construction steel demand.
The numbers of new dwellings constructed also reflect Japan's current housing situation where a lot of new dwellings are constructed while the population decreases. Japan's population size is about a quarter of the population of the EU, while the number of constructed dwellings in Japan ranges from a quarter to half the number of dwellings built in the EU (The World Bank, 2015). Rather than dealing with old dwellings, new ones are being constructed in Japan which will most likely result in more abandoned homes (Otake, 2014).

When comparing new dwellings to increase in floor area, it is quite remarkable that there is a positive correlation for new while there was none for increase of floor area. That is unexpected because the increase in floor area is caused by the construction of new dwellings. In Figure 33 can be observed that the increase in floor area shows an overall decline while the number of new dwellings constructed continues to increase until the financial crisis. Perhaps the difference is caused by wrong assumptions when determining the increase in floor area. Another explanation could be that in some of the years, more buildings with smaller floor areas were build. This however seems unlikely since the per capita floor area continued to increase (Enerdata, 2015).

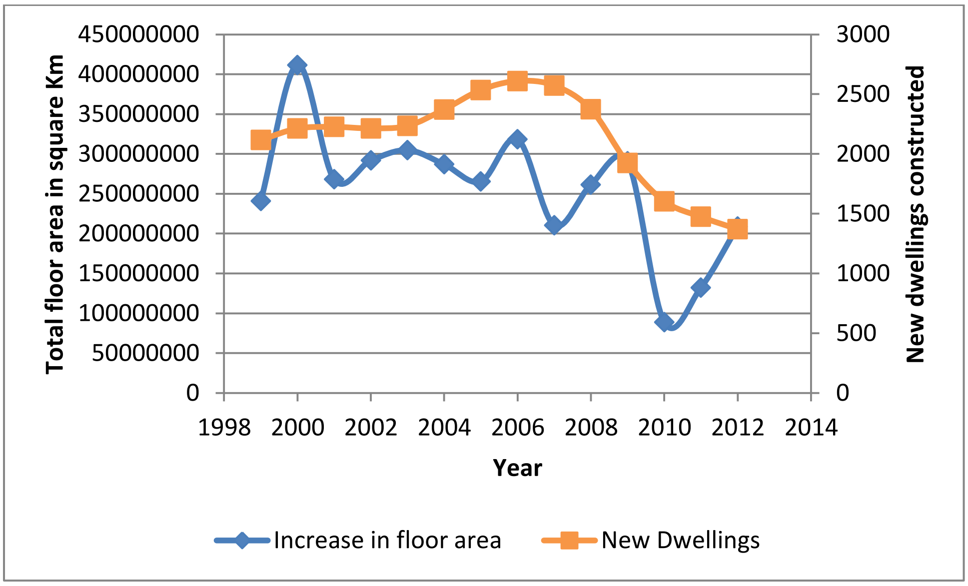

Figure 33: EU increase in floor area and new dwellings plotted over time (Enerdata, 2015; Eurofer, 1999-2014; World Steel Association, 2005, 2014)

Concrete reinforcing bars

As mentioned in chapter 3, concrete reinforcing bars has a very large share in the steel consumption of both buildings and infrastructure. It was reasoned that concrete reinforcing bars have such a large share in steel consumption for construction, it might be a driver for total steel consumption for the construction sector. Concrete reinforcing bars as driver would be connected to building floor area, since the type of building and building size determine how much reinforcing bar is needed.

Concrete reinforcing bars as a driver for modeling construction steel demand is not usable. For both the EU as the U.S. the statistical correlation is modest. Furthermore, the correlation is negative for the EU. The amount of concrete reinforcing bars produced does not seem to influence the amount of construction steel produced.

To find an explanation why statistically concrete reinforcing bars do not seem to be a driver for construction steel demand, the trend of both were compared over time in Figure 36. Where the crude steel consumption in the construction sector shows a general increase over time, the concrete reinforcing bars show a decrease. From a 35-40% share of total construction steel, concrete reinforcing bars decline to a 20-15% share. This could indicate a shift towards construction types that require less concrete reinforcing bars.

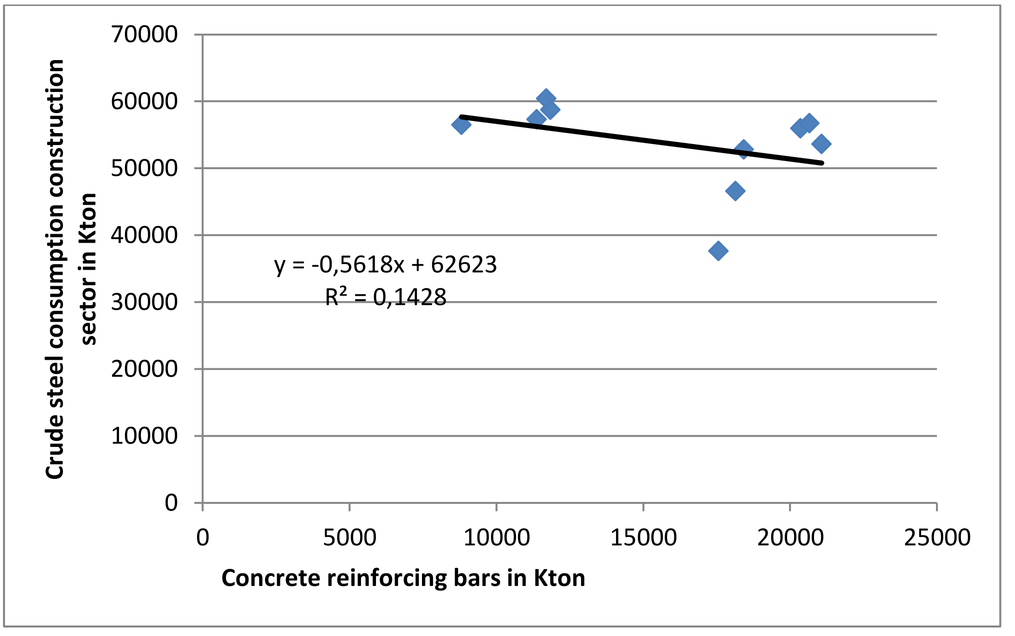

Figure 34: EU construction steel consumption plotted against concrete reinforcing bars for 2004-2013 (World Steel Association, 2014b)

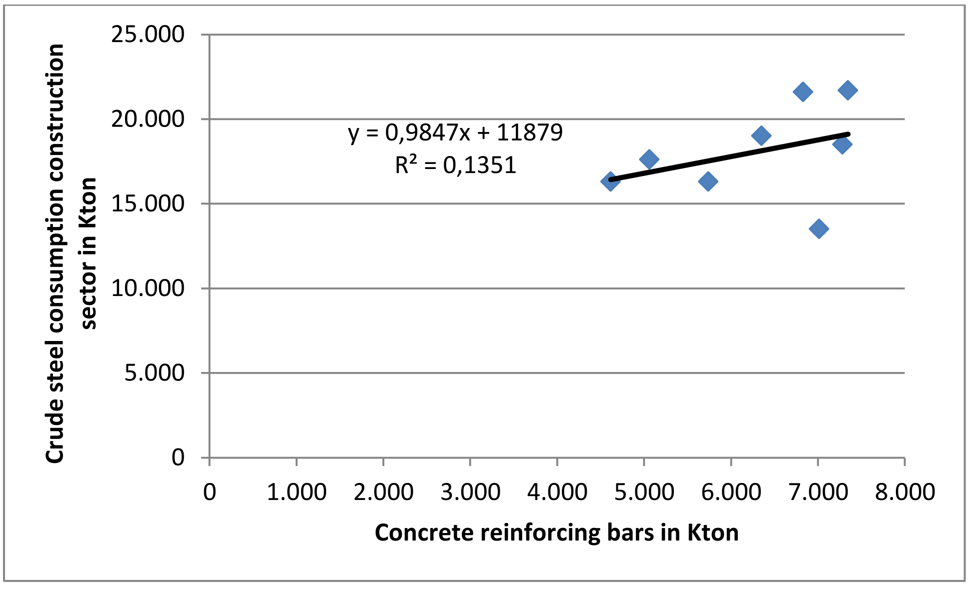

Figure 35: USA construction steel consumption plotted against concrete reinforcing bars for 2004-2011 (World Steel Association, 2014b)

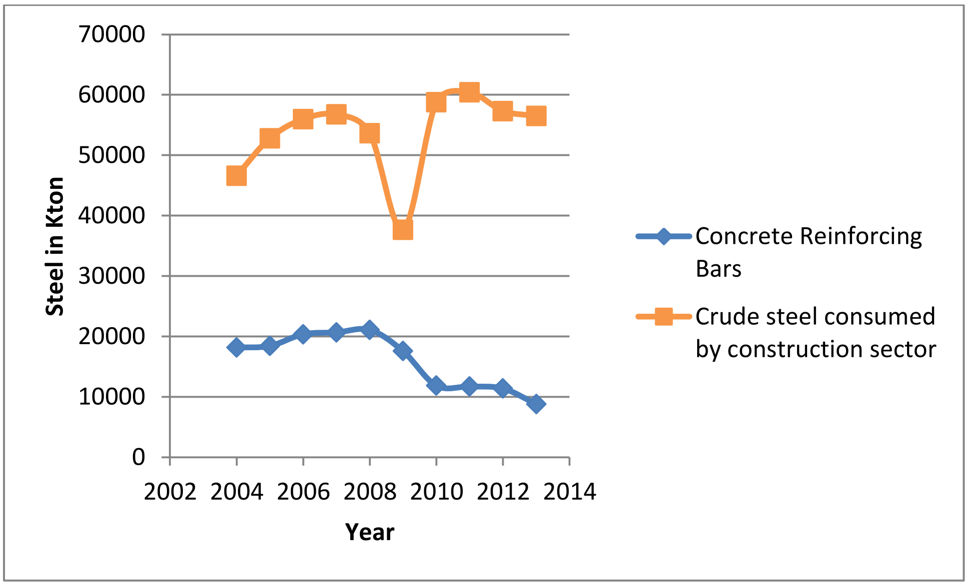

Figure 36: EU construction steel consumption and concrete reinforcing bars plotted over time (World Steel Association, 2014b)

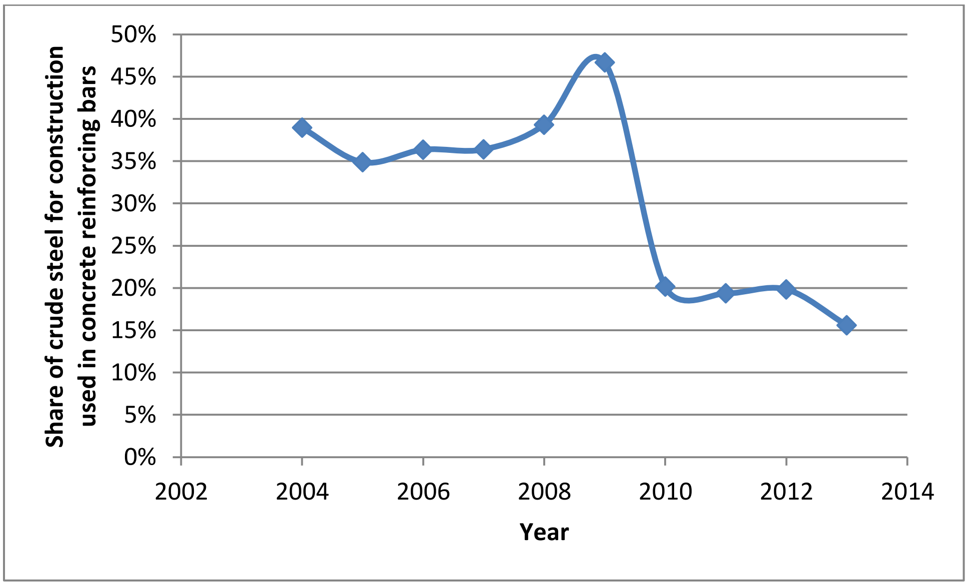

Figure 37: EU concrete reinforcing bars as share of construction steel consumption (World Steel Association, 2014b)

Total rail length

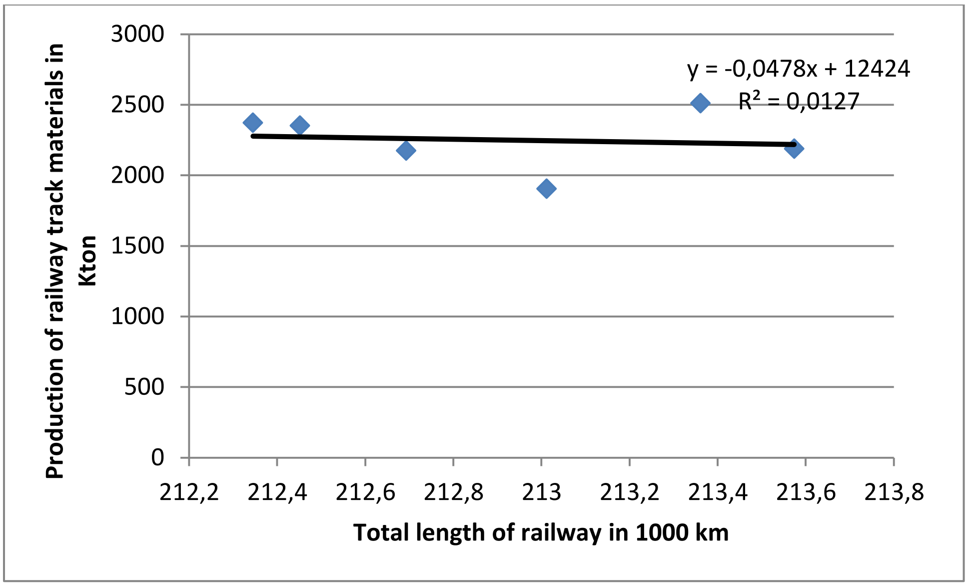

Figure 38: EU railway track materials plotted against railway length for 2007-2012 (European Commission, 2011, 2012, 2013, 2014; World Steel Association, 2014b)

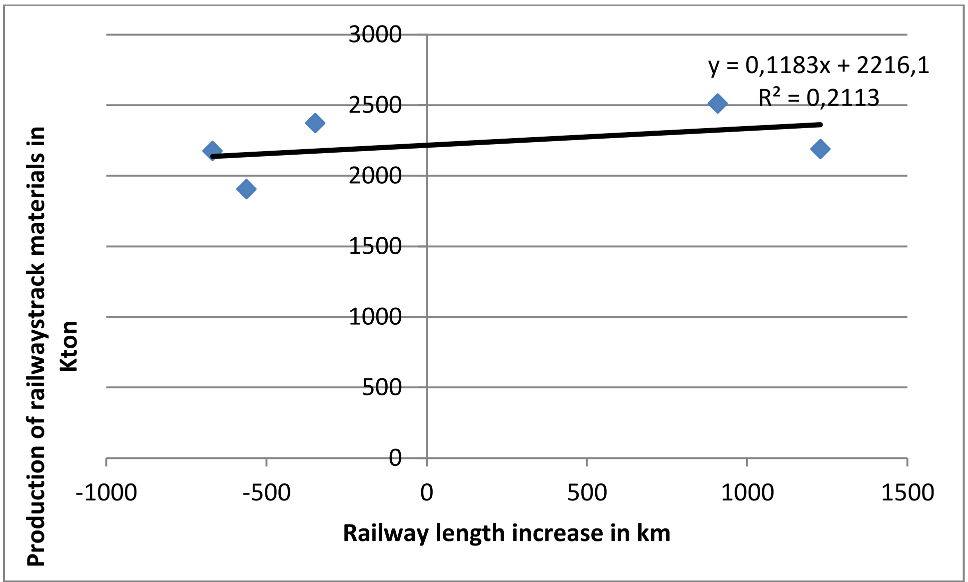

Figure 39: EU railway track materials plotted against increase of railway length for 2008-2012 (European Commission, 2011, 2012, 2013, 2014; World Steel Association, 2014b)

Railroads are a part of infrastructure construction that requires steel railway track materials for its construction. The assumption behind using total length of railways as a driver for railway track material is the expectation that the longer railways get, more railway track material is required to build it. The statistical correlation between the length and production of railway track material can however be classified as weak. The production of railway track material seemed relatively stable while the total railway length in Europe continued to increase. To find an explanation for the stable production of railway track material, the increase in railway length was considered. As can be observed, in some years the total railway length actually decreased, while the amount of railway track material produced was still around the same level as the years when the length increased. It is possible that this occurred by replacement of railway sections in the years that the total length decreased, since replacement still requires railway track material. A second possibility is that railway track materials is produced at a steady rate and added to a stock of railway track materials. Without awareness of the size of the stock, more railway track materials might be used in the construction than is produced in that year. Regardless of possible explanations, the weak correlation between length and materials produced indicates that the total railway length is not a usable driver for modeling rail material produced.

Total road length

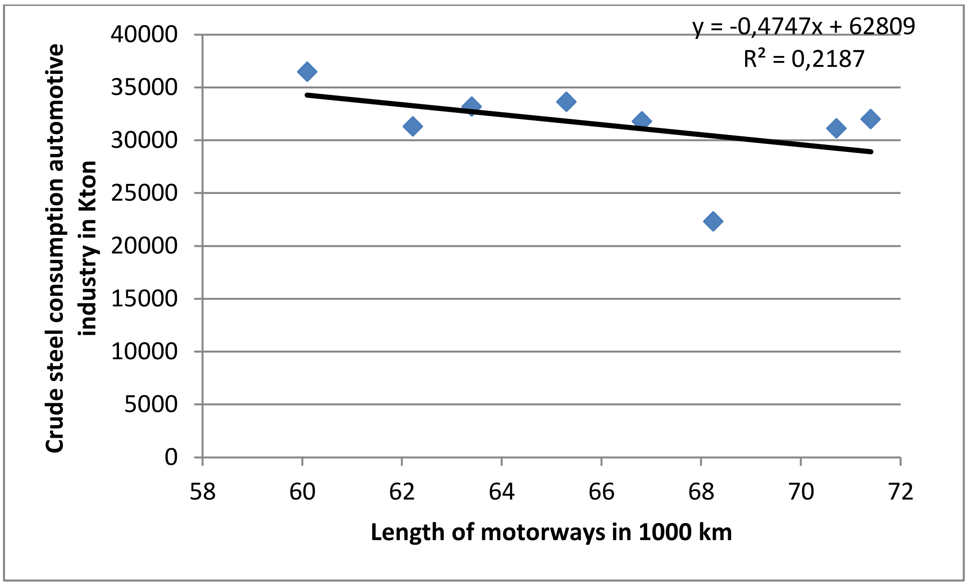

Figure 40: EU automotive steel consumption plotted against lenght of motorways for 2004-2011 (Eurofer, 1999-2014; European Commission, 2009- 2014; World Steel Association, 2005, 2014)

The idea behind considering total road length as a driver for steel demand is the assumption that the more road length there is available for driving, the more vehicles would likely occupy it. Therefore, if the roads would get longer, more vehicles would be produced which would require more steel. This theory did not seem to hold true. Only a modest correlation is visible between the length of motorways and crude steel used in the automotive industry. Furthermore, it is a negative correlation, indicating that when the roads got longer, less steel was used. Therefore length of motorways is not a usable driver for modeling steel demand of the automotive industry.

Motor vehicles produced

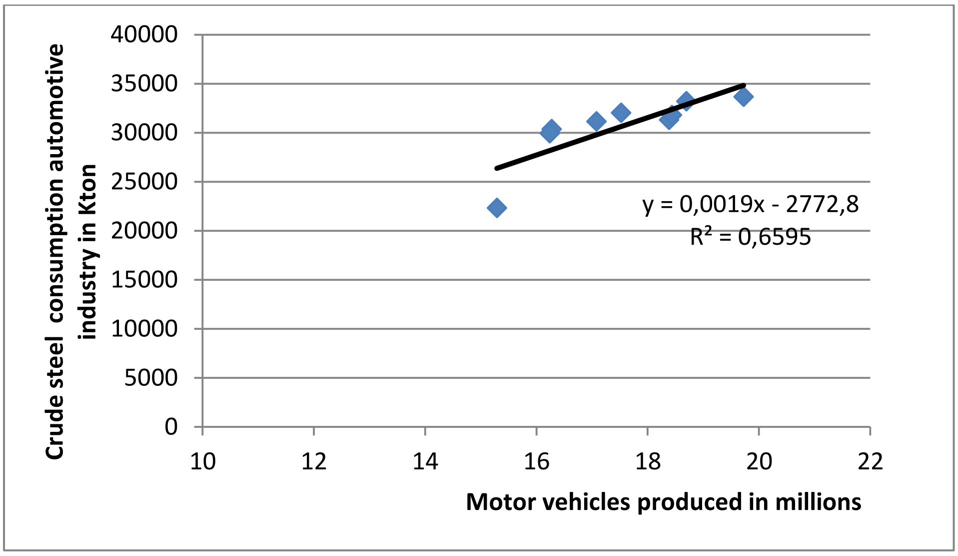

Figure 41: EU steel consumption automotive plotted against motor vehicles produced for 2005-2013 (Eurofer, 2004-2014; OICA, 2015; World Steel Association, 2014)

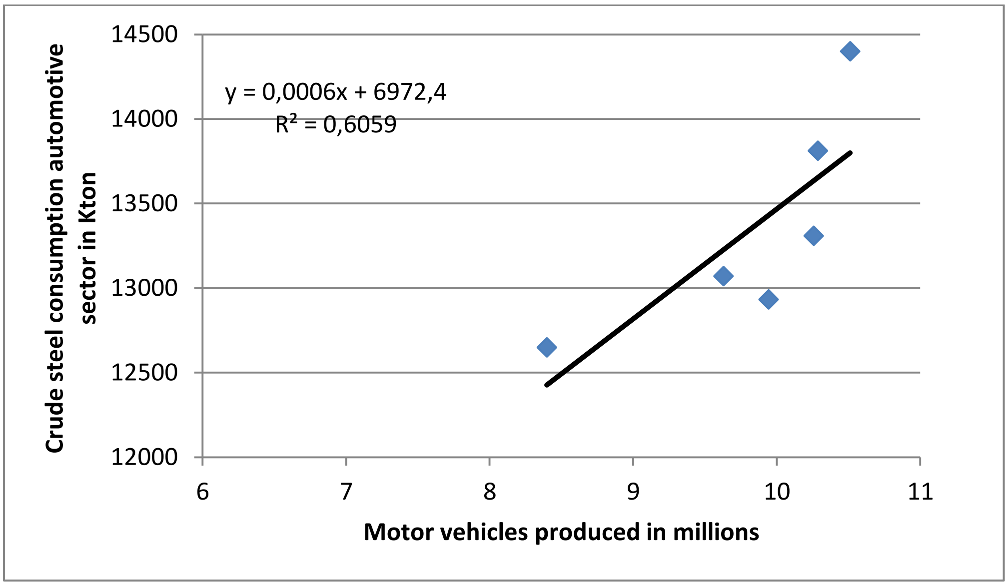

Figure 42: Japan steel consumption automotive plotted against motor vehicles produced for 2002-2004 and 2011-2013 (OICA, 2015a; The Japan Iron and Steel Federation, 2005, 2015; World Steel Association, 2005, 2014b)

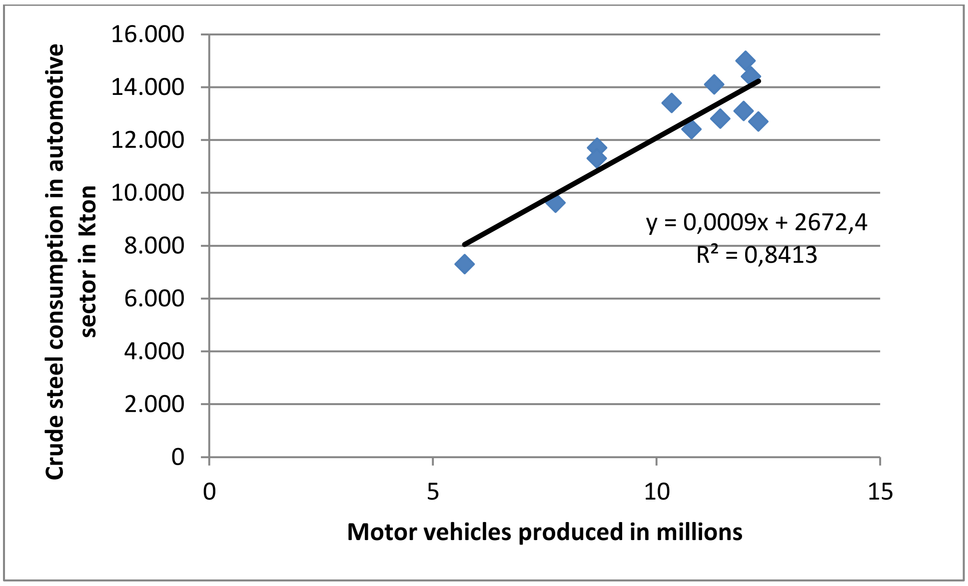

Figure 43: USA steel consumption automotive plotted against motor vehicles produced for 2001-2012 (OICA, 2015; USGS, 2002-2012; World Steel Association, 2005, 2014)

The steel used in the automotive sector is directly used in cars, light trucks, trucks, etc. as explained in chapter 3. Therefore the most direct driver for steel consumption in the automotive sector is the number of motor vehicles that are produced. Within these numbers passenger cars, light commercial vehicles, heavy trucks, busses and coaches are included (OICA, 2015a). For all three regions shown, a positive correlation is visible. For the U.S. a very strong statistical correlation is visible. Higher amounts of steel were used in years that had a large number of motor vehicles produced. The correlation between vehicles produced and steel consumption for the EU and Japan are both strong. This makes vehicles produced a usable driver for modeling future steel demand in the automotive sector.

Vehicles per capita

Vehicles per capita is an indicator of ownership. As driver, an increase in car ownership would increase the demand of vehicles and therefore steel consumption. Unlike the vehicles produced however, the total number of vehicles per capita does not seem to have a strong connection to the amount of steel consumed in the automotive sector, the statistical correlation is only modest. The number of vehicles per capita slowly increases, but the amount of steel consumed in Europe's automotive industry stays about the same. Furthermore, the increase in vehicles per capita does not lead to an expected increase but rather a decrease in steel consumption which makes the correlation a negative one. Therefore vehicles per capita is not a useful driver in modeling future automotive steel demand.

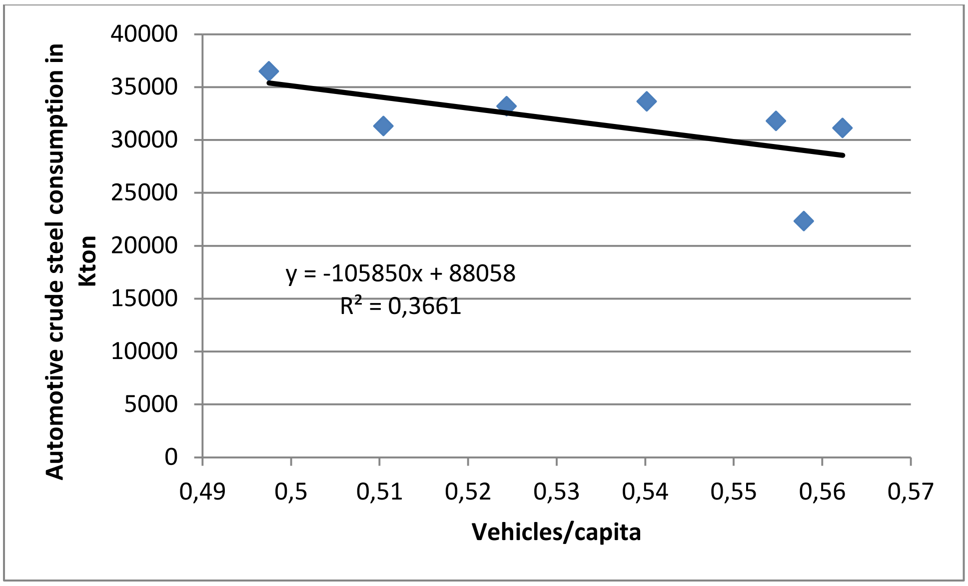

Figure 44: EU automotive steel consumption plotted agains vehicles per capita for 2004-2010 (Eurofer, 2004-2014; OICA, 2015b; The World Bank, 2015; World Steel Association, 2014)

Usable drivers

Five drivers were identified for the construction sector. Of those, only total railway length was not used to model the steel demand for the entire construction sector. It however had a very low statistical correlation, and therefore was not deemed suitable for demand modeling. Of the other four, only concrete reinforcing bars was also not suitable for demand modeling. The other three, new dwellings constructed, total floor area and floor area per capita are all based on the same type of construction and all show strong statistical correlations. Since total floor area and floor area per capita are very similar, they will be combined in the driver total floor area. More explanation on how floor area per capita is included can be found in chapter 5.

Three drivers were identified for the automotive sector. For both total road length and motor vehicles per capita the correlation was negative, making them unsuitable for demand modeling. Motor vehicles produced, a flow based drive, did have a strong positive correlation. This makes it even more surprising that motor vehicles per capita, which is a service stock per capita driver, showed a negative correlation. Since the correlation of motor vehicles produced implies that the amount of steel per vehicle not decreased, vehicles per capita should not have showed a negative correlation. The reason it does have a negative correlation is unknown.

The final driver is population size. It turned out that for 3 out of 4 regions it was a suitable driver for total steel production. It however did not have strong or positive correlations when it came to the steel demand of the construction and automotive sectors.

Concluding, the drivers that were suitable for modeling and will be used in the next chapter are: population, total building floor area, floor area per capita and motor vehicles produced

5. A method to model steel demand based on past activities.

In the previous chapter, 4 physical demand drivers for steel were identified. For this step a method will be explored to use these drivers to model steel demand.

This method was created with the aim of leaving GDP out of the equation and to focus on physical demand drivers instead. It is very loosely based on the method for material flow analysis proposed by Daniel Müller, in the sense that it includes population and steel intensity, and can include unit service stock. The largest difference is that it can also use data on flows, rather than using lifetime distribution to calculate flow rates. It is easily adjustable to allow for changes in factor that could change steel demand. Furthermore, it would not be difficult to integrate this method within an IAM since its main variable is population, which is already incorporated within the different scenarios IAM's use. The modeling method in its most basic form can be seen in Equation 4 and Equation 5.

$$Steel = product\ intensity * steel\ intensity * population$$

Equation 4

Where:
- Product intensity = the number of (produced) product per capita
- Steel intensity = the amount of steel incorporated within a product
- Population = the number of people within the chosen region
- Steel = Total demand of steel

$$Steel = \frac{Product}{Population} * \frac{Steel}{Product} * Population$$

Equation 5

Where:
- Product = the physical driver in quantity produced or total volume
- Steel intensity = the amount of steel incorporated within a product
- Population = the number of people within the chosen region

Besides projections on population size, this method requires projections on product and steel intensity. These intensities can be added in the form of either a fixed value or equations that show the change of intensity over time. Equation 6 shows how the equation of this method would look when the intensities are represented by equations.
One method of finding the necessary intensities for the equation is to let the intensities reflect expected future intensities. This would require making assumptions on the values of future intensities. A second method of finding intensities is looking at historic data. Based on the historic data either an average can be chosen as a fixed value to represent intensity or a trend based on historic data can be used. The chosen trend should predict the change in intensity over time. Based on this trend an equation can be extrapolated with time as the independent variable. The advantage of past trends is that it reflects the increase or decrease of intensity that has been happening for different regions. When using a trend based on historic data to represent the intensities, a "business as usual" scenario is projected. Using historical trends for intensities is the method that will be used further on in this chapter.

$$Steel = PI(t) * SI(t) * Population_t$$

Equation 6

Where:

- PI(t) = the equation for the product intensity of a product over time t
- SI(t) = the equation for the steel intensity of a product over time t
- Population = the number of people within the chosen region for year t

The advantages of this method of modeling are its simplicity and the ability to adjust to changes in population or steel intensity. If for example a material like aluminum would become very cost effective, and replace a large amount of steel within a product, the steel intensity can easily be adjusted to reflect this. The same is possible for the product intensity when for example a new policy reduces the car ownership and therefore leads to a reduction in production of cars. Furthermore, since only one driver is used to model an entire sector, much less data is needed than if multiple drivers based on service stock are used to model one sector.
The downside of using a method that incorporates historic trends is that events like the financial crisis can have disrupting effects on the identified trend. The last financial crisis happened recently and its long term effects are not yet visible. After the 2009 drop in steel production caused by the financial crisis, a strong increase in production can be observed in many regions. If this strong growth of steel demand were to be modeled, a gross overestimation of steel demand could occur. Therefore it would be better to start including these years after a new stable trend has emerged. Consequently in many of the following examples only a period up to 2008 is considered to exclude the effects of the financial crisis.

The demand drivers modeled

Population

When using population as a driver for demand, the Equations 4 to 6 are not applicable. Therefore, Equation 7 was used instead.

$$Steel = \frac{Steel}{Population} * Population = Steel\ intensity * Population$$

Equation 7

Where:

- Steel = Total demand of steel in Kton for year t
- Steel intensity = the equation for intensity of steel in Kton per capita
- Population = (projected) population

Steel divided by population is the steel intensity and will be represented by a trend based on historic data. Within this equation, only population is the independent variable. However, this does not mean that if population decreases so does the steel demand, since the steel intensity can still increase over time. The values for steel intensity can be found in Table 5 and the equations used for intensity can be found in Appendix I. The United States was excluded because it did not show a strong statistical correlation in chapter 4.

Table 5: Steel intensity over time in kg crude steel per capita (The World Bank, 2015; World Steel Association, 2005, 2014b)

Year / Region	1995	2000	2005	2008
World	132	139	177	200
EU	394	396	394	396
Japan	810	839	880	927

When looking at the world steel intensity in Figure 45, no large effects can be observed from the financial crisis. Both the population and crude steel production kept increasing worldwide. Just like the world's population, the steel intensity growth appears to be exponential. When using the exponential equation found for the steel intensity trend, the resulted steel demand closely follows the historical data (Figure 46). Since the modeled demand is based on a trend, the results are a smooth line while in reality more fluctuations can be observed.

Table 5 shows that for the EU the steel intensity stayed relatively stable over the years. This is mirrored in Figure 47 where it is visible that the steel production increased when the population increased, resulting in a stable steel intensity. When using the historical steel intensity trend the modeled steel production is very close to the historical steel production (Figure 48).

Japan's population started decreasing in 2010, which coincides with the period of the financial crisis. Therefore it is unclear if the decrease in steel demand is caused by the financial crisis or the decreasing population. Consequently, the data from 2009 onwards is not included, despite the fact that it matched the historic trend of the previous years. When looking at Figure 49 the stabilization of population can be seen in the cluster of data points around 128 million people. The steel intensity however did continue to increase, resulting in an increase in steel production which can be observed in Figure 50. In the modeled steel demand the growth is slower from 2003 onwards which is most likely caused by the stabilization of population size, while other factors caused a peek in historical steel growth in that same period. This peak cannot be seen in the modeled growth since it is based on a trend rather than the intensities of individual years.

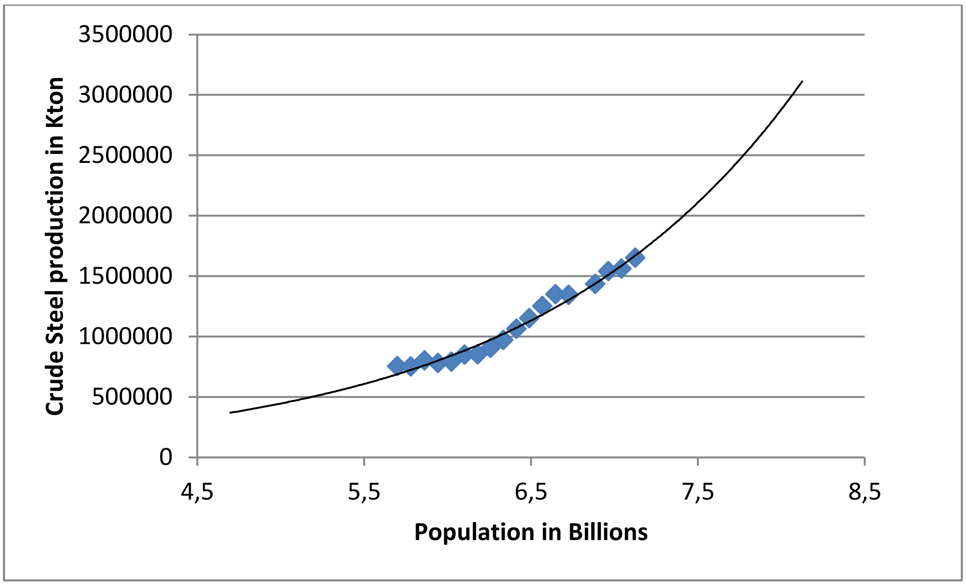

Figure 45: World steel intensity for 1995-2013 (The World Bank, 2015; World Steel Association, 2005, 2014b)

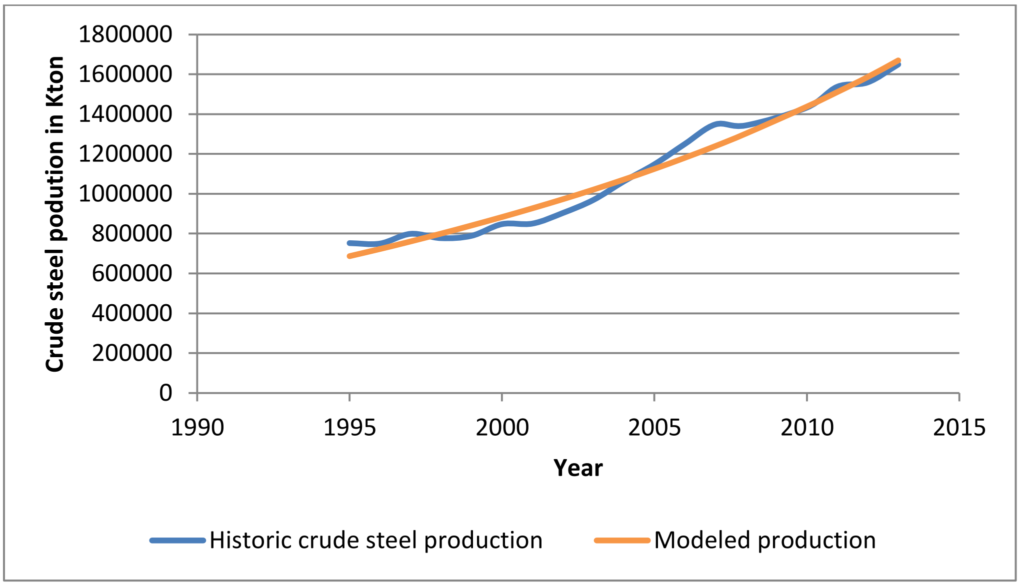

Figure 46: World steel production over time(World Steel Association, 2005, 2014b)

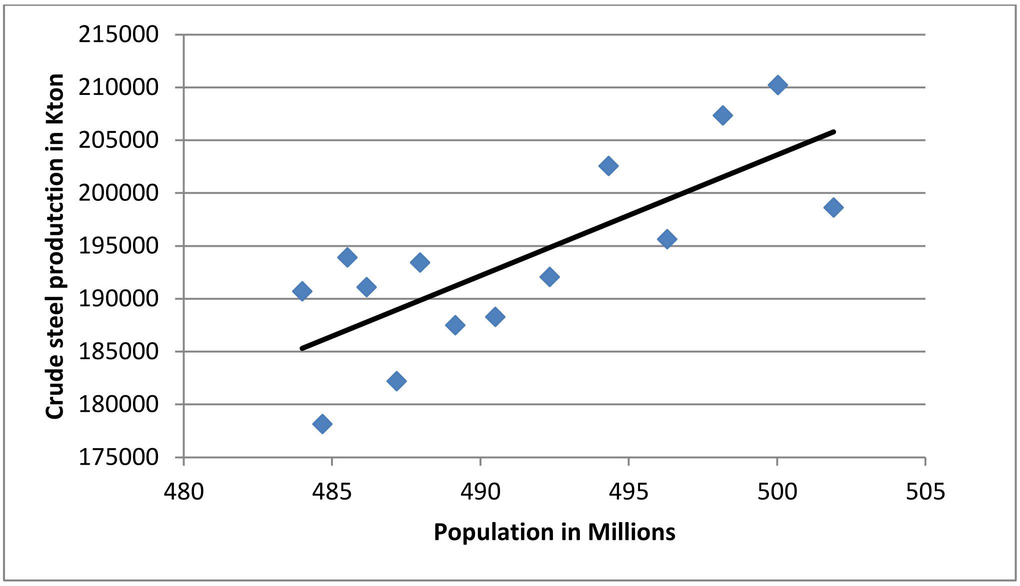

Figure 47: EU steel intensity for 1995-2013 (The World Bank, 2015; World Steel Association, 2005, 2014b)

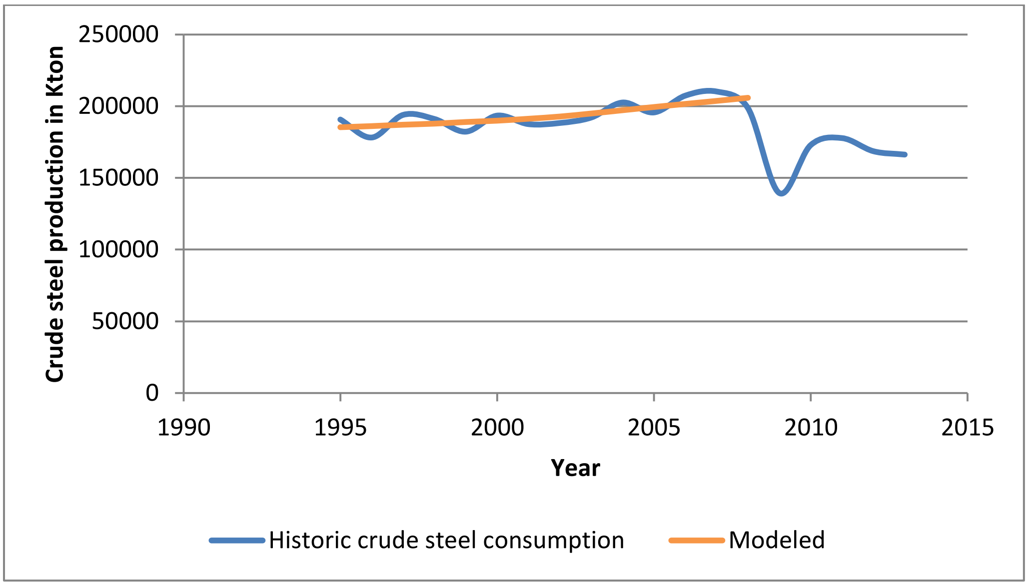

Figure 48: EU steel production over time (World Steel Association, 2005, 2014b)

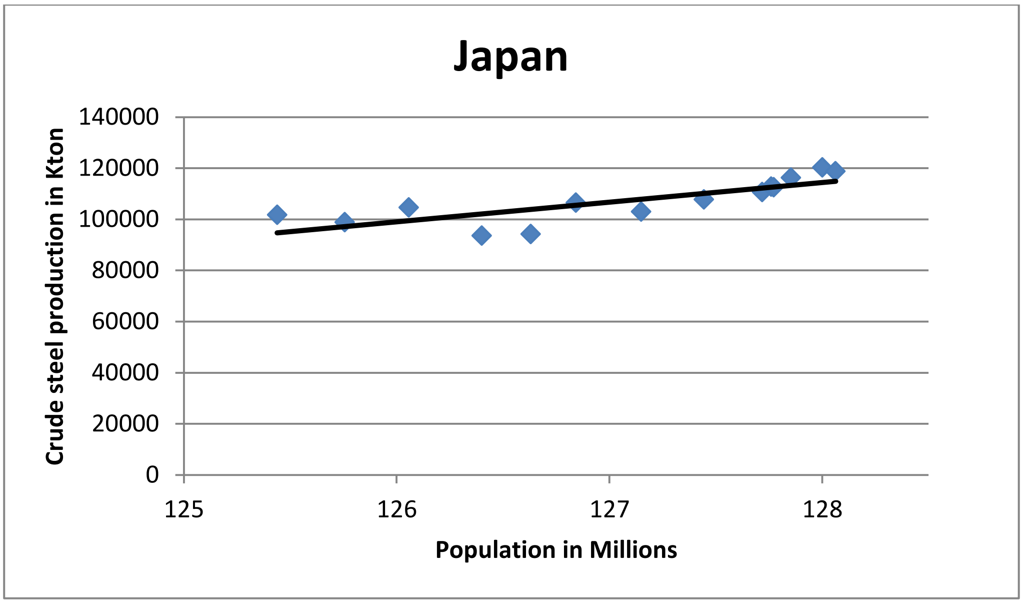

Figure 49: Japan steel intensity for 1995-2008 (The World Bank, 2015; World Steel Association, 2005, 2014b)

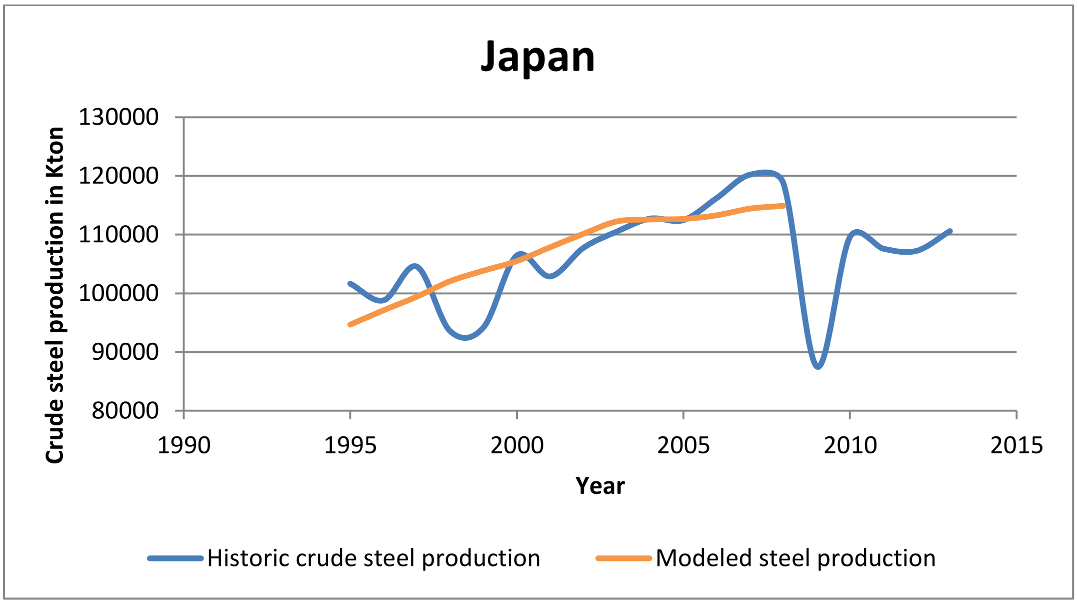

Figure 50: Japan steel production over time(World Steel Association, 2005, 2014b)

Motor vehicle production

Of all the usable physical drivers, motor vehicle production is the driver that can most accurately predict the steel consumption of its entire sector, since the main product of this industry are motor vehicles. To model demand on motor vehicle production as driver, Equation 5 can be rewritten as:

$$Steel\ consumption = \frac{Vehicles\ produced}{Population} * \frac{Steel\ consumption}{Vehicles\ produced} * Population$$

Equation 8

In this case the product intensity is the number of cars produced per capita. The steel intensity is in Kton of crude steel consumption per vehicles produced.
Since *total* motor vehicle production is used, both the product intensity and steel intensity say nothing about for example the amount of steel in a single car, because they represent the entire sector. The advantage of using a trend rather than an average steel intensity is that one region might make more heavy vehicles than another region. If average motor vehicle steel intensity would be used, this difference would disappear.

Table 6: Product intensity in motor vehicles produced per capita (OICA, 2015a; The World Bank, 2015)

Year / Region	2001	2004	2005	2008
EU			0,037	0,037
USA	0.040	0.041	0.040	0.029
Japan	0.077	0.082		

Table 7: Steel intensity in Kg steel per motor vehicle produced (Eurofer, 2004-2014; OICA, 2015; The Japan Iron and Steel Federation, 2005; USGS, 2002-2012; World Steel Association, 205, 2014)

Region \ Year	2001	2004	2005	2008
EU			1702	1723
USA	1120	1251	1097	1349
Japan	1230	1370		

As can be observed in Table 5 and Figure 53, the steel intensity in the EU stayed very stable in the years before the crisis, indicating that the composition of vehicle production stayed roughly the same. The product intensity also stayed in a very small range, showing a very slight increase. Overall, for the EU the modeled steel demand seems to be correct for the 4 years it was modeled for. For the USA more data was available than for the EU. The steel intensity shows a lot of variation, but an overall increase is visible. The product intensity however shows an overall decline. Since the modeled steel is based on two linear intensities, the variation in steel consumption is not reflected in the modeled steel consumption. For Japan, only a 4-year time range was available before the financial crisis. It has been modeled, with the modeled consumption showing a similar shape to the historic consumption. Both steel and product intensity show an incline from 2001 to 2004 which results in a very steep increase. Perhaps the steep increase in product intensity can be explained by an unchanged motor vehicle production, but a declining population. Since Japan is a known vehicle producer country, a share of the vehicles could be for export, which could explain why the production has not decreased while the population is decreasing. The role of export within this method of modeling will be discussed later on.

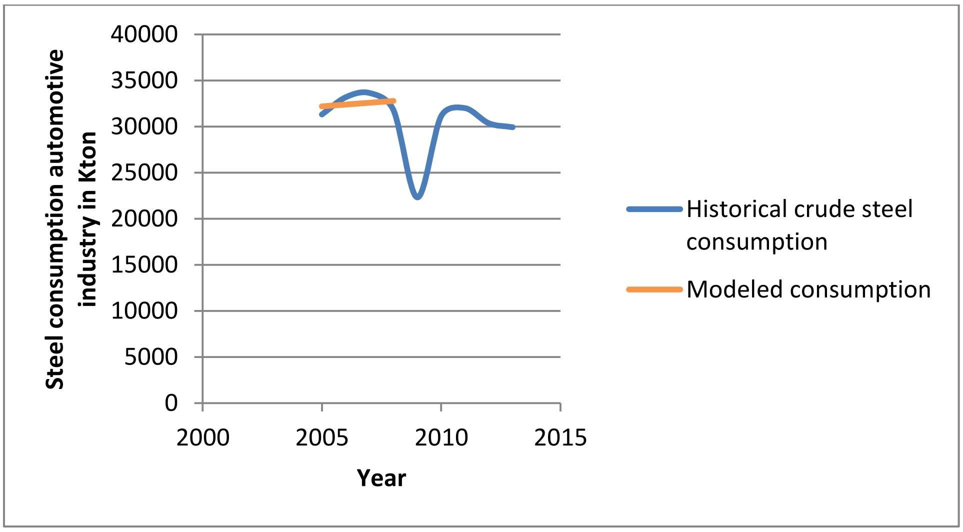

Figure 51: EU steel consumption automotive sector over time (Eurofer, 2004-2014; OICA, 2015; World Steel Association, 2005, 2014)

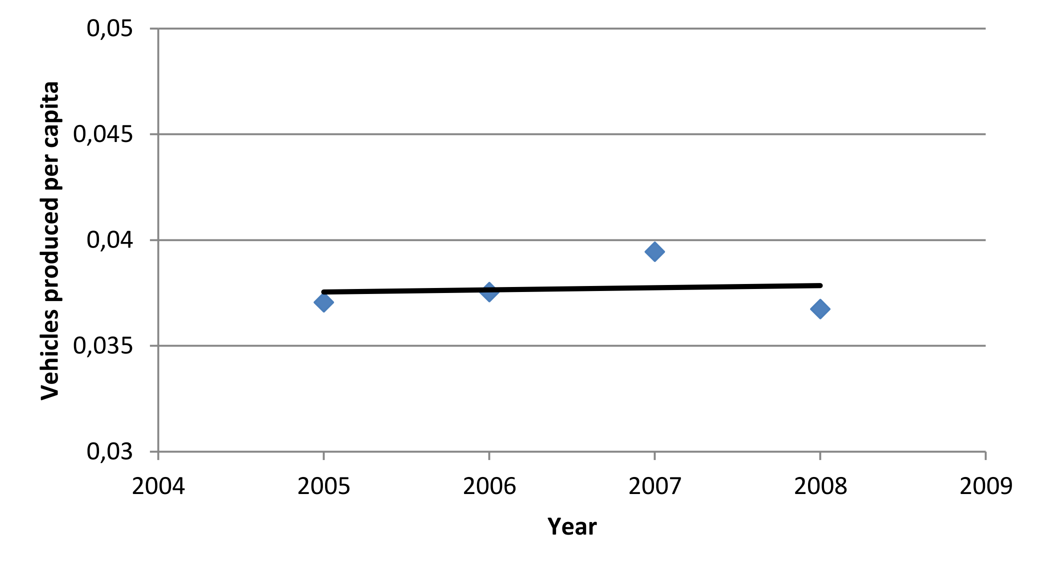

Figure 52: EU product intensity motor vehicles produced over time (OICA, 2015a; The World Bank, 2015)

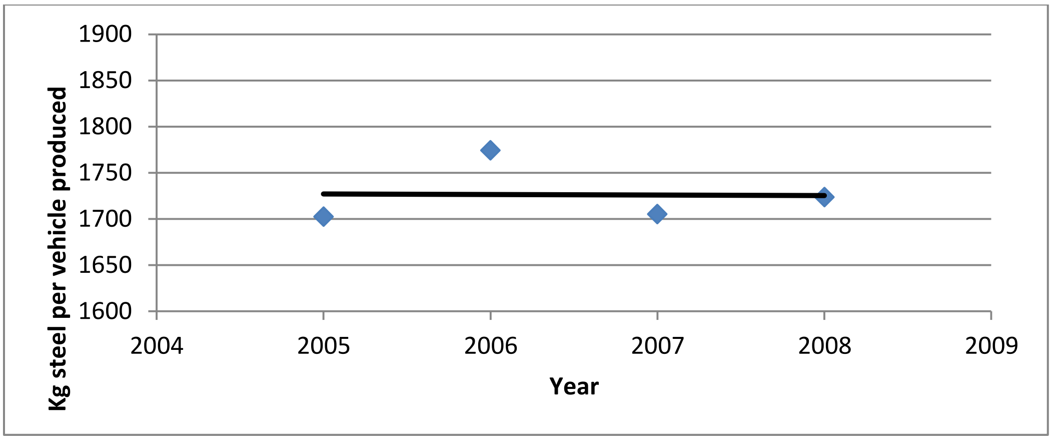

Figure 53: EU steel intensity motor vehicles produced over time (Eurofer, 2004-2014; OICA, 2015; World Steel Association, 2014)

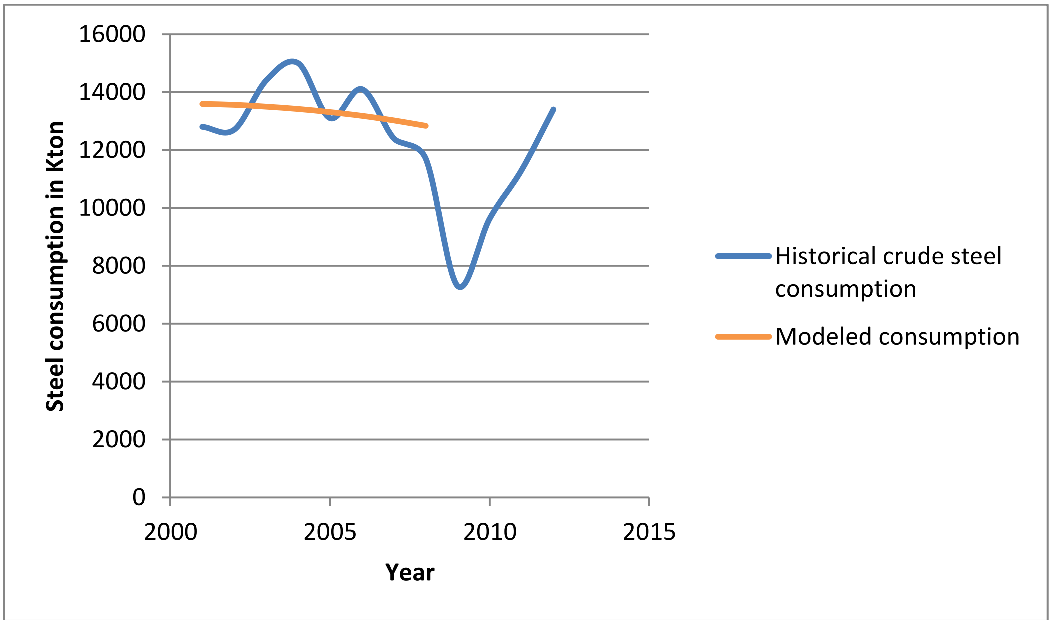

Figure 54: USA steel consumption automotive sector over time (USGS, 2002-2012; World Steel Association, 2005, 2014)

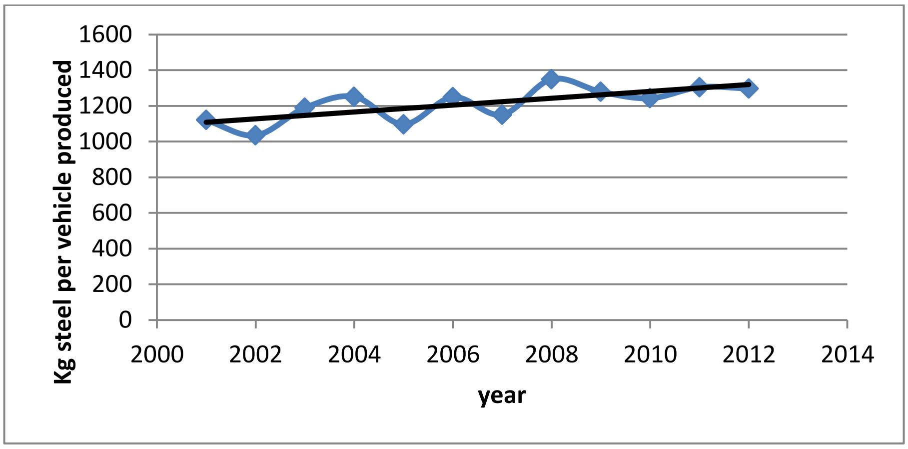

Figure 55: USA steel intensity motor vehicles produced over time (OICA, 2015; USGS, 2002-2012; World Steel Association, 2005, 2014)

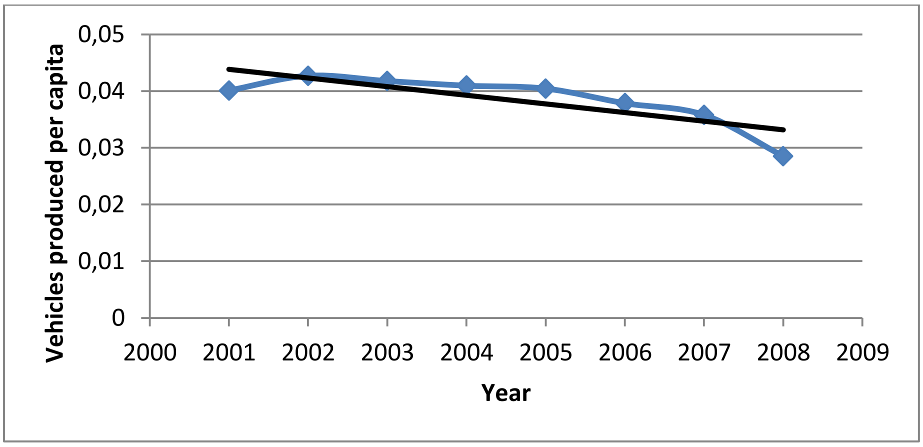

Figure 56 USA product intensity motor vehicles produced over time (OICA, 2015a; The World Bank, 2015)

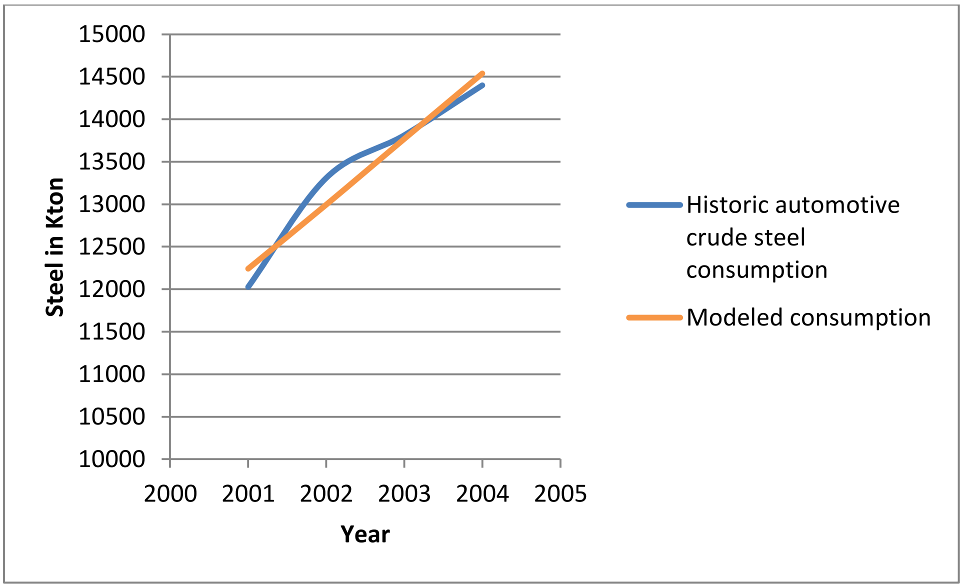

Figure 57: Japan steel consumption automotive sector over time (The Japan Iron and Steel Federation, 2005; World Steel Association, 2005)

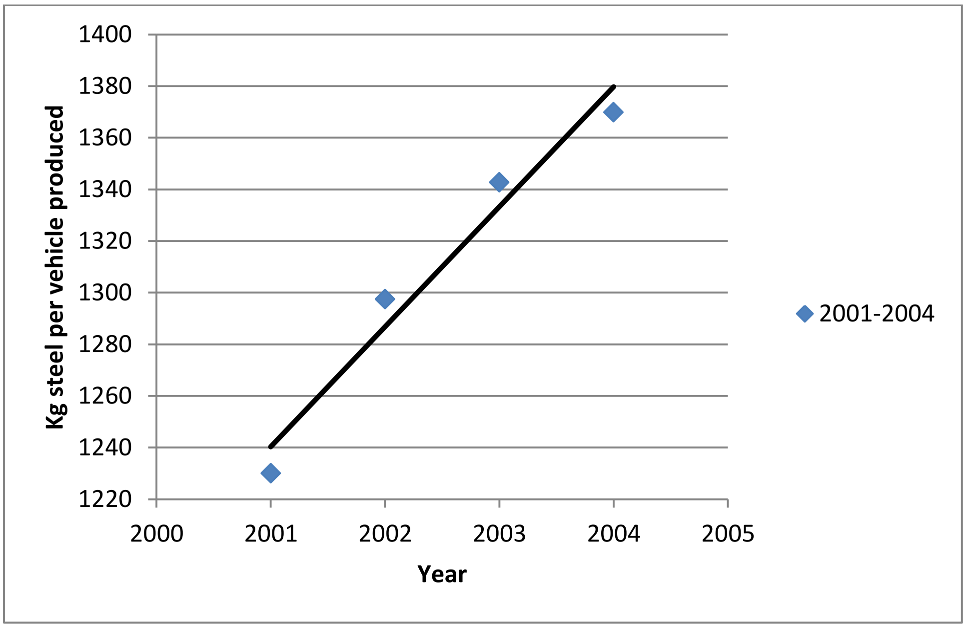

Figure 58: Japan steel intensity motor vehicles produced over time sector (OICA, 2015a; The Japan Iron and Steel Federation, 2005; World Steel Association, 2005)

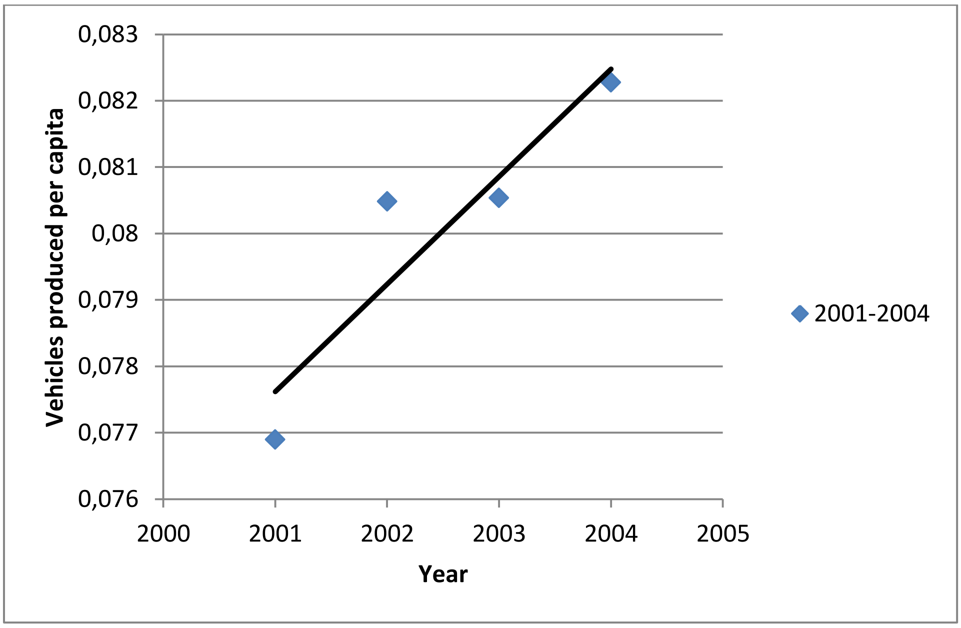

Figure 59: Japan product intensity motor vehicles produced (OICA, 2015a; The World Bank, 2015)

New Dwellings

Regardless of the fact that there are more types of construction than dwellings, in the previous step the data showed that the construction of new dwellings could represent the steel demand of the entire construction sector. The equation used for the predictions of steel demand in the construction is:

Equation 9

$$Steel\ consumption = \frac{New\ dwellings}{Population} * \frac{Steel\ consumption}{New\ dwellings} * Population$$

The product intensity is the number of new dwellings built per capita. The steel intensity is Kton steel consumed per new dwelling. Because this formula represents the entire sector, the steel intensity calculated for the equations does not represent the steel intensity of actual dwellings. The average steel intensity of actual dwellings can only be used when calculating the steel consumption of dwelling construction only. In Table 9 the steel intensity of new dwellings constructed can be observed. In 2001 the intensity is about the same for Europe as it is for Japan, however after 2001 Europe's steel intensity shows an increase while Japan's steel intensity stays about the same. Since only one type of construction is used to represent the entire sector, the steel intensity cannot tell anything about why there is such a large difference between the steel intensities of both countries.

When looking at the modeled steel for the EU, the shape of the steel demand is a linear increase (Figure 60). This is caused by a combination of both intensity equations being linear equations and the linear increase of population size. The historical product intensity in Figure 61 does not show quite a linear increase, so an equation that would have better matched its shape could have contributed to a modeled steel demand that better matches the shape of the historical steel demand. However, if for example a polynomial equation was chosen, it might have matched the historic period quite well, but could lead to an unrealistic increase or decrease of intensity if that equation was used for predicting future steel demand. For that reason only linear trend equations are used in this thesis with the exception of population as a driver for total world steel demand.

The shape of the modeled steel demand for Japan in Figure 63 also does not match the shape of historical steel consumption. Since it is modeled over such a short time period the difference is extra visible because in a longer time period the small historical fluctuations would not stand out as much.

Table 8: Product intensity in new dwellings constructed per capita (Enerdata, 2015; Statistics bureau Japan, n.d.; The World Bank, 2015)

Year / Region	2001	2004	2008
EU	0,0046	0,0048	0,0047
Japan	0,0092	0,0093	

Table 9: Steel intensity in ton steel per new dwelling constructed (Eurofer, 1999-2014; Statistics bureau Japan, n.d.; The Japan Iron and Steel Federation, 2005; World Steel Association, 2005, 2014)

Year / Region	2001	2004	2008
EU	12,6	19,6	22,6
Japan	12,2	11,9	

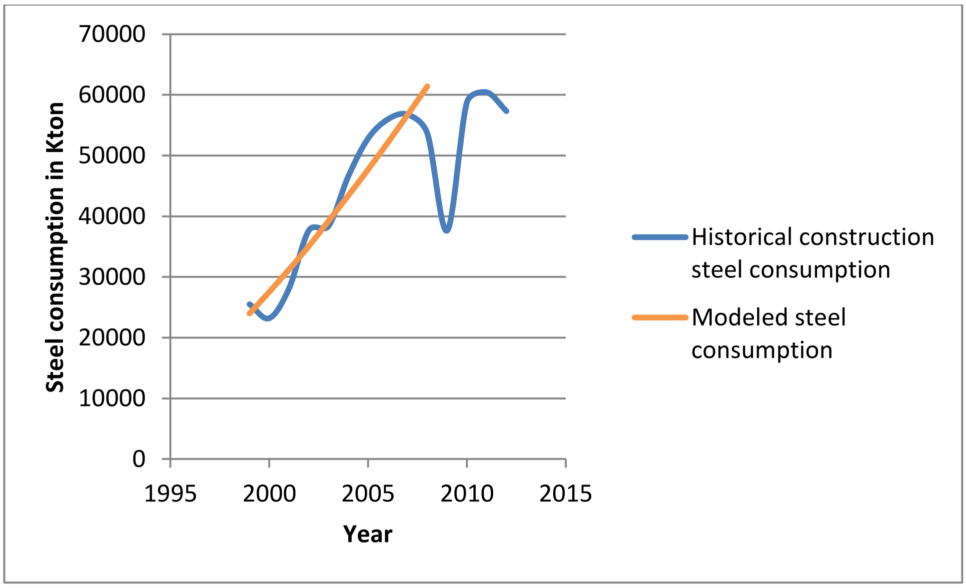

Figure 60: EU steel consumption construction sector over time (Enerdata, 2015; Eurofer, 1999-2014; World Steel Association, 2005, 2014)

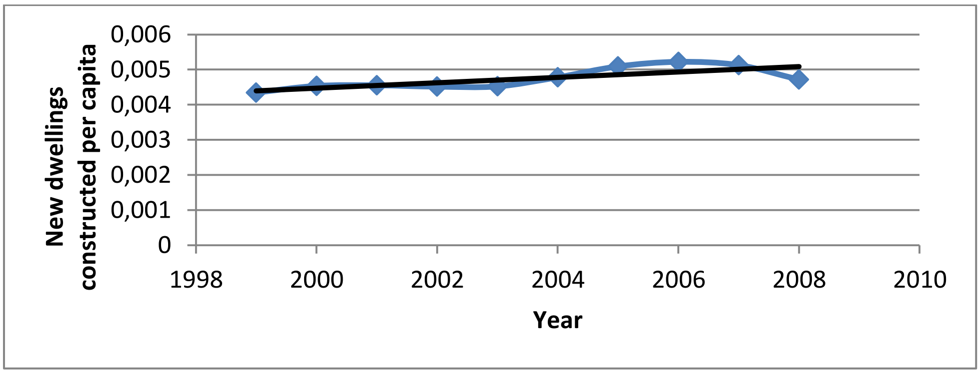

Figure 61: EU product intensity new dwellings constructed over time (Enerdata, 2015; Eurofer, 1999-2014; The World Bank, 2015; World Steel Association, 2005, 2014)

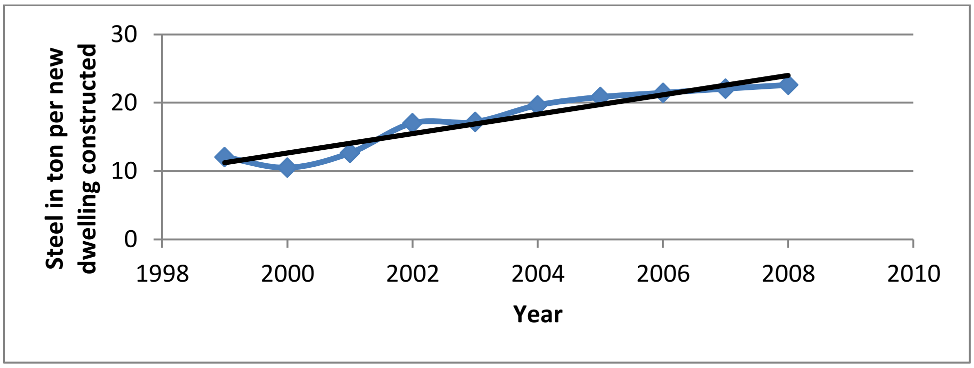

Figure 62: EU steel intensity new dwellings constructed over time (Enerdata, 2015; Eurofer, 1999; World Steel Association, 2005, 2014b)

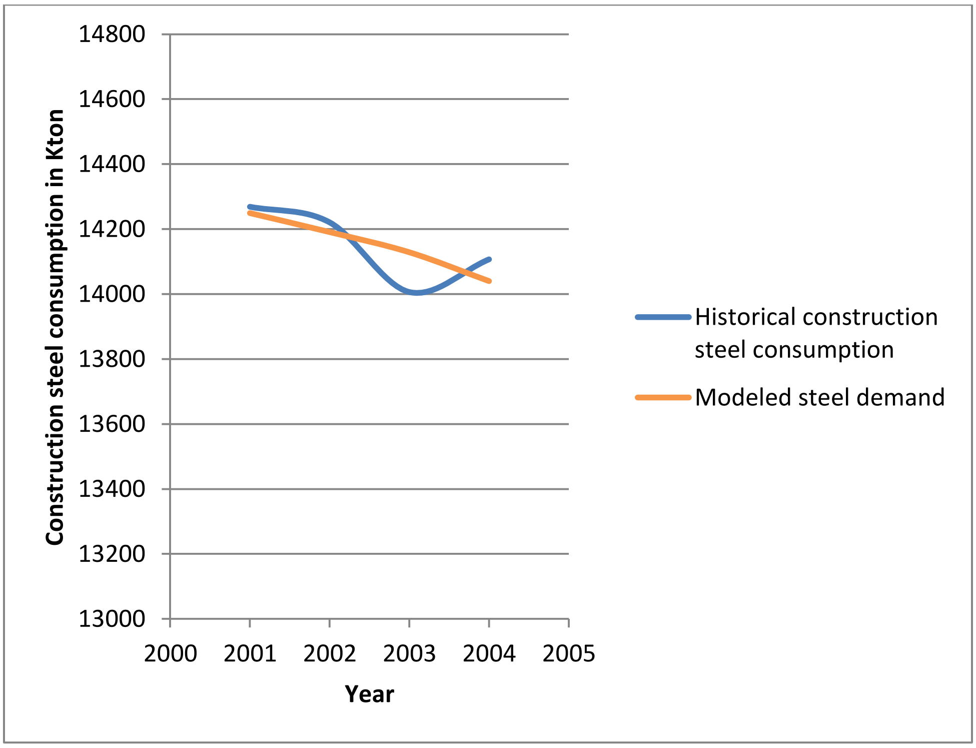

Figure 63: Japan steel consumption construction sector over time (The Japan Iron and Steel Federation, 2005; World Steel Association, 2005)

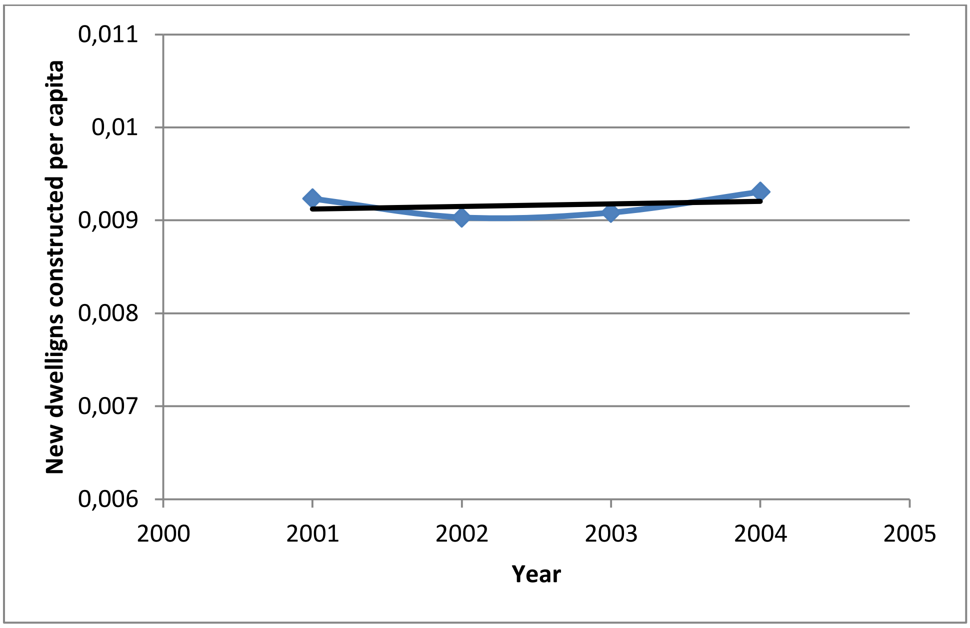

Figure 64: Japan product intensity new dwellings constructed over time (Statistics bureau Japan, n.d.; The World Bank, 2015)

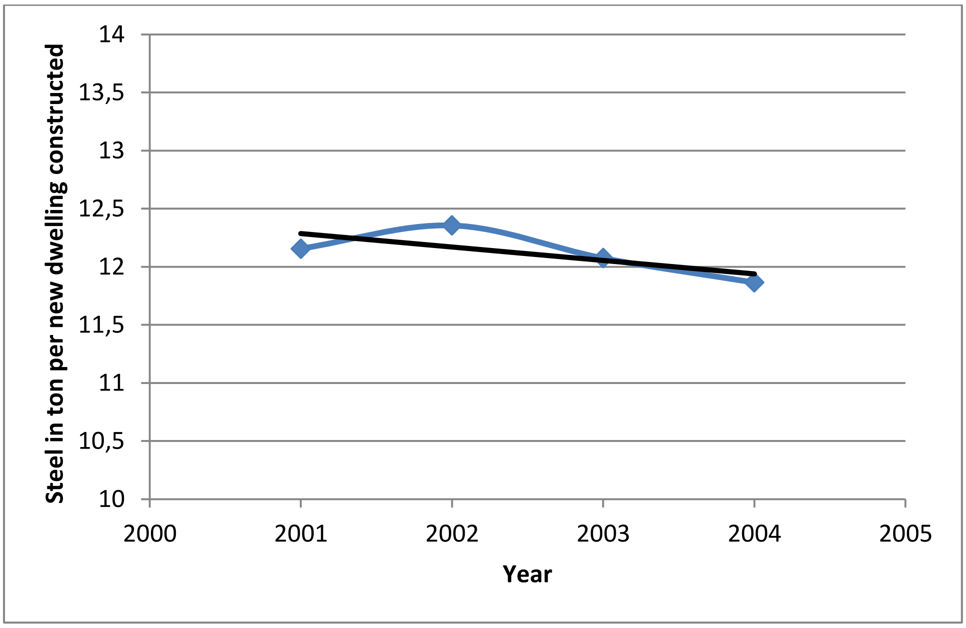

Figure 65: Japan steel intensity new dwellings constructed over time (Statistics bureau Japan, n.d.; The Japan Iron and Steel Federation, 2005; World Steel Association, 2005)

Building floor area

This driver is a combination of building floor area and floor area per capita, since floor area per capita is the product intensity in Equation 10. It is the only driver based on service stock per capita included in demand modeling. Again the floor area for dwellings will be used as a driver for the steel demand of the entire construction sector. Therefore the calculated steel intensity is the total amount of steel consumed in the construction sector per square meter rather than the actual steel demand per square meter of dwelling. If desirable, urbanization rate could be incorporated in the change of steel intensity over time. Since the construction of urban houses requires more steel than rural houses, the steel intensity would increase as the urbanization continues.

Equation 10

$$Steel\ consumption = \frac{Total\ floor\ area\ dwellings}{Population} * \frac{Steel\ consumption}{Total\ floor\ area\ dwellings} * Population$$

Table 10: EU intensities for building floor area (Enerdata, 2015; Eurofer, 1999-2014; The World Bank, 2015; World Steel Association, 2005, 2014)

Year / Intensity	1999	2004	2008
Product intensity	31,4 m^2/cap	34,0 m^2/cap	35,4 m^2/cap
Steel intensity	1,67 Kg/m^2	2,76 Kg/m^2	3,02 Kg/m^2

As can be observed in Table 10 and Figure 67, the product intensity showed a linear increase over time. Every year the dwelling floor area per capita increased. The steel intensity also shows an increase, indicating that every year more steel is used for construction. The combination of increase in both intensities and population size leads to a fast increase in modeled steel demand over time (Figure 66).
Because the same method of modeling steel demand for the construction sector has been applied here as for new dwellings as a driver, the modeled steel demand for both drivers looks identical (see Figure 60 & Figure 66). This indicates that the proposed modeling method is consistent when applied to different drivers. The modeled outcome would however have been different if for any of the trends another method than a linear equation had been used.

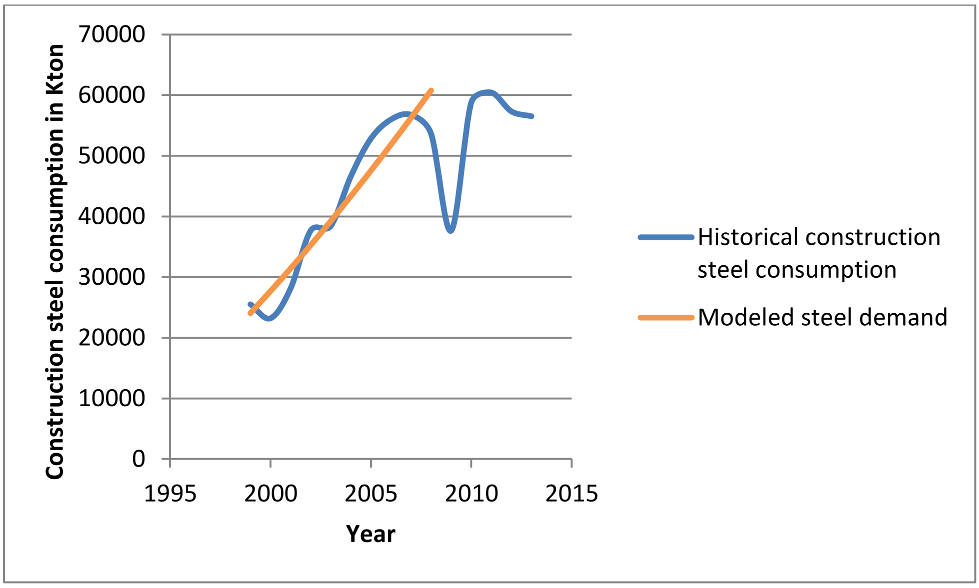

Figure 66: EU steel consumption construction sector over time (Enerdata, 2015; Eurofer, 1999-2014; World Steel Association, 2005, 2014)

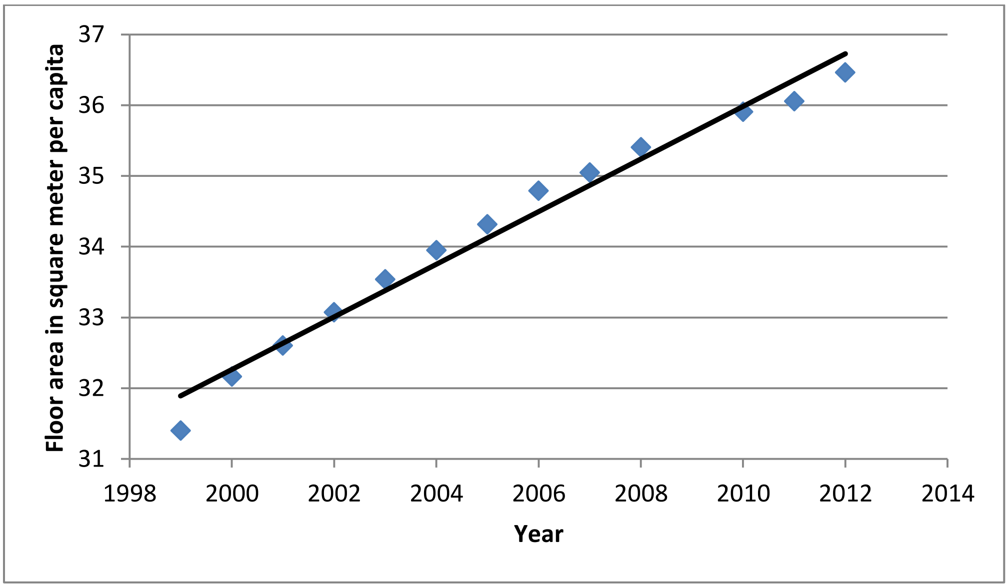

Figure 67: EU product intensity dwelling floor area over time (Enerdata, 2015; The World Bank, 2015)

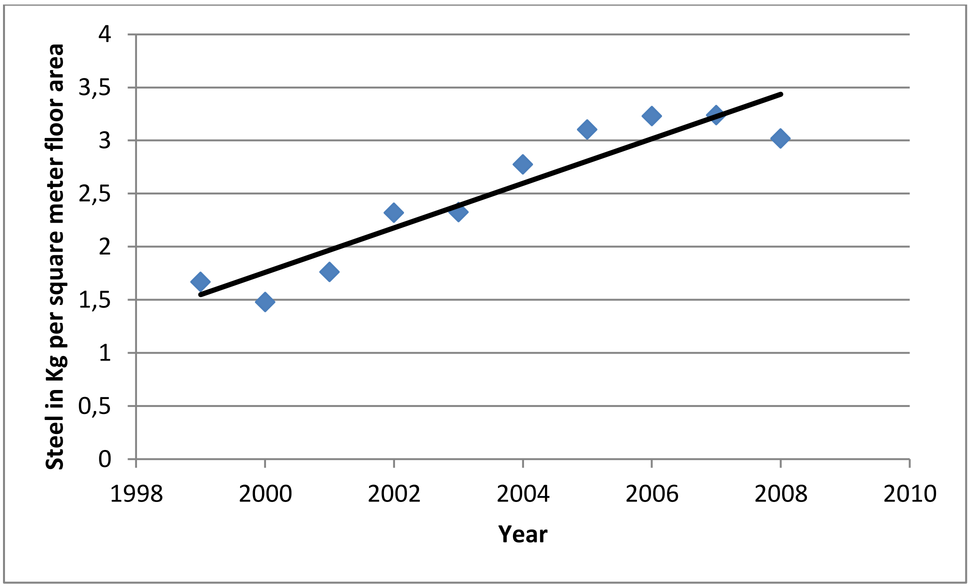

Figure 68: EU steel intensity dwelling floor area over time (Enerdata, 2015; Eurofer, 1999-2014; World Steel Association, 2005, 2014)

Multiple drivers for modeling steel demand have been proposed. However, some of them overlap and model the same demand. When using population to model total steel demand, it overlaps with all other drivers. Building floor area as a driver overlaps with new dwellings constructed, since both model construction steel demand. Which driver to use could be dependent on the situation. Population as a driver for example only requires limited data and can therefore be used for quick and easy demand calculations. A stock based driver like total floor area is very suitable for long term modeling, since changes in stock size over time are relatively small compared to changes in flow size. Drivers based on flow size, like new dwellings constructed and motor vehicles produced, show more fluctuation over time, which makes them more suitable for short term modeling. If for example steel suddenly gets substituted by aluminum, the changes in flow size can be instantaneous, while the stock size takes longer to adjust.

How to model steel demand for other sectors?

Within this study a driver for overall steel demand, automotive steel demand and construction steel demand have been determined and a method for using them to model has been proposed. This leads to the question, how to model steel demand in IAM's for other sectors?

One of the options is to find physical drivers for the other steel consuming sectors and apply the same method of modeling. In this way the complete steel demand can be modeled bottom-up. A downside however is that it requires data on the chosen physical drivers for all chosen regions. Furthermore, product and steel intensities should be determined, requiring even more data.

A second option is to base the steel demand of an entire region on its population. It is most likely not the most accurate method of modeling future steel demand, since chapter 4 showed that there was no strong statistical correlation for the USA between population and steel production. It is however the simplest solution since there is data available on population size and steel production for most countries.

A third option is to calculate the steel demand by looking at the share of steel consumption by sector. In step 1 it could be observed that the share of sectorial steel demand only showed minimal changes over time. If the method proposed in this thesis is used to model steel demand for the construction and automotive sectors, and a minimal change of sector share over time is assumed, the steel demand of the other sectors could be calculated simply by using their percentage of total steel demand.

A final option is to model steel demand of the sectors not considered in this study by using the IU method. Regardless of the critique on GDP as a driver for demand, it has proven its usefulness in the past. It could be replaced by a method using physical driver or another effective method, when one is found. A combination of the IU method and sectorial steel share could also be applied. Steel demand for the entire country could be calculated using the IU method, sectorial steel share are then applied to find sectorial steel demand. The sectorial steel demand found using the IU method could then be compared to the one found using the proposed bottom-up method to find an average.

Import and Export

Within this method of modeling steel demand, there is no attention for the import and export of steel and steel products. Since the steel demand is linked to production levels rather than the use of the product import and export, it only indirectly influences steel demand. If a country decides to start importing rather than creating a steel product themselves, their product intensity will decrease if their own production decreases. If their own production stays the same, the product intensity will not change either. When it comes to export, the product intensity of the producing country will increase if it starts producing more products for export. This effect can be built into a product intensity equation if it is used. Another option is to simply adjust product intensity if a new situation regarding import or export of a country is anticipated.

6. Conclusion

This study has been performed in order to identify methods that can improve steel demand modeling in Integrated Assessment Models. Instead of using monetary drivers like GDP, the focus was on physical drivers of demand. The third chapter identified the construction and automotive sector as the two main steel consuming end-use sectors. Together these two sectors consume 60% of the world steel production. Based on literature and the end use-sectors identified in combination with their steel products, 9 physical drivers were identified. All drivers were tested for a statistical correlation with the sectors' steel consumption. The physical drivers that had a positive high statistical correlation were: population, motor vehicle production, new dwellings constructed and total floor area of dwellings. A bottom-up method for material demand modeling that allows the modeling of sectorial steel demand rather than steel demand for a single product was created. Historical trends of stock and flows of steel containing products, together with trends of historical sector steel intensities can now be used together with population projections to model future steel demand.

In conclusion, steel demand modeling in IAMs can be improved by using a bottom-up method of modeling that uses physical drivers based on the end-sectors and uses of steel, and incorporates trends based on historical data of (service) stock size, flow size, steel intensity and changes in steel production.

7. Discussion

Limited data availability

The largest problem during this research was the lack of data availability. Only very limited information was available on shares of sectorial steel demand. Therefore the countries and regions that are included in this thesis (Japan, the United States and Europe) can only represent developed countries. Furthermore, the limited timeframe for which data was available also restricted the analysis and modeling. For example, some trends for Japan were only based on historical data of 4 consecutive years. For all countries data of the most recent years needed to be excluded due to the effects of the financial crisis. If data had been available for a longer timeframe, the real trends could have been observed better. The lack of consistency within data labeling also played a part. In the data for the USA, service centers and distributors was named as an end-use sector. It is however unclear what that steel was eventually used for. Therefore it is possible that the share of steel consumption named for the automotive and construction sector is actually lower than reality, because a part of their share could have been incorporated within services centers and distributors. Because the historical and current stock of steel within the different countries and regions is unknown, only stocks or flows of steel containing products could be used as drivers. Furthermore, as a consequence of limited data availability for the distribution of steel used within the end-use sectors, most drivers had to be linked to the steel demand of the entire end-use sector.

Since demand needed to be modeled for the entire sector, it also affected the steel intensity of the product which had to be determined by using the total steel production within the end-use sector. As a result the modeled historical steel demand was based on the data of the historical steel consumption. This could have been avoided if the drivers only had to model their own steel end-use with actual steel intensities. Consequently, a recommendation for future research is more research into data for steel stock, sectorial steel demand and steel intensities.

The lack of data excluded also developing countries from this thesis. This is unfortunate as the IU theory suggests that the steel demand should be increasing in those countries. Due to the lack of data, it is not clear if the historical trends of product intensity and steel intensity indicate a growth for these countries. Therefore it is not clear if the method of modeling proposed in this thesis can be used to model the steel demand of these countries. By performing more research into sectorial steel demand of different countries it can be investigated if the proposed drivers and method also work for other developed, and developing countries.

Method

The method used to determine usability of the identified driver was by calculating the coefficient of determination. The main disadvantage of this method is that the value of R^2 does not indicate if there was indeed causality. However, since it was used as a method that could help exclude some of the identified drivers its use in this thesis was appropriate.

Some of the limitations to the proposed method of modeling have already been discussed under data availability. As a result of data limitations, drivers were used to model the demand of entire sectors rather than for their end use. Drivers that have a large share of the steel consumption for the entire sector should be relatively accurate in the predictions. However, drivers that have a smaller share, like the driver new dwellings which has to represent the entire construction sector, are most likely less accurate in forecasting future steel demand.

One of this method’s strengths, but also its weaknesses is the simplicity of the formula. The proposed method of modeling is a method that could be seen as a way to transition from the current model where GDP is used to model demand, towards a more bottom-up method that separates end-use sectors into more products rather than use one driver to model the entire sector. To better embed this method in an IAM, some non-physical drivers like competitiveness of other materials and policy measures should be linked to the product and steel intensity. Research should be performed to explore if and how this method can be incorporated in IAMs.

The focus of this thesis was on physical drivers while there might be other new methods of material demand modeling that include non-physical (monetary) drivers. Therefore the final recommendation for future research is to analyze different methods of material demand modeling and compare them to one another on accuracy, complexity and required data.

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Appendix I: Equations used for steel intensity trends

Region	Equation
World	Intensity = $19801,5370844902e^{(0,0000000000622394244448624 * \text{Population})}$
EU	Intensity = 0,00114469798718385*population - 368734,866005996
USA	Intensity = - 0,0000659573128803102*population + 114835,9858513290
Japan	Intensity = 0,00771407753558775*population - 872989,578668665

Region	Product intensity equation	Steel intensity equation
EU	Intensity = 0,0000995168590975481 * year t - 0,161990001727827	Intensity = - 0,0000005587796032102690000000000 * year t + 0,0028473459235101500000000000000
USA	Intensity = - 0,00152140924316091 * year t + 3,08817342792948	Intensity = 0,0000262709539516745 * year t - 0,0514802666903485
Japan 2001-2004	Intensity = 0,00161922176757798 * year t - 3,16244329973124	Intensity = 0,0000464642674291582 * year t - 0,0917346747461124
Japan 2001-2013	Intensity = 0,00495922825624954 * year t - 9,90487325952078	Intensity = -0,0000743739032624073 * year t + 0,151028299625371

Region	Product intensity equation	Steel intensity equation
EU	Intensity = 0,00007750204701138 * year t - 0,150535722095237	Intensity = 0,00141778370609962* year t - 2,82293779860956
Japan	Intensity = 0,0000275721170311272 *year t - 0,0460497643449344	Intensity = - 0,000115577785373944 * year t + 0,243556472379714

Region	Product intensity equation	Steel intensity equation
EU	Intensity = 0,371815055719733 * year t - 711,365473480937	Intensity = 0,00000209660372439329 *

		year t - 0,000417562849778402