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Lubricating the recycling machine

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Abstract – When introducing a new control paradigm in industry or society one has to accept that it is an evolutionary process where people, methods and processes must develop simultaneously, and this takes time. The recycling of material has been studied intensely for the last ten years using different approaches to material flow analyses, MFAs. They have given a good view of the magnitude of material flows but their use has been limited by lack of relevant data. In the case of recycling, data must be acquired from the practitioners of the trade and in order to get it, the value of the output for them and for society must be proved and visualized. This paper is based on a MFA model developed at KTH for steel flows in Sweden (part of the Swedish environmental research program, the "Steel-Eco-Cycle"). The aim of the work reported on here was to initiate the process of motivating better sampling of data in industry and society for performing MFAs. The KTH model is based on a product-to-product approach for steel, describing the recycling machine. Data is presented in a simplified model for Sweden with total figures and figures per capita. Areas where improvements can be made are identified and ways to "lubricate" the recycling machine are discussed. The main idea is to provide a way of describing flows that can be of use to recyclers and steel producers and form a basis for discussions on improvements. Finally, the underlying model is briefly described and the uncertainties of data are discussed.

1 Introduction of a new technology

When introducing a new control paradigm in industry or society one has to accept that it is an evolutionary process where people, methods and processes must develop simultaneously, and this takes time.

As an example, one can look at the early stages when model-based control was introduced. In this concept a mathematical model of a process is used to calculate process data such as temperatures or chemical component concentrations that cannot be measured directly and these calculated values are then used for process control.

The main obstacle in introducing this approach was that most of the data sampled was actually collected for other purposes such as equipment control or just manual supervision. The data was consequently not accurate enough to be used for model-based control or was simply missing. However, when the economic potential of model-based control was proven, it became possible to raise the necessary funds to invest in better measuring devices and sampling systems and today this technology is not questioned.

Presently, in our effort to estimate flows of material for environmental protection purposes, we have introduced *material flow analysis*, MFA, and *substance flow analysis*, SFA. In this work we rely on data which in most cases is collected for other purposes. Taxes, customs and law enforcement are the three most important generators of statistics employed in MFA. This data can be used together with interview results and other estimations to paint a broad picture of material flows. In order to mobilize society to collect better data, MFA must be proven to be of significant value to society and thus deemed a wise investment.

This paper is based on a MFA model developed at KTH for steel flows in Sweden (part of the Swedish environmental research program, the "Steel-Eco-Cycle"), presented for the first time at SAM1 2007 [1]. The aim of the work reported on here was to initiate the process of motivating better sampling of data from society for performing MFAs.

Brunner [2] states the importance of developing MFA databases to connect to MFA tools. In order to do this a further classification of different types of MFAs, their purposes, the granularity of the data needed and the methods to obtain the data is probably necessary.

Behrens [3], Weisz [4] and Šèasný [5] are examples of applications of MFA with an economy-wide scope with a global, EC15 and national (Czech) perspective. In Sweden the work on the national perspective has started; Statistics Sweden [6], Carlsson [7]. Moriguchi [8] states that the main benefit of this type of study is to give an idea of the size of the physical economy. Moriguchi also discusses flow indicators to be used with this scope, difficulties in calculating recycling flows and the need for disaggregated data by material and sector to analyze underlying structural changes.

Steel as a recyclable material has been visualized for Japan by JISF [9] and EU15 EUROFER [10], based mainly on steel production and trade statistics. Michaelis [11, 12] calculates the material and energy flow through the UK Iron and Steel sector and finds that 48% of the steel in obsolete goods was not recovered (1994) based on the assumption that the average lifetime of a product was 15 years.

In order to deal with the lack of recycling data, Kakudate [13] estimates scrap generation from consumption figures of products and distributions of expected lifetimes. This technique was, for example, applied by Daigo [14, 15] for calculating steel stock and the collection rate for buildings, civil engineering and machines. The in-use stock was estimated at 900 mton, which represents about 7 tons per capita. The collection rate averages were 0.96, 0.15 and 0.48, respectively. Daigo notes that the output is strongly dependent on the assumed lifetimes. Geyer [16] and Davis [17] continued the work on MFA for the UK by using the same technique, reaching the conclusion that 30% of the steel was either lost or part of an undocumented accumulation in society. Finally, Müller [18] used a similar approach in a MFA for the USA.

In order to use MFA as a tool to promote change one needs commonly accepted key indicators to visualize the system. Hashimoto [19] presents six indicators representing three kinds of materials and three manners of use. Hashimoto points out the problem of capturing data for by-products, used products and products in stock.

Finally, Binder [20, 21] gives us an idea on where the MFA research is heading by suggesting that it should be accompanied by methods to involve the importance of social structure and processes on how decisions with material consequences are made. The results are yet to be seen.

From a control perspective it seems that the data used in MFAs in [3–18] gives a good view of how the system works. It is, however, probably not sufficient for control, i.e. using the models to make decisions about corrective actions in a feedback manner. To create processes to capture this data is a remaining task.

2 The product-to-product recycling machine

The concept "recycling machine" in this work refers to: all organizations, functions and mechanisms that help conserve matter and energy during the life cycle of a product. This means that the consumer with his ability to choose, the recycler, the steel producer and the product designer are all parts of the recycling machine.

"Lubrication" of the recycling machine refers to any action that improves how the recycling machine works. The "mechanics" lubricating might be a part of the machine or controlling from the outside, e.g. governments or other authorities.

A simple picture of the recycling system for steel using 2006 data for Sweden is shown in Figure 1. In order to emphasize that the recycling aspects are studied in the MFA, instead of working cradle to grave, the KTH model works from product to new product. Virgin material from the cradle and losses going to the grave are flows that should be minimized.

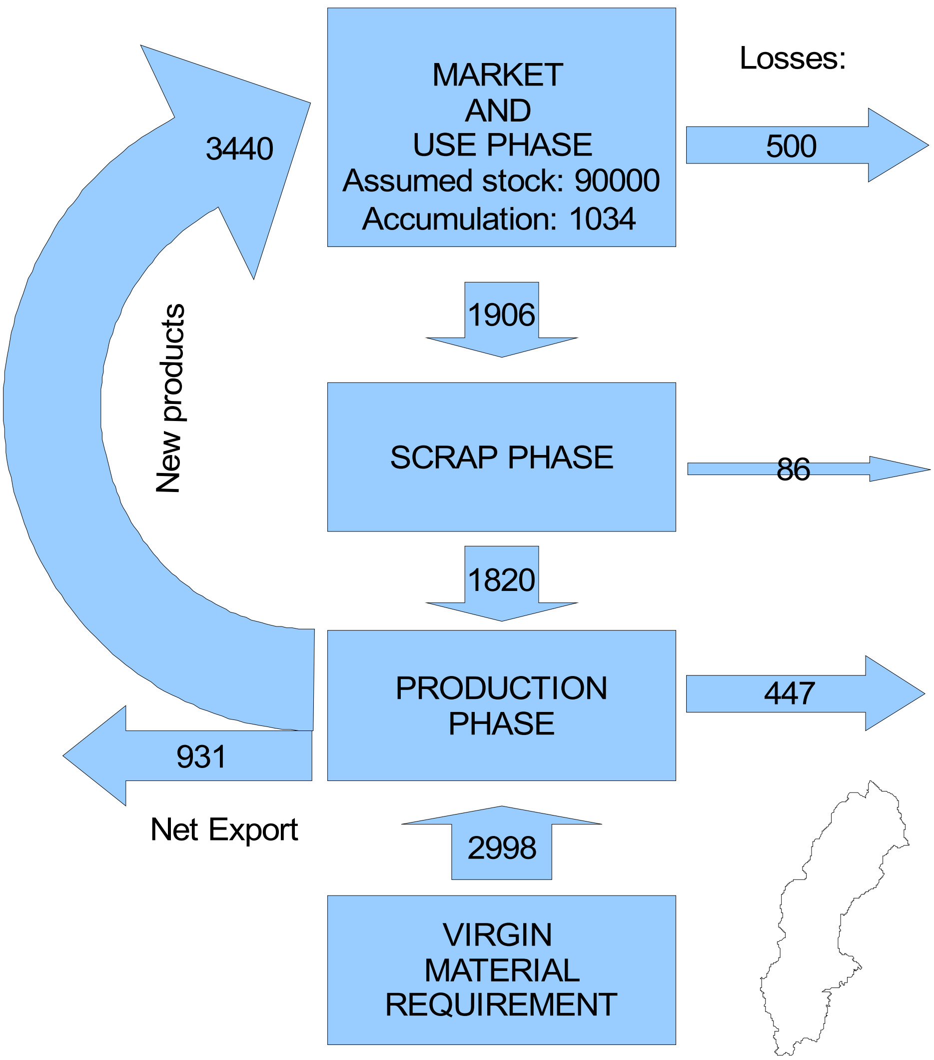

Fig. 1. The product-to-product recycling machine as a control model. Figures in arrows show net flow of steel in products and scrap in kton for the Swedish market in 2006. The model is simplified compared with the model in Figure 4. For example, all collected scrap is used for production and the virgin material production reduced accordingly.

Consequently, the KTH model starts with the product market-and-use phase where products are bought and used. Three main loss flows are identified: corrosion, radioactivity and dislocation, which implies that the steel products are used in such a way that they cannot be recollected in a cost-efficient way.

The second process or phase is the collection of material. This is carried out by the recycling companies and the loss in tons consists mainly of material degradation in the incineration process and fragmentation. However, the biggest environmental loss here might be that alloying elements are diluted since ferritic material is not further processed and separated into fractions of different alloy contents.

In the third phase, new steel is made from scrap and new products are made from steel. The main losses of iron and alloying elements are through slag, pickling acid and grinding dust. In order to make up for the losses and provide material for the accumulation of steel in the system, virgin material such as blast furnace iron, DRI and alloys is introduced into the system.

The following figures presented reflect the flows of the Swedish market. The model is simplified in order to serve as a control model that is easy to understand.

Sweden is a net exporter of scrap and uses virgin material as the main iron source. In studying the recycling machine, this is irrelevant and therefore all the scrap is assumed to be used in the production process and virgin material is only introduced to balance the system. This means that the focus in controlling the recycling machine should be on identifying the losses and developing strategies to reduce them.

With a production of some 4.9 mton steel and a consumption of 3.4 mton, losses in Sweden are estimated at 1.0 mton. The figures are large and to some extent hard to understand. To make it more comprehensible, the data can also be presented as per capita. This has been done in Figure 2.

Each person consumes some 382 kg of steel, accumulates 115 kg and sends 212 kg to recycling, and the loss from the use phase is 56 kg per capita. More than 50% of this consumption represents investments in buildings and infrastructure made by society and large organizations. It should be noted that the amount of virgin material needed, 333 kg, represents an extra load of 433 kg CO_2 on the environment compared with a 100% scrap-based production.

The major advantage of the per capita model is that it relays the possibility of the individual to make a difference by changing his or her preferences or behavior. More specifically, each individual has the potential to contribute to a decrease in these losses by changing their habits, as will be covered in greater detail later.

3 Lubricating the recycling machine

How can we improve the way the recycling machine works? Some ideas are shown in Figure 3, starting with "Improved consumer awareness". The individual, in his own private life or as a representative of an organization, is a key actor in making the system work more efficiently. We can identify at least three important aspects:

- Optimal lifetime.
- Optimal redundant stock.
- Optimal losses.

For every recycling loop we inevitably lose material in the production phase to slag, pickling acid, etc. An important measure the consumer can take is therefore to choose products of higher quality with reasonable lifetime lengths, with consideration also of other economic or environmental aspects such as energy consumption. The presence of maintenance and second hand markets are therefore also of importance when we talk about optimal lifetime.

As can be seen in Figures 1 and 2, we have an accumulation of material in the use phase. This is partly due to economic growth, but also probably results from an increased redundant material stock. This material can be found in the average garage or attic or is stored as buildings or other constructions waiting for demolition. Quite common in the agricultural business is that one keeps old machinery as a spare or backup when one invests in new. Readily scrapping permanently redundant equipment when there is reasonable certainty that they will not have to be replaced shortly afterwards is essential in considering optimal redundant stock.

Decreasing loss due to corrosion is also essential in dealing with redundant stock. Material that is not in use is probably not well protected against corrosion. Dislocated material such as sunken ships, equipment used in remote places or steel used for ground reinforcement may be hard to recover in a feasible way. However, the recycling of reinforcement bars was considered impossible a couple of years ago and is now a standard practice in many countries. Another example of dislocated materials can be found in pieces that are too small to be collected in an efficient way. Wire, capsules, etc. are hard to separate in the waste stream if they are collected at all. Finding a way to judge what loss sources we can accept and not is the meaning of the concept optimal losses. Radioactive material is another loss that has to be monitored and where reasonable levels of acceptable losses must be established.

The scrap phase separation of steel before incineration and separation of steel from aluminum, copper and non-metallic fractions in the fragmentation process are important factors in reducing material losses. In order

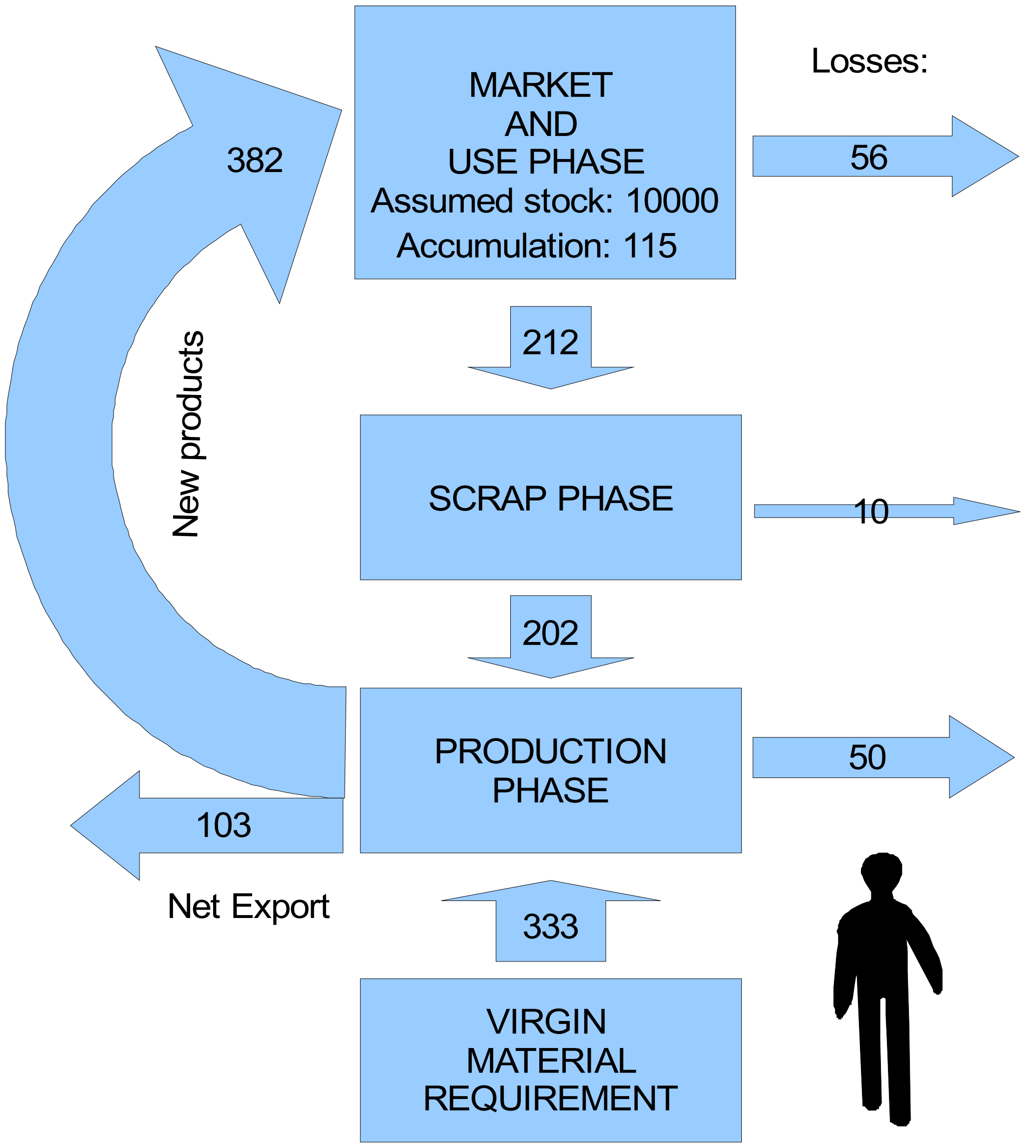

Fig. 2. The recycling machine control model from the individual perspective. Figures in arrows show net flow of steel in products, and scrap in kg per capita for the Swedish market in 2006.

to conserve the alloying elements in steel, improved separation and sorting of steel qualities in the fragmentation process is necessary. Separation means that the fragmentation process separates parts made of different materials. Sorting means that the equipment can identify different fractions and thereafter load them into different storage bins. This might, for example, be realized with development of LIBS, Laser-Induced Breakdown Spectroscopy, for on-line analysis in the near future.

The Production phase consists of everything from steel production to manufacture and construction work. Here we can identify a number of factors:

- Improved yield.
- Improved process design.
- Improved material design.
- Improved product design.

Losses to slag, etc. are primarily reduced with improved yield in downstream processes and operations. With improved process design further reductions may be realized and with improved material design the same performance can be achieved but with less material input, which in turn reduces the

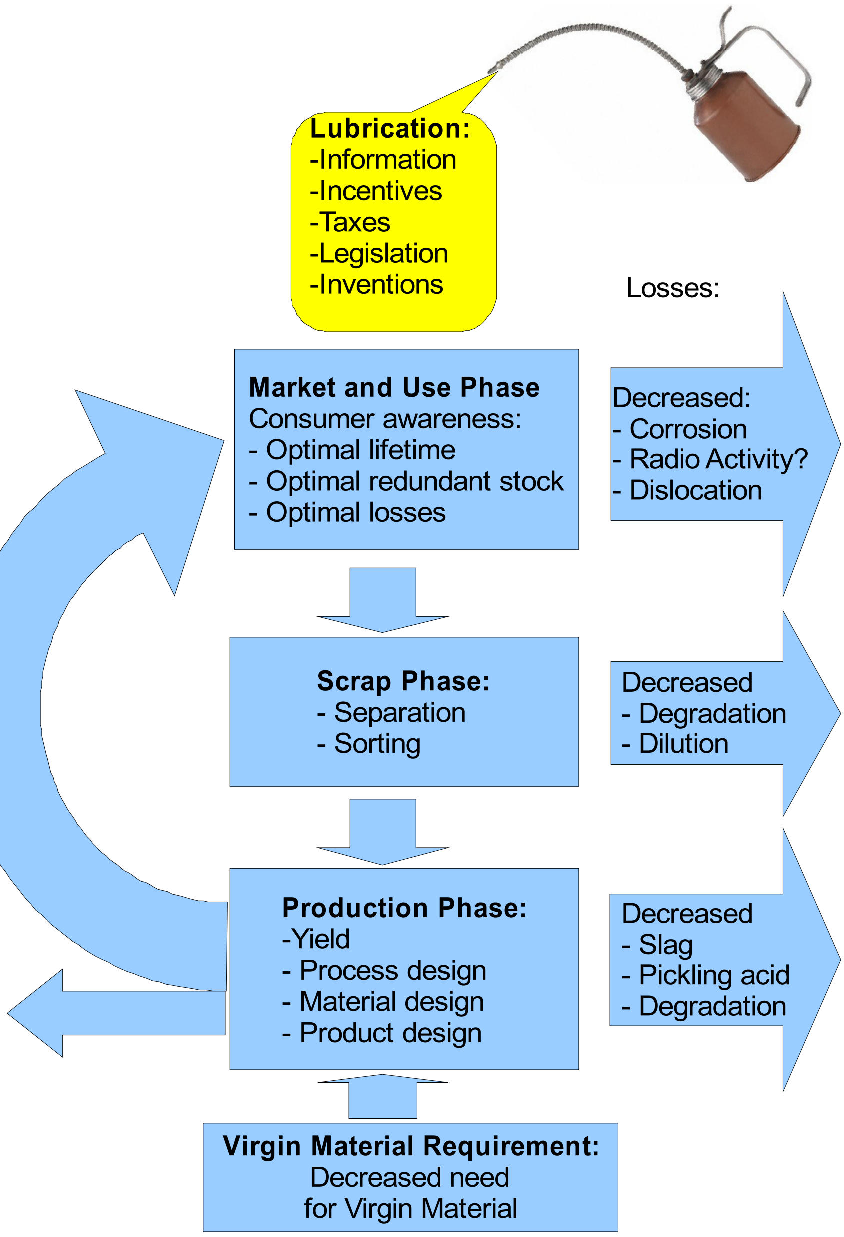

Fig. 3. Lubricating the recycling machine. The recycling machine's operation can be considerably improved by taking actions such as supplying information about how the machine works, providing incentives for functional behavior and finally, by taxation and legislation. A key question is, what information is needed for efficient application of these measures?

need for virgin material. Finally, improved product design is the key to optimal lifetime and improved separation and sorting.

4 Choice of means for lubrication

Some of the improvements mentioned above are part of normal efforts to cut costs and improve what is offered to customers. This would normally not require action from external actors such as the government or EU other than providing funds for research. In other cases, some external intervention is necessary.

The means of lubrication listed in Figure 3 are:

– Information.
– Incentives.

- Taxes.
- Legislation.
- Innovation.

Information about the environmental properties of materials is a task for material producers, product producers and their organizations together with governmental organizations. Conducting material flow analyses, MFAs, is one way to show the importance of keeping track of the material to avoid unnecessary stocks and losses. A sound MFA requires high-quality data, which must be provided by the companies that constitute the machine. This is discussed later in the paper.

Incentives are often used for packaging of beverages for other materials than steel. With today's scrap prices the possibility of selling steel scrap to the recycling companies is open and could be viewed as an incentive. Other incentives are focused campaigns to collect redundant material. This has been done in Sweden for used equipment in the farming sector with promising results.

Taxes are sometimes used to change behavior in the market. A very effective example of this in Sweden has been the implementation of a fee for the deposition of waste material. This has resulted in increased recycling of dust, sludge, etc. and has initiated inspiration as to what can be done with the residual material.

The authorities have used the legislation tool in several cases in previous years, for example when introducing producer responsibility for packaging material, electrical equipment and cars. In these cases, legislation was the basis for creating organizations to finance and administer recycling systems for sectors of the market.

Finally, innovation is the key to a recycling machine that operates smoothly. Fragmentation techniques together with methods of separating the different fractions are an example of a field that has developed a lot in recent years. In order to improve recovery of alloying elements in steel, methods and technology for identifying and sorting fragmented material by alloy content must be further developed.

5 Some issues to be solved

5.1 Responsibilities for future scrap quality and alloy conservation

Copper is in most cases considered an undesirable trace element and steel producers often have a limit of around 0.2% copper in scrap. This is quite easy to maintain for the recycling companies. They all claim that it is possible to decrease this level but the steel companies are not ready to pay for the extra cost. Copper wire is often stuck to the steel scrap and therefore difficult to separate. It is therefore most effectively separated in a step before the shredding process. Vehicles are treated by specialist companies before shredding, but since the shredding companies for obvious reasons do not encourage the separation of copper at this stage, this is seldom done.

With increased nickel prices, the amount of ferritic stainless steels with high contents of manganese and chromium has increased. These fractions are not easily separated after fragmentation with today's technology. A recycler reported that he had made a test batch with only washing machines and acquired a fraction with about 3% chromium. However, he did not succeed in negotiating a bonus for this fraction from the steelmakers. He found a dismantling of the washers that would give a fraction of about 7% would not at all be feasible due to the extra handling costs.

The task becomes even harder when one discusses capturing alloys that often exist in low concentrations such as molybdenum. Here one relies on new technology like LIBS and a fragmentation technique together with product design that allows different steel qualities to be separated from one another.

5.2 Designing for recycling

Apart from the possibility of removing copper wire and motors from products, designing for recycling is probably less a matter of dismantling and more a matter of good shredding properties. It probably involves the material selection, design and information. No doubt it will not be on top of the designers' agenda but increasing care about alloy recovery will make it more important.

5.3 Getting hold of the redundant material

Since materials like steel represent an investment paid with CO_2, it could be considered a capital worth managing like any other asset. In order to judge their importance these assets must be made visible. When investing in new infrastructure, an LCA is often made to study different alternatives. In this the use of new material is discussed. However, very little is said about the existing assets and if they are to be recycled or kept as a backup.

Today most companies, authorities and organizations make an environmental report together with their financial statements. Perhaps "Material Employed" in the environmental statements could be a figure as interesting as the "Capital Employed" in the balance sheet.

5.4 Monitoring the performance of the recycling machine

As mentioned earlier, the recycling of material has been studied intensely for the last ten years using different types of material flow analyses, MFAs. The reason for performing MFAs is often to demonstrate the recyclability of a material and where and in what sectors of society it is used.

In order to produce a MFA, high-quality data is needed. For some parts of the cycle, data is easily accessible, but for others the researcher is forced to make rather blunt assumptions. Research teams often have to accept that these assumptions can have a significant impact on the outcome of the study.

Figures 1 and 2 are based on the KTH model, and a MFA for the Swedish market is presented in Figure 4. Whereas steel production and steel trade are well documented and reported [22, 23], the team had to base the current study on calculations based on interview results [24–27] and assumptions when it came to:

– The share of new prompt steel in collected scrap.
– The steel content in exported and imported manufactured goods.
– The steel content in exported and imported used goods.
– Stock in the use phase.
– Accumulation in the use phase.
– Losses.

Although the data probably reflects the situation quite well, and can be used to improve the understanding of the recycling system, it is not sufficient to provide a means to study changes from year to year or to divide the flows into different groups of applications.

In working with the study, it has become evident that the actors in the market do not have the information needed in their internal accounting and information systems. Data is often structured by region and customer, not branch or application. It may seem logical to assume that a recycling company would know approximately what percentage of its resources come from demolishing houses, scrapping cars or new prompt scrap, but that is, however, not always the case. As for the steel companies and traders, they have only rough ideas and little reliable data on how much of their product goes to different segments of the market.

6 Conclusion

Managing material assets in the future will demand better and more detailed data. As was the case in introducing model-based control for metallurgical processes, the development of new sensors and investment in new procedures will take time.

Another similarity with model-based control is that in order to work for control purposes the model must be much simpler than the ones describing every aspect of the process.

More in-depth understanding on the part of the companies participating in the recycling machine must be acquired and old habits of "smart negotiating" must be replaced by transparent rules and commonly agreed-on ways of calculating costs and benefits.

The material business is highly international and actions taken in one part of the world affect the others. Accepting responsibility can therefore not only be a company business, a national business or even an EU business, but must be dealt with in the global arena.

Solutions will probably come from a combination of all five lubrication components presented in Figure 3, with legislation

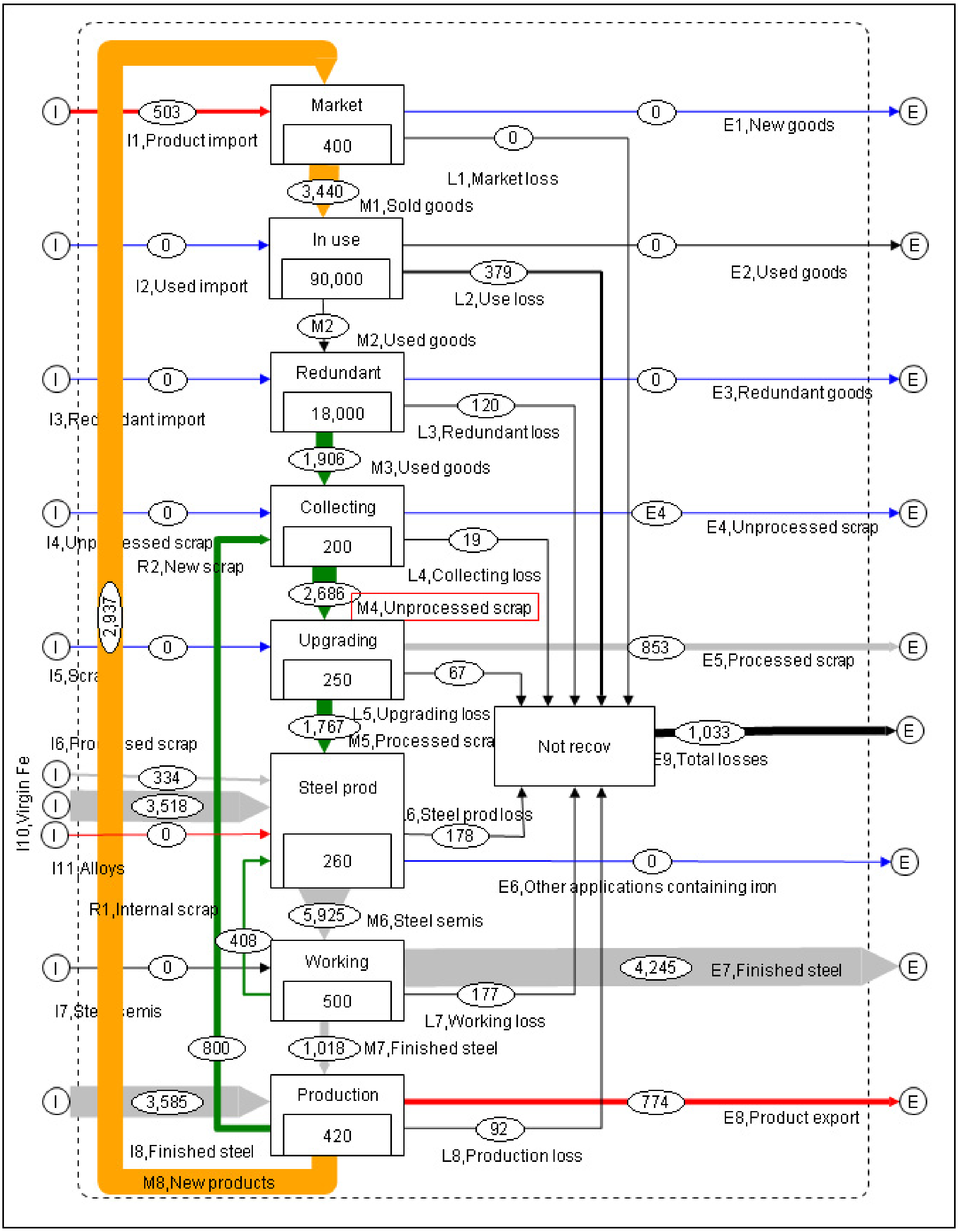

Fig. 4. MFA model of the recycling machine in Sweden with data from 2006 displayed in the STAN software from the Technical University of Vienna. The data reflects the actual flows in society. This has been simplified for Figures 1 and 2 in order to serve better as a control model.

having the most impact and largest risks of malfunction. Information and innovation, on the other hand, will always work in a functional way, but sometimes require a little help to take full effect.

Though scrap dealing is not the most heroic field where a researcher can win his reputation, it is of vital importance that the research community becomes involved with the practitioners of the trade.

Understanding the functionalities and dysfunctionalities of the market, analyzing the processes and finding models to estimate environmental costs and benefits under commercial restrictions in the recycling business are key activities to earn acceptance from the industry and motivate new data sampling routines.

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