MODELING PRODUCT LIFE CYCLE NETWORKS IN SYSML WITH A FOCUS ON LCD COMPUTER MONITORS

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MODELING PRODUCT LIFE CYCLE NETWORKS IN SYSML WITH A FOCUS ON LCD COMPUTER MONITORS

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SUMMARY

Electronic waste has become a growing concern in the world among governments, businesses, and consumers. These concerns are well founded as electronics waste presents economic, social, and environmental challenges. Economically, discarding electronic waste into landfills represents inefficient use of valuable materials and energy resources. Socially, improperly recycled electronic waste that takes place in third world countries with poor labor standards represents a moral dilemma for developed countries. Environmentally, electronic waste is a threat to all living organisms as it contains proportionally high levels of poisonous and toxic materials. To deal with these growing challenges a strong response needs to be made by all the stakeholders in the life-cycle of electronic devices.

However, despite the apparent need, compared to the rapid increases in electronic technology that make it faster, more available, and more affordable, the technology to process electronic waste has not kept pace. This fact alone points to the inadequate funding, attention, and research that has been invested in the problem. Though it also points to an opportunity; the opportunity to build an efficient system to deal with the problem using what is already known about the lifecycle of electronic devices. Therefore, the goal of this work is to create a modeling tool to help stakeholders in the lifecycle of electronic devices understand the consequences of their choices as they affect the use of material and energy resources.

To focus the research, LCD computer monitors are chosen as a case study. LCD computer monitors provide a level of sophistication high enough to be interesting in terms of the stakeholders involved, yet simple enough to provide a reasonable scope for this research that is still accessible to the layman

As a corollary to this modeling effort, the relatively new systems modeling language SysML and ParaMagic, a program that integrates analysis modeling capability into SysML, will be evaluated. SysML was designed with Model Based Systems Engineering principles in mind thus it seems that it is a natural fit to the problem domain. Furthermore, testing SysML will provide insight into the advantages and disadvantages of the new language.

The findings with respect to LCD computer monitors show that increasing the number of end of life options and the amount of monitors flowing into those options could result in substantial network wide material and energy savings. The findings with respect to SysML and ParaMagic are mixed. Although SysML provides tremendous modeling freedom, this freedom can result in increased upfront costs for developing executable models. Similarly, ParaMagic was found to be an effective tool for creating small executable models, but as the size of models increase its effectiveness tends to zero.

CHAPTER 1: INTRODUCTION

1.1 Electronics Recycling

In a time when ever more electronic devices are permeating everyday life, the question of disposing these electronics becomes more and more important. It does not take an expert to see that the number of electronic devices in the United States has been increasing for many years. In Figure 1 and Figure 2 below, the dramatic rise in the use of computers, the internet, and cell phones is very apparent.

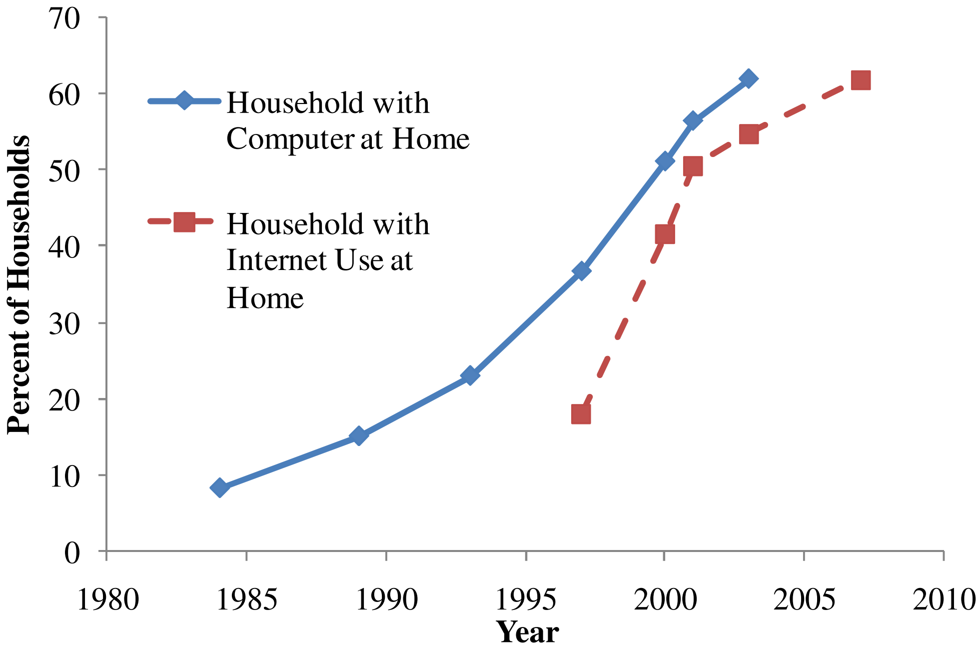


Figure 1: United States Household Computer and Internet Trends (U.S. Census Bureau 2007)

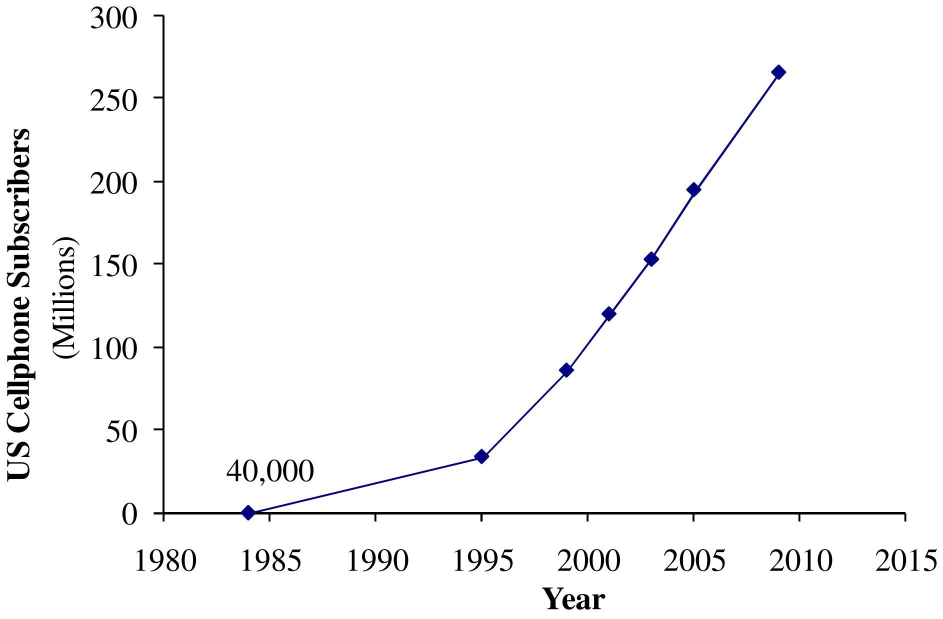


Figure 2: US Cell Phone Subscriptions Trend (Tesar 1983; World Almanac 2001; McFarland 2002; CTIA 2005; Bureau 2009; Lance 2009)

This is due in part to the rapid increase in technology coupled with continuously falling prices. The cell phone, for example, in 1983 cost around \$4000 (1983 dollars) (Retro Brick 2010). By 2002, a cell phone could be purchased for around \$300 (Ogasawara 2004). Currently, a cell phone can be purchased for less than \$30 (Walmart 2010), making the price drop over roughly two decades about two orders of magnitude. Similarly, the relative price for computers has also plummeted, as based on the producer price index shown in Figure 3.

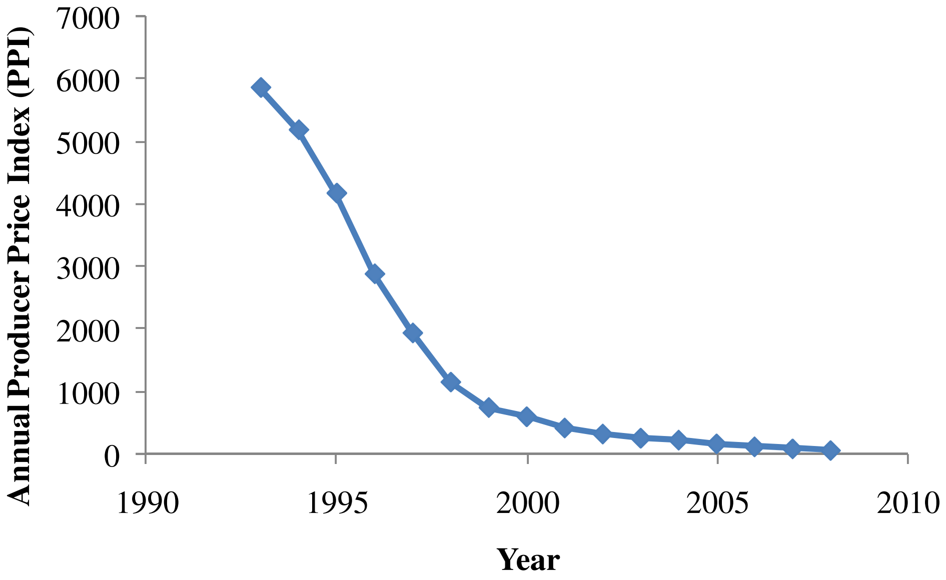


Figure 3: Producer Price Index for Personal Computers and Workstations (Bureau of Labor Statistics 2010)

With respect to increases in technology, Figure 4 depicts Moore's Law, which states that the number of transistors that can be inexpensively placed on an integrated circuit should double every two years, along with various processors that have been released since 1971, note the logarithmic scale. It should be noted that similar trends have been observed in other aspects of electronics technology such as memory capacity. Essentially, Figure 4 represents exponential increases in processor speed over time.

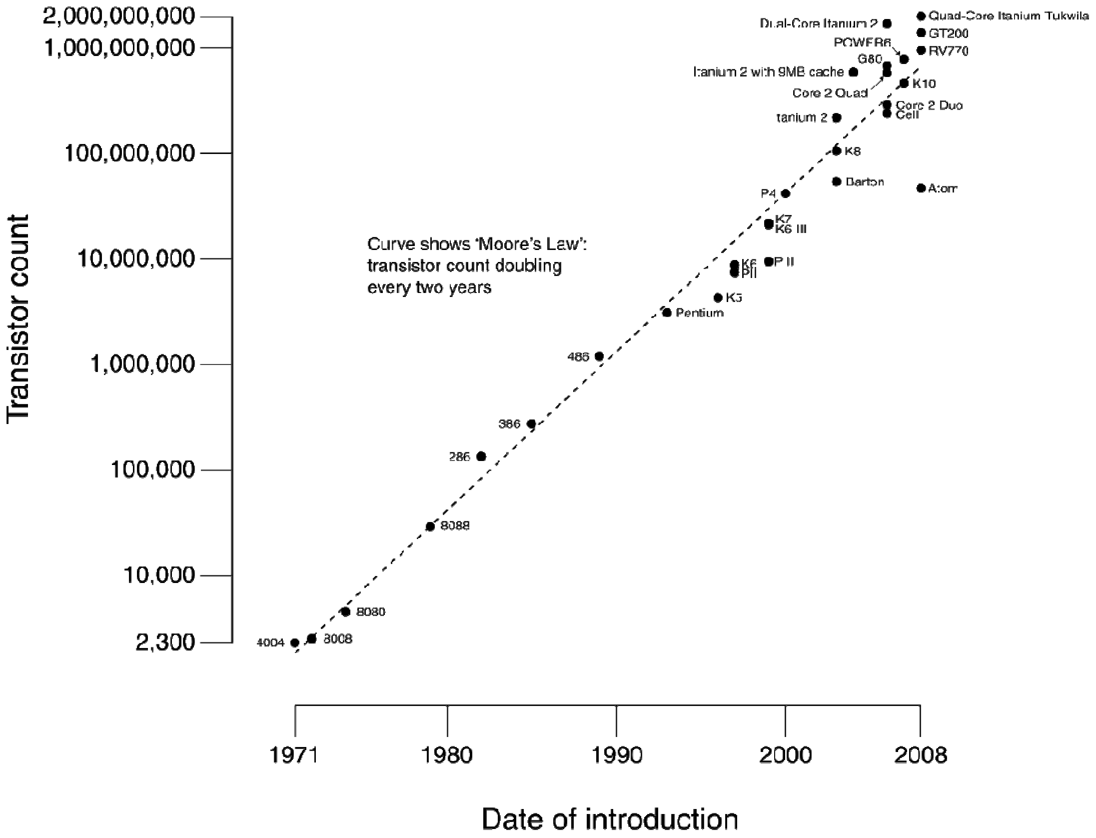


Figure 4: Moore's Law (Wikipedia 2010)

However, despite the ability of designers to release faster, more powerful, and cheaper devices at exponential rates, there has been far less innovation in the realm of electronics recycling in the United States, for example many of the same techniques used in electronics recycling today have been around for 50 years (Wills 1988).

From a human health perspective the fact that more and more electronic devices are appearing in landfills should be a major concern to most, as electronic devices contain proportionally larger amounts of heavy metals, including lead, mercury, and cadmium, than other waste (Macauley, Palmer et al. 2003; UNEP 2005). From an economics perspective, the disposal of electronics represents a massive waste of resources, as in addition to their high concentration of heavy metals, electronics also contain relatively high concentrations of precious metals such as gold, silver, and platinum group metals (Realff, Raymond et al. 2004; Kang and Schoenung 2005). In addition to these concerns raised by disposing electronics within the United States, there is also a moral, human-rights issue. There are many documented reports detailing the illegal export of electronics waste to third world countries where substandard labor practices in reclaiming the precious materials are commonplace (UNEP 2005; Environmental Leader 2009; Milmo 2009; Senn 2009). Therefore, given the stakes of continuing to neglect electronics recycling in the United States, more research and investment must be poured into this area.

Traditionally, electronics recycling research has been focused on the end of the electronics' life because there is not yet a solid infrastructure in place (Kang and Schoenung 2005). While this approach is important in providing valuable data for electronics recyclers, it is not complete. Just focusing on what happens to electronics at the end of their life ignores many important stages throughout the entire lifecycle of the devices that may provide significant insight into how to reduce the burdens of disposing the devices. For example, consider the case where electronics waste is processed by a third party recycler, which is not uncommon (Kang and Schoenung 2005). If that third party recycler has no relationship with the OEM, then the savings of reusing valuable components that could offset the manufacture of new products are lost. In other words, significant gains in mitigating the burdens associated with electronics waste may result from taking a systems level approach to the problem.

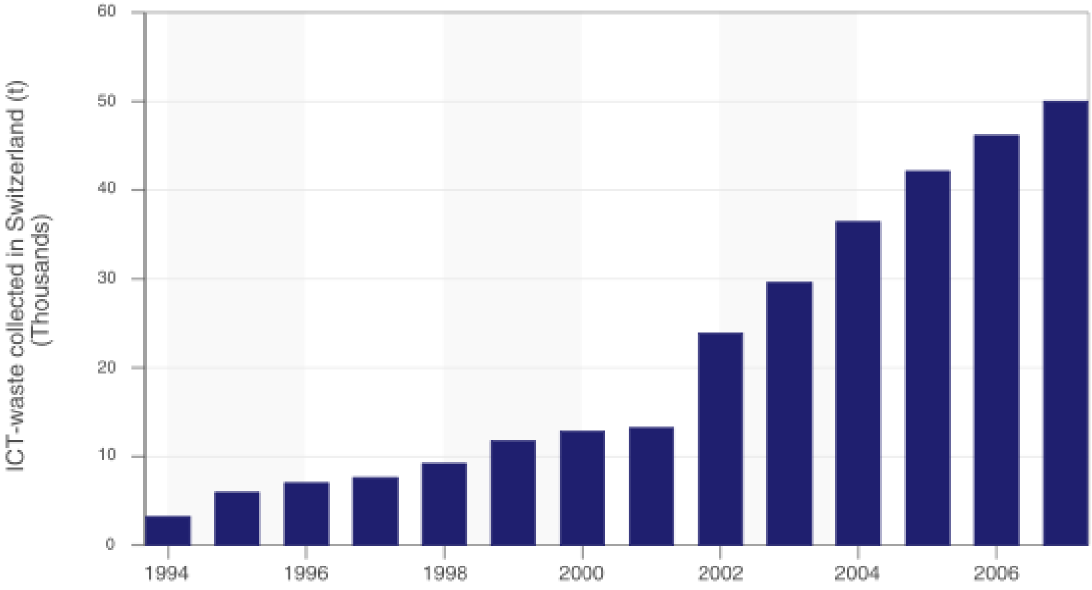


Figure 5: Electronic Waste Collected in Switzerland (EwasteGuide 2009)

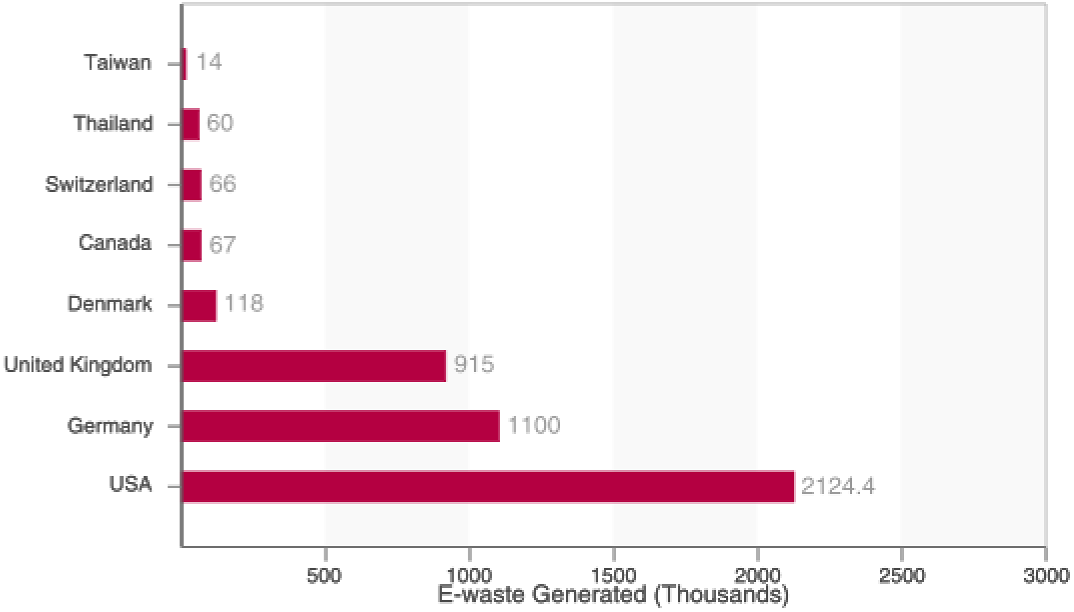


Figure 6: Estimated Yearly E-waste Generated by Country (EwasteGuide 2009)

To begin to understand the scale of the problem Figure 5 displays the rising amount of electronic waste collected in Switzerland in thousands of tonnes. Switzerland was the first country to implement an industry-wide organized system for the collection and recycling of electronic waste (Sinha-Khetriwal, Kraeuchi et al. 2005). Compare Figure 5 with Figure 6 which displays estimates for the yearly amount of electronic waste generated by various countries. From the figures it quickly becomes apparent that electronic waste is a growing international problem. Especially in countries like the United States and Germany where the amount of electronic waste being generated is two orders of magnitude greater than that of Switzerland.

However, given the massive scale of the problem, it stands to reason that before any real steps are taken to change the infrastructure that currently contributes to the burdens associated with the disposal of electronic devices; a modeling effort should be undertaken. From a practical standpoint, a modeling effort is the natural choice as it will allow for the exploration of many system configurations at a much lower cost than changing/creating the physical system.

Given that a modeling approach is the first natural step to understanding and overcoming the electronic waste problem and that there may be potential gains from taking a systems level view of the problem, this work will strive to implement the principles of model based systems engineering (MBSE). To this end, a systems modeling language designed to support MBSE known as SysML will be employed in the modeling effort. SysML is a relatively new modeling language, so in addition to studying electronic waste, the implementation of SysML will provide insight into its advantages and disadvantages in a domain specific application.

Thus, it is the goal of this work to present a model developed in SysML to begin to quantify some of the burdens associated with the lifecycle of electronics.

1.2 Brief History of SysML

SysML is a relatively new modeling language that has been made available by the Object Management Group. SysML was designed after the success of UML, which for years has been the leading general-purpose visual modeling language for software engineering (Hause, Thorn et al. 2005). In the past, UML's software focus has discouraged many system engineers from adopting it in earnest (Hause 2006). A good overview of the short comings of UML in the context of systems engineering can be found in (Hause 2006).

Thus after six years of systems engineers struggling with UML, a request for proposals (RFP) was issued by OMG to create a customized version of UML for systems engineering. In response to the RFP there was only one submission which was made by the SysML group. The group made up of system engineers, tool vendors, government organizations and academic institutions would spend the next three years creating the official SysML standard which was released in late 2006 (Hause 2006).

The goal of SysML is to provide a "standard modeling language for systems engineering to analyze, specify, design and verify complex systems, intended to enhance systems quality, improve the ability to exchange systems engineering information amongst tools and help bridge the semantic gap between systems, software and other engineering disciplines (OMG 2007)." Many resources and examples detailing the semantics of SysML can be found in the literature including (Hause 2006; Balmelli 2007; Balmelli 2008; Friedenthal, Moore et al. 2009).

Like UML, SysML is a graphically based, using diagrams to represent system models. Unlike UML, SysML is built on four pillars known as requirements, parametrics, structure, and behavior. Figure 7 shows the diagrams that are used in SysML including the new, reused, and modified diagrams from UML. The other main distinctions between SysML and UML are as follows (Johnson 2008):

- It extends UML classes with blocks
- It supports requirements modeling
- It supports parametric modeling
- It extends UML dependencies with allocations
- It reuses and modifies UML activities
- It extends UML standard ports with flow ports

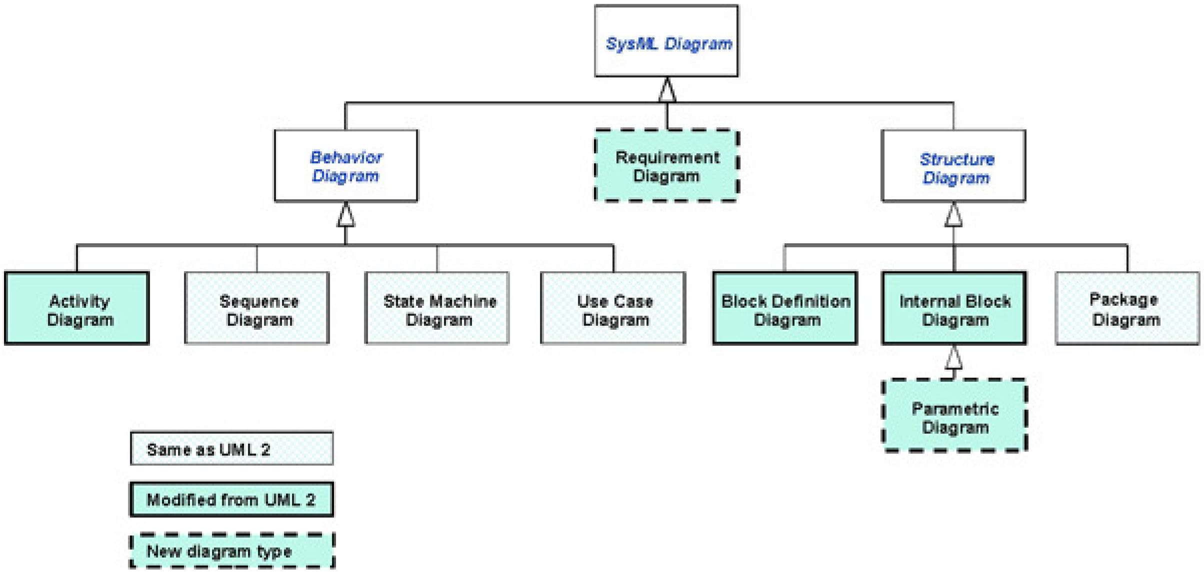


Figure 7: SysML Diagram Taxonomy (OMG 2007)

One of SysML's greatest strengths that is inherited from UML is its ability to take the abstract modeling element 'block' and specialize it to represent specific system elements. This method of customization allows SysML to be applied to almost any domain of interest. No doubt the designers of SysML foresaw this feature as the key to wide spread SysML adoption.

In addition to its brief history, to further understand SysML it is necessary to understand model based systems engineering. The next section will provide insight into MBSE and its advantages over more traditional approaches.

1.3 Model Based Systems Engineering (MBSE)

In short, Model Based Systems Engineering (MBSE) focuses on elevating models in the engineering process to a central and governing role in the specification, design, integration, validation, and operation of a system (Estefan 2007). MBSE has been standard practice in many engineering disciplines since the 1980s (Friedenthal, Moore et al. 2009). For example, in mechanical engineering such MBSE tools include Computer Aided Drafting (CAD), Computer Aided Machining (CAM), and Finite Element Analysis (FEA). However, MBSE has not been universally adopted, and in some disciplines the engineering process is still document based.

The document based systems engineering approach is characterized by the generation of textual specifications and design documents, in hard copy or electronic file format, that are then exchanged between customers, users, developers, and testers (Friedenthal, Moore et al. 2009). Figure 8 shows the document based systems engineering approach as described by (Friedenthal, Moore et al. 2009). Each box in the figure represents a different set of documents that needs to be maintained and communicated between system stakeholders.

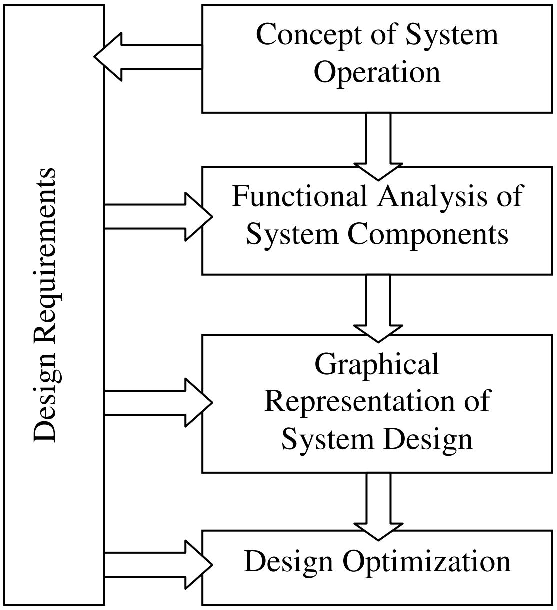


Figure 8: Document Based Systems Engineering Approach

Many criticisms of the document based approach appear in the literature and some are presented below (Pahl, Beitz et al. 1998; Grobshtein, Perelman et al. 2007; Peak, Burkhart et al. 2007; Friedenthal, Moore et al. 2009; Qamar, Carl During et al. 2009):

- Difficult to maintain validity, traceability, and completeness
- Documentation generated by domain specific engineers is not universal and can hinder communication
- May overlook emergent system behavior that does not exist in individual components
- Limits modularity and reusability
- Imposes unidirectional sequence on design
- Does not capture idealization knowledge

Looking at the list above, almost all of the criticisms of the document based approach are symptoms of system complexity. Perhaps one of the largest contributors to system complexity is the fact that modern design efforts are becoming more and more sophisticated and require more and more interdisciplinary interaction and communication. In fact, studies generally show that problems associated with the development of satisfactory systems have more to do with the organization and management of complexity than with the direct technological concerns that affect individual subsystems and specific physical science areas (Huang, Ramamurthy et al. 2007). For example, systems engineers recognize that once a concept for a solution is articulated, 70% of the cost of a solution is committed (Cloutier and Griego 2008). Upon further consideration these ideas seem quite plausible, as systems engineering is typically focused on building complex systems from known ideas and components in a variety of disciplines, rather than discovering new science in one particular field.

In MBSE, many of the difficulties that accompany the document based approach can be overcome using computer technology. By creating computer based models, exchanging and integrating model information becomes more readily available. Thus, it is much easier to maintain model consistency between stakeholders. Also, computer models created in a systematic way can be reused in later design efforts. However, despite the many advantages that can be realized by employing computer technology in MBSE, some of the short comings of the document based approach can still arise. For instance, domain specific engineers create models in many different software packages. Often the information stored in a domain specific software model cannot be easily exchanged with other models, even between software packages designed to model the same aspect of a system. A common example of this is exhibited in CAD files from different software manufacturers. Similarly, with respect to systems engineering, high level system models have very little support in terms of exchanging information between a global system model and domain specific subsystem models (Bassi, Secchi et al. 2006). To illustrate this, assume a high level systems model that includes a motor, only represents the motor in terms of voltage, speed, and torque. Furthermore, that this model does not contain part specific information of the motor such as the state of stress at any given location in the shaft, which is stored in a domain specific subsystem model. If these two different models cannot communicate effectively, then it is possible that when the motor is put into practice the shaft will break because it is too small for the application. While this is an elementary example, it nevertheless demonstrates that ultimately there is one motor, with one set of specifications that must be communicated effectively between models to avoid system failure.

In order to reduce the risk of system failure, systems engineers have developed software to facilitate communication between different stakeholders in the design effort. One such tool developed specifically to address the criticisms of the document based approach and support MBSE is SysML.

1.4 Research Questions

Given the need to understand the nature of electronic waste and the application domains of SysML, the central research question for this body of work is:

Motivating Question: Can an executable model that overcomes the failings of the document based design approach be created in SysML to evaluate the energy and material usage footprints of LCD computer monitors?

With respect to the first half of the question, currently SysML, by itself, is not capable of producing executable analysis models. There are many institutions that have or are in the process of developing tools to add this functionality to SysML as discussed in 2.4. One of the goals of this work is to exploit these efforts, namely InterCAX's ParaMagic, and apply the modeling capabilities of SysML to the study of electronic waste. To this end, the first research question becomes:

Question 1: Can ParaMagic be implemented to effectively incorporate executable analysis models in SysML?

Furthermore, SysML was created with the MBSE approach in mind, which inherently attempts to overcome the pitfalls of the document based design approach. This combined with the fact that the application domains of SysML have not been well explored, makes SysML a natural choice for the modeling platform in this research.

Looking at the second half of the motivating question, energy and material usage footprints provide a useful basis for the modeling methodology. This is due to the fact that the fundamental flows of energy and material can be used to make environmental and economic predictions. For instance, material flow can be monetized to look at the economic flows between stakeholders, or energy could be converted into a CO2 equivalent to make environmental predictions.

Also, LCD computer monitors were chosen as a trace product due to the relatively high availability of data and to better scope the research. LCD computer monitors provide a level of sophistication high enough to be interesting in terms of the stakeholders involved, yet simple enough to provide a reasonable scope for this research that is still accessible to the layman.

> Question 2: What factors in the lifecycle network of LCD computer monitors have the greatest impact in terms of the material and energy usage footprints?

Therefore, in order to better understand the impacts of electronic waste, the second research question is seen above.

1.5 Thesis Overview

The journey begins in Chapter 2 by providing the reader with background information. The first portion serves to familiarize the reader with the modeling entities and constructs of SysML. Following is a literature review of the advantages and disadvantages cited in using SysML in support of MBSE. Then, an overview of previous and current efforts to integrate analysis modeling capabilities into SysML is given. Lastly, the focus shifts to a review of different modeling techniques that have been employed in the understanding electronics waste.

Chapter 3 provides insight into the modeling schema and practices employed in this research. The sections detail how material and energy are organized in the model and how they move from stakeholder to stakeholder. The chapter ends with a simple, small-scale example model of a glass manufacturing facility.

Chapter 4 details the lifecycle network of LCD computer monitors. The sections describe the various stakeholders including manufacturers, users, recyclers, etc. along with the relevant model parameters, data, and assumptions. The chapter ends by presenting several model scenarios and a discussion of their results.

Finally, Chapter 5 provides an overall discussion of the work, presenting some conclusions and lessons learned. The chapter begins with a discussion of SysML as a modeling tool based on the lessons learned in this work in terms of the praises and criticisms raised in the literature. It then discusses some of the conclusions and recommendations for dealing with electronic waste in the future based on the results from the LCD computer monitor lifecycle model. Lastly, the chapter ends with a discussion about the research question.

CHAPTER 2: BACKGRONUD

This chapter provides background information in the areas of current electronics recycling practices, an introduction to SysML, a review of the advantages and disadvantages of implementing SysML, current techniques for integrating analysis models into SysML, and previous modeling efforts of electronics recycling. This chapter sets the stage for the modeling work that follows in subsequent chapters.

2.1 Current State of Electronics Recycling

The problem of electronics waste begins in 1980s with the development of consumer-oriented electrical and electronic technologies. Historically, the conventional and primary disposal method for this waste in the U.S. is disposal in landfills and incineration. It should be noted that, at present, electronic waste recycling has a short history in the U.S., so that there is not yet a broad and fixed infrastructure in place. (Kang and Schoenung 2005)

Electronics waste has continued to gain attention from legislative bodies. As early as April 2000, Massachusetts became the first state in the United States to issue a ban on dumping CRT televisions in public landfills and incinerators (Greene 2000). In 2003 the Restriction of Hazardous Substances (RoHS) Directive was adopted by the European Union to restrict the use of certain hazardous materials in electronic devices (European Union 2003). Also in 2003, California passed the Electronic Waste Recycling Act requiring retailers to collect a fee on covered electronic devices from consumers for the collection and recycling of certain electronic wastes (Yee, Leonard et al. 2003). In 2004 the Waste Electric and Electronic Device (WEEE) Directive came into force outlining extended producer responsibility requiring manufacturers of electronic devices in the

European Union to take back their products from consumers and ensure environmentally sound disposal (Widmer, Oswald-Krapf et al. 2005). In March 2006, Washington State passed an electronics recycling bill that requires manufacturers to finance the collection, transportation and recycling of old computers, monitors and televisions (WA State 2006).

Many have seen this increase in government legislation and lack of an infrastructure as an economic opportunity because electronics waste commonly contains valuable materials such as gold, silver, and platinum group metals (Realff, Raymond et al. 2004). However, extracting these resources can be difficult due to the high complexity and heterogeneity of electronics waste (Cui and Forssberg 2003). Despite such challenges, a basic electronics recycling model has emerged which is depicted in Figure 9.

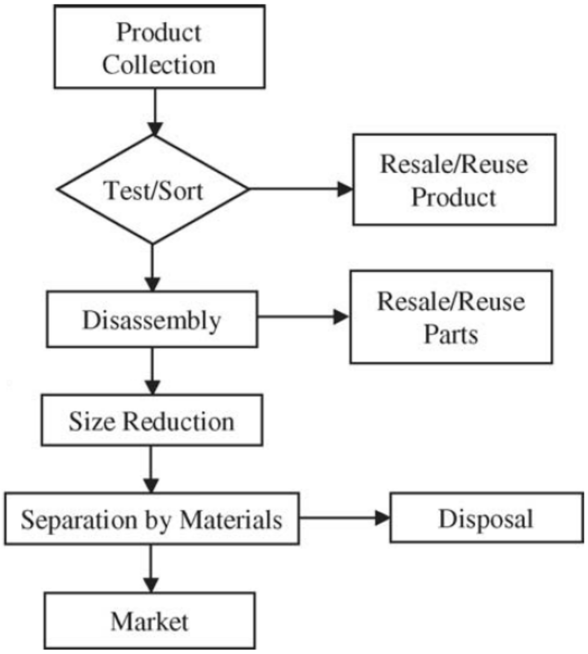


Figure 9: Simplified Flow Diagram for the Recycling of an Electronic Product (Kang and Schoenung 2005)

Collection of electronics waste is typically carried out either by curbside pickup or special collection events (Kang and Schoenung 2005). Raising awareness in consumers has been a major challenge in that historically they tend to store outdated and obsolete electronics in homes under the false pretense that the devices still hold value rather than disposing of the devices properly (Matthews 1997; Kang and Schoenung 2005). After collection, electronics are sent to recyclers for processing.

Processing begins with disassembly. The disassembly phase is typically done manually; however there have been some attempts to automate the process (Kopacek and Kopacek 2006). Disassembly is carried out either by third party establishments or by OEMs (Arensman 2000; Grenchus, Keene et al. 2004). The purpose of this phase is to either remove valuable components for reuse or to remove hazardous components. After disassembly, low value components are sent to a landfill and high value components are sent to a material processor.

The material processing phase is broken into three parts: size reduction, sorting/separation, and refining. Many of the techniques employed in the material processing phase have been borrowed from well established mineral processing techniques (Wilson, Veasey et al. 1994).

The purpose of size reduction is to liberate the constituent materials of a device. A detailed description of several size reduction techniques can be found in Section A.1. Following liberation, the constituent materials are sorted based on various criteria that usually include ferrous metal content, non-ferrous metal content, and density (to retrieve plastics). A detailed description of separation techniques can be found in Section A.2.

Lastly, refining of the separated consentient materials takes place to make them acceptable for their original use (Cui and Zhang 2008). For metals metallurgical processes are employed. Plastics are either further sorted into purer forms or consumed for caloric recovery in furnaces.

A process flow diagram for plastics recovery is shown in Figure 10. Air separation is used to remove labels and films. Resign identification can be carried out in several ways including triboelectric and shape separation techniques (Dodbiba, Sadaki et al. 2005) which are both detailed in Section A.2. Extrusion and pelletizing techniques are used to melt and form the recovered plastics into pellets that can be reused by manufacturers.

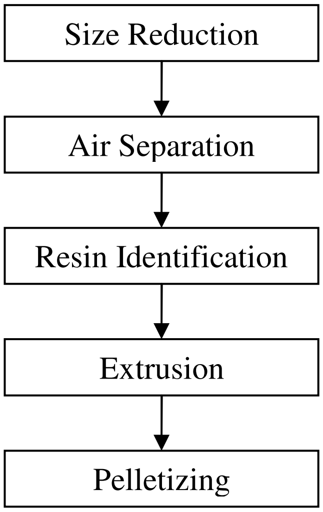


Figure 10: Example Process for Recycling Post Consumer Plastic (Kang and Schoenung 2005)

For metals metallurgical processes are employed. A detailed description of metallurgical processing techniques in the context of electronic waste is given by (Cui and Zhang 2008). Typically, purification for metals begins by applying heat to melt the metals and burn away impurities. In molten form, certain metals such as iron, lead, and zinc form oxides. Once cooled the oxide layer is milled away. This process is followed by various chemical processes designed to leach the desired metals from the melted slag. Final purification takes place in an anode furnace

2.2 Introduction to SysML

This section serves to describe some of the main modeling entities in SysML that are used in this work. For a complete description of modeling entities consult (Hause 2006; OMG 2007; Friedenthal, Moore et al. 2009).

2.2.1 Blocks

The block is the modular unit of structure in SysML that is used to define a type of system, system component, or item that flows through the system, as well as conceptual entities or logical abstractions. The block describes a set of uniquely identifiable instances that share the block's definition.(Friedenthal, Moore et al. 2009)

The concept of specifying a block into essentially any system or system component is a powerful concept that demonstrates the flexibility of SysML. Blocks and their interrelationships with other blocks can be arranged in a block definition diagram (BDD). The inner relationships between a block and its parts can be arranged in an internal block diagram (IBD).

A simple example of a BDD for different types of cycles can be seen in Figure 11. In the model a cycle is modeled as having one or many wheels (1…*), such as the unicycle, bicycle and tricycle cases, with a certain radius, a frame with a certain height, and a drive assembly, representing the pedals, crank set, and rear sprocket. While this is certainly a simplified model, many useful predictions can be made from it including what size person might want to ride the cycle from the frame height, or how fast the bike will travel given a certain pedal cadence.

An IBD representing the flow of power from Drive Assembly to the Wheels is shown in Figure 12. In the diagram, power flows out the Drive Assembly from the pedals into the Wheel through the hub.

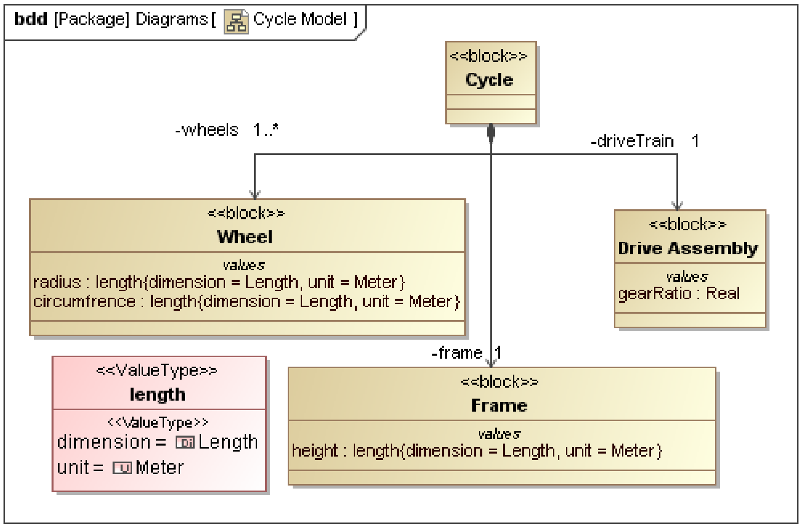


Figure 11: Simple Cycle Block Definition Diagram (BDD)

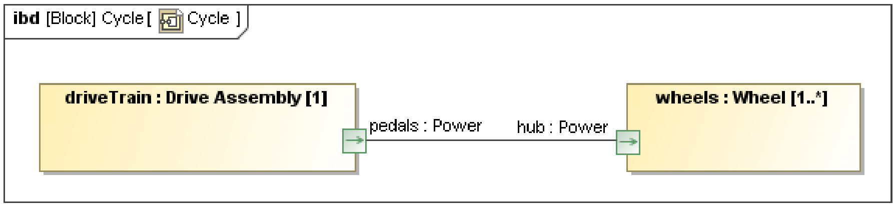


Figure 12: Simple Cycle Internal Block Diagram (IBD)

It is important to take note that the models in the figures above are not unique. SysML provides tremendous flexibility, so there could be many other decompositions of a cycling system that includes much more detail. These examples merely serve to demonstrate the graphical nature of SysML, the use of blocks, and the relationships between them

2.2.2 Value Types

Value types are used to categorize the properties of blocks in terms of their units and dimensions (Hause 2006). In Figure 11, the value type “length” is shown. The value type length is used to describe the radius, circumference and height properties of the Wheel and Frame blocks in terms of their respective units and dimensions.

2.2.3 Properties

Properties are the primary structural feature of blocks. Part properties describe the decomposition of hierarchy of a block and provide a critical mechanism to define a part in the context of its whole. Value properties describe quantifiable physical, performance, and other characteristics of a block such as its weight or speed. Value properties are defined by value types that describe valid range of values, along with its dimensions (or quantity kind in SysML v1.2) and units. Value properties may be related using parametric constraints. (Friedenthal, Moore et al. 2009)

In Figure 11, the Wheel, Frame, and Drive Assembly are part properties of Cycle. In other words, Cycle can be decomposed into Wheel, Frame and Drive Assembly. Also from the figure, it can be seen that radius, circumference, height, and gearRatio are value properties of the Wheel, Frame, and Drive Assembly blocks, respectively. These value properties represent the important physical quantities of these blocks needed in the model.

2.2.4 Constraint Blocks

A constraint block is a specialized form of the SysML block and is intended to package commonly used constraints in a reusable, parameterized fashion (OMG 2007). SysML does not provide a built-in constraint language because it is expected that different constraint languages, such as OCL, Java, or MathML, would be used as appropriate to the domain (Friedenthal, Moore et al. 2009). In other words a “constraint” in SysML is a textual expression that constrains or limits a model element, and because SysML is meant to be the foundation for system models, the designers expected that implementations of SysML would use the constraint syntax from other languages. For example some languages might use the expression “a = = b” to denote equality between a and b, while another language might use equals(a,b). Either of these syntaxes could be built into SysML.

As was previously mentioned, value properties can be related by parametric constraints. These relationships between value properties and constraints are depicted in parametric diagrams (PAR). Figure 13 shows a simple parametric diagram relating the value properties of Wheel from Figure 11. In the figure, the constraint block relates circumference to length by specifying a constraint that circumference is equal to twice pi multiplied by the radius.

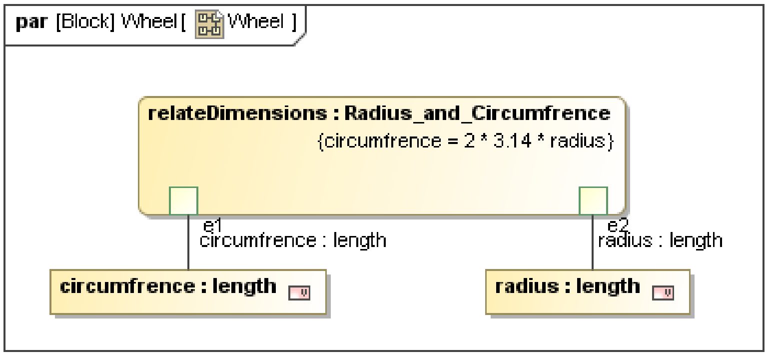


Figure 13: Simple Cycle Parametric Diagram (PAR)

Creating PAR diagrams like the one seen in Figure 13 is a powerful way to create modular, reusable mathematical models between system parameters that can be used to quantitatively link different aspects of a model.

2.3 SysML in Support of MBSE

As mentioned previously, SysML aims to mitigate and even eliminate many of the shortcomings of the document based approach engineering design process and support MBSE. Though, given the vast number of available software programs and programming languages, what are the advantages and disadvantages of SysML? The following sections explore SysML's advantages, disadvantages, and the tradeoffs between them.

2.3.1 Advantages

Many of the advantages of using SysML in support of MBSE can be summarized into four main points:

- Flexible and open enough to be used in most, if not all, stages of the design process (top/down or bottom/up) (Linhares, Silva et al. 2006; Balmelli 2007; Balmelli 2008)

- Supports easy model decomposition to increase model traceability and completeness (Hause, Thorn et al. 2005; Balmelli 2007; Pietro Colombo 2007; Balmelli 2008)
- Complies with many data exchange standards (Kwon and McGinnis 2007; Mura, Murillo et al. 2008; Bahill and Szidarovszky 2009)
- Graphically based (Hause 2006; Grobshtein, Perelman et al. 2007; Balmelli 2008)

The first point is likely the most important. SysML was designed to be open enough to support the engineering modeling effort at all stages of design. Some examples from the literature that demonstrate SysML's support of different design phases and its wide ranging applications include: the ideation phase of fire detection systems (Cloutier and Griego 2008), the product design and development phase of hydraulic systems (Johnson, Paredis et al. 2007), the manufacturing phase of semi-conductors (Kwon and McGinnis 2007), and even the end-of-life phase of LCD computer monitors as in this work, to name a few. Abstractly, SysML is similar to that of a structured database, providing the foundation on which models can be built which affords it such wide applicability.

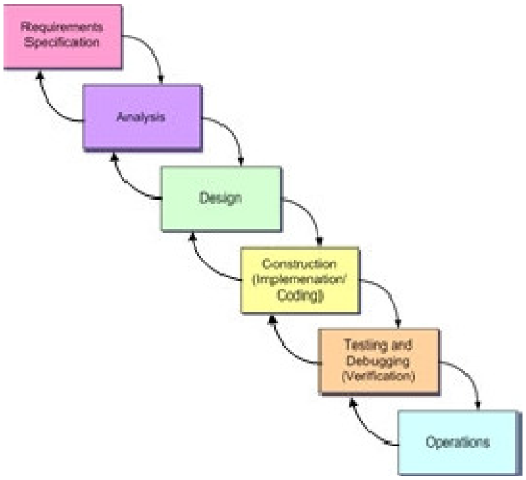
The importance of SysML's flexibility and openness cannot be overstated because SysML was designed to support systems engineering (OMG 2007). The necessity for flexibility is made evident by looking at the definition of systems engineering given by INCOSE:

> "Systems Engineering is an interdisciplinary approach and means to enable the realization of successful systems. It focuses on defining customer needs and

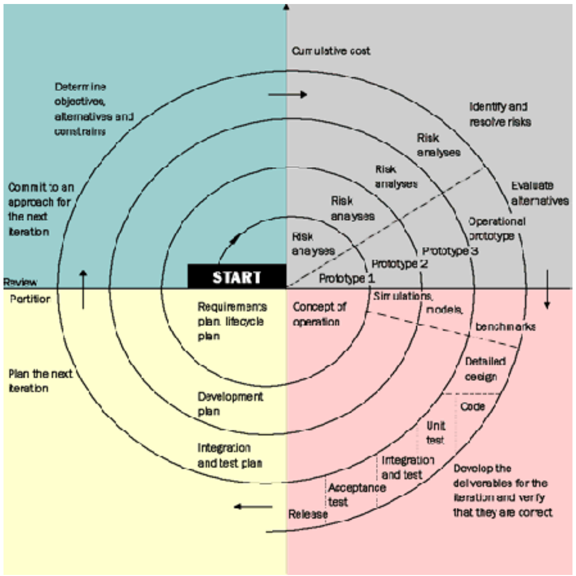
> required functionality early in the development cycle, documenting requirements, then proceeding with design synthesis and system validation while considering the complete problem. Systems Engineering integrates all the disciplines and specialty groups into a team effort forming a structured development process that proceeds from concept to production to operation. Systems Engineering considers both the business and the technical needs of all customers with the goal of providing a quality product that meets the user needs. (INCOSE 2004)"

The shear broadness of this definition harks on the need for SysML to be very flexible.

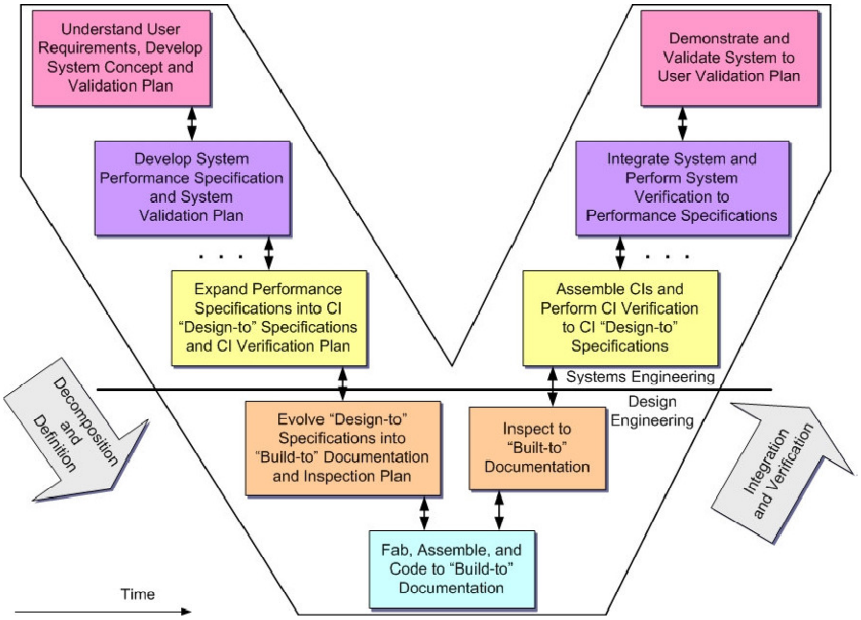
However, despite the apparent need for flexibility, some have criticized this aspect of SysML citing that it does not support a specific modeling methodology (Pietro Colombo 2007). Nevertheless, SysML was not designed to support a specific modeling methodology rather SysML is designed to support systems engineering (OMG 2007), as can be described by the above definition. Therefore, it must be able to support many systems engineering methodologies. To illustrate some of the differences between different systems engineering methodologies, Figure 14 graphically depicts three well known methodologies.



Waterfall Model



Spiral Model



"Vee" Model

Figure 14: Seminal Lifecycle Development Models (Estefan 2007)

Looking at Figure 14, it becomes apparent that SysML not only has to be flexible enough to support the broad definition of systems engineering, but it also must be flexible enough to support the widely varying systems engineering methodologies.

Though it is important for SysML to be flexible enough to accomplish the goals it has set forth for itself, there are difficulties that arise from its flexibility. Because SysML is so open, it is inherently up to the SysML user to define how the model will be created. The model can be as systematic and rigorous, or as informal and lax as the user desires within the rules that the OMG specification provides. Either can present a problem, for example an informal textual description is easily understood by humans yet difficult for machines, while complied code is easily understood by machines but almost impossible for humans to read. However despite the fact that SysML does not lend itself to a specific methodology, the fact that it gives the user the ability to choose his preferred methodology is considered a great advantage here.

To summarize this first point, flexibility is an advantage of SysML because SysML must be flexible if it is designed to support systems engineering. On the other hand, because there is a great deal of flexibility, the specific implementation of SysML is shifted from the designers of the language to the user. Therefore, from a user's perspective this increase in flexibility represents a tradeoff, either an increased cost upfront for a fully functional piece of software or an increased development cost to implement SysML.

The second big advantage of SysML is its natural ability to decompose a system into its constituent parts through SysML's different relationship types and diagrams. This is a great advancement for systems engineering especially with respect to traceability. SysML gives designers the resolution to track changes all the way to the lowest levels of a system. One highly praised example of this feature is requirements tracking. On the surface this may seem like a trivial feature, but requirements traceability can make the difference between success and failure in the design process. For example, in the design of mission-critical, airborne software systems, the standard DO-178B specifies that requirements must be traceable from the top-most system goals all the way down to test cases and low level requirements (Hause 2008). In a system that can depend on hundreds or even thousands of parts, the need for automated requirements tracking and traceability of components is obvious.

The third big advantage of SysML is its conformity to common data exchange protocols, including XMI (Hause 2006). It is important for SysML to be compatible with such standards to facilitate data exchange between SysML and outside software tools (Kwon and McGinnis 2007). In fact, this exchange of information is on the forefront of SysML research. From the previous discussion of the document based approach to systems engineering, one of the greatest difficulties in the design process was maintaining model consistency. It is the hope of designers that SysML's conformity to this data exchange standard will help to allow it to avoid one of the major pitfalls of the document based approach that is linking the high-level system models to domain specific software tools (Peak, Burkhart et al. 2007). The ultimate goal as one author points out, creating an executable specification is the gold standard of systems design (Sameh 2007).

Although SysML does conform to common data exchange protocols, there is an important corollary that follows. In order to utilize these exchange protocols, one must have knowledge of how to use them, which can be nontrivial. For example, as of this writing, there are many tools available to edit SysML including: MagicDraw, Topcased, and Rhapsody. After creating a SysML file using one of these tools, it is not guaranteed that the file created can be opened by the other SysML editors! Moreover, even after a

SysML model has been created, to access the data contained in that model with an outside program requires either detailed knowledge of XML and parsing techniques, or detailed knowledge of the application programming interface (API) of the SysML editing software which could also require knowledge of programming languages like JAVA.

The final advantage of SysML is the fact that it is graphically based. Certainly the appropriate cliché for this instance is to say, "A picture is worth a thousand words," but perhaps further study of SysML will yield another significant digit to that estimate. The graphical nature of SysML certainly aids in the ability to manipulate models by drawing the connections between elements (Balmelli 2008). Furthermore, SysML embraces both tabular and graphical specifications allowing the user to choose his preferred method (Grobshtein, Perelman et al. 2007), though most will likely choose the graphical representation. Although the graphical nature of SysML is listed as an advantage here, there has been some criticism. In (Grobshtein, Perelman et al. 2007), the authors make the claim that non-technical people, who can always read text, find it difficult to comprehend diagrams. Furthermore, they present a table which identifies some general rules for textual information versus graphical information, which is recreated in Table 1. The purpose for considering SysML's graphical nature an advantage here is that it is assumed that systems engineering is largely composed of a technical audience and that goals of SysML fall more in line with the second column; however, as authors of (Grobshtein, Perelman et al. 2007) suggest, an empirical study as to which representation is more efficient at conveying information would be of value.

Table 1: Textual vs. Graphical Representations Summary (Grobshtein, Perelman et al. 2007)

Textual Representation	**Graphical Representation**
Expression of many details in a relatively small space	An easy way to get a general view of the system
Depicting constrains that are hardly expressible in the graphical representation	Easy to depict different relations among system components
Very flexible and can also include some formalism (mathematics, etc.)	The representation is usually more structured and formal
Must be read in a predefined order	Can be interpreted in a "random access" mode

2.3.2 Disadvantages

Along with the many praises of SysML, the new language is not without its critics. There have been many criticisms of SysML made in the literature which can be grouped into three main points:

- Lack of domain specific support (Grobshtein, Perelman et al. 2007; Huang, Ramamurthy et al. 2007; Johnson, Paredis et al. 2007; Kwon and McGinnis 2007; Sameh 2007; Bahill and Szidarovszky 2009; Qamar, Carl During et al. 2009)
- Lacks formal approach to modeling (Pietro Colombo 2007; Balmelli 2008; Mura, Murillo et al. 2008)
- In addition to detail, the number of diagrams, model elements, and system views can increase quickly with model complexity, making models difficult to navigate and

understand (Linhares, Silva et al. 2006; Grobshtein, Perelman et al. 2007; Vernadat 2007)

With respect to the first criticism, one of the most active areas of SysML research is in creating connections between SysML and executable domain specific software tools, and also in performing simulations based on SysML models, as mentioned previously. Many examples of these efforts can be seen in (Hassaıne 2007; Johnson, Paredis et al. 2007; Kwon and McGinnis 2007; Peak, Burkhart et al. 2007; Peak, Burkhart et al. 2007; Sameh 2007; Qamar, Carl During et al. 2009) to name a few. Although SysML is a computer language, by itself it is not “executable.” This can be very unsatisfying for many users, especially those familiar with UML and its code generating capabilities. One paper in particular highlights some of the fundamental challenges in applying software engineering concepts from UML to systems engineering and modeling in SysML with respect to the generation of executable code (Bassi, Secchi et al. 2006):

- Software models are designed to be executable, making code the means and the end of the software modeling process, which has led the way to automated mapping (code generation) of UML diagrams into software.
- The existence of an execution model is implicit in UML diagrams, and UML is supported by object oriented languages.
- Systems engineering models are simulated (mathematical abstractions), unlike software models which are compiled and executed
- In general it is not possible in systems engineering to use the same kind of mathematical description for the whole system, so it ends up that there are a number

of (in general non-compatible) models of computation, such as partial and ordinary differential equations, finite element models, discrete event systems, etc.

All of these distinctions present lofty challenges to SysML users who desire an executable model.

In addition to these concerns, from definition of systems engineering that was quoted from INCOSE previously, systems engineering is highly interdisciplinary. Thus, SysML must foster communication between many different domain specific engineers and their modeling tools. As many engineering domains have already created their own modeling tools, the idea of creating an interdisciplinary modeling language between domains is met with skepticism to say the least. However, only time will tell if SysML sill succeed in this respect for two reasons.

First, SysML is still in its infancy. UML certainly was not created with the ability to instantly generate executable code (in fact, UML models that generate executable code rely on outside tools (OMG 2009)) even with the advantage of its sole focus on software, unlike SysML which also supports hardware modeling. Moreover, there have already been numerous examples of simulations and executable code derived from SysML models, and it is likely that more will be produced as the language matures.

Secondly, looking at the SysML standard, the language was designed primarily to support the systems engineering domain as previously mentioned, not to support mechanical, electrical, or industrial engineering domains for example. This is not to say that the designers of SysML were not thinking about the ability to automatically generate domain specific modeling code; on the contrary, the language was designed to conform to standard data exchange protocols. Therefore, SysML models are by definition designed to share information with other software tools. Still, it must be remembered that the main goal of SysML is to support systems modeling and systems engineering, not specific domains.

The second criticism of SysML, that it lacks a formal approach to modeling, is not to say that there is not a formal specification of the language. Rather critics making these arguments focus on the fact that SysML requirements, in addition to other modeling entities, are text based which can lead to ambiguity. Moreover, another argument that is typically made by those attempting to make executable SysML models is that the ability for the modeler to use SysML's modeling elements in many ways can lead to semi-formal models that ultimately cannot support well defined behavior. In other words, one modeler may decide to use a SysML modeling element in one way, and another modeler may decide to use the same modeling element in a different way. While both of these arguments are built on facts, rather than viewing them as weaknesses, they should be viewed as strengths. The fact that modeling elements can be used in many different ways at the modeler's discretion is a tribute to the language's flexibility. As mentioned previously, SysML provides the foundation for models to be built on, and it is up to the modeler to decide how the model will be built. The fact that SysML allows this modeling freedom does not limit one's ability to create rigorous, systematic, structured SysML models that can be operated on by third party algorithms to perform simulations or extract requirements. The only detriment is that perhaps the modeler must be careful to follow a specific set of guidelines required by the third party algorithm, or that model error checking features may have to be created to analyze the SysML models before they are executed.

Another slight of SysML seen by some is that the amount of detail, along with number of diagrams, model elements, and system views can increase rapidly with model complexity, making the model difficult to navigate and understand. Though this could certainly be a valid claim for certain SysML models, it is not likely a systematic problem with SysML. For instance, any graphical system model created with sloppy modeling practices can become cluttered; however, there is also the case whereby some concepts are so complex that it is difficult to reduce them to an easily viewable and widely understandable format. Even simple line graphs, for example, can become difficult to navigate to the untrained eye when many dimensions and axes are added, such as Ternary Phase Diagrams or Ellingham Diagrams. As one might recall, one of the major reasons for creating SysML was for the management of complexity, and perhaps some models are so complex that without a certain baseline understanding of the subject, regardless of how simplified the model is, there will be minimal gains in understanding. To use an example from electrical engineering, if the audience cannot understand the principle of Ohm's Law, then it does not matter to what degree a circuit model/diagram is condensed or simplified because the audience will not be able to understand it beyond the fact that there are components interacting by means of electricity. However with respect to SysML, as was mentioned previously one of the language's strength is the ability to decompose a system into its constituent parts at the modeler's discretion. Therefore, the case could be made that SysML was designed with this very issue in mind in hopes of reducing it.

The final argument against SysML is that the diagrams require expert knowledge to understand. This argument is not only true for SysML, but arguably every modeling tool ever created. It must be granted that some knowledge about the semantics of SysML in terms of the different modeling elements, the relationships between modeling elements, and the nature of the various diagrams is needed to be able to understand a SysML model, and to that end there have been many works published that describe these semantics in detail.

2.3.3 Discussion

Presented above are the main advantages and disadvantages of SysML. After considering both the advantages and disadvantages together, one is lead to realize that rather being separate, mutually exclusive factors, they really represent tradeoffs. A tradeoff that is typically the difference between learning and understanding SysML to create useful, working modeling schemas, or employing either less sophisticated, ad hoc modeling tools and practices such as in the document based approach or other systems modeling languages which can be subject to many of the same criticisms as SysML. The following sections are concerned with some of the tradeoffs that arise from the advantages and disadvantages discussed in the previous sections and the decisions that arise from them.

It was previously mentioned that SysML is like a structured database that provides the foundation on which model's can be built. Bearing in mind that SysML was conceived with systems engineer's in mind, it is fortuitous that the language is flexible and open enough to support the many different methodologies that exist in systems engineering. However, this flexibility comes at a price. The fact that SysML is so open means that it by itself cannot produce executable models. For those looking for such functionality, they must be satisfied with the knowledge that SysML is compliant with common standard data exchange protocols and the burden of creating executable software is up to outside parties. This is not a trivial fact as it dictates that in addition to the domain specific knowledge that is captured within a SysML model, there also must be knowledge in the domain of the data exchange protocols, which can lead to increased cost in either developing that knowledge or outsourcing it.

Despite the increased cost, linking domain specific tools to SysML can have significant advantages. Two of these advantages include increased model consistency which improves model communication efficiency between the system engineer and the domain specific engineer, and potential reductions in the amount of modeling work by saving the effort of creating two separate models.

The idea of reducing the amount of modeling work by saving the effort of creating two different models simply means that once a SysML model has been created, domain specific models can be automatically generated from it. Essentially, this assumes that the system engineer and the domain specific engineer are the same person, or that the specific domain knowledge is so well understood that its manipulation has been automated. In either case, this raises the question as to where the system models should end and where the domain specific models should begin. It is certainly tempting to consider a model that completely specifies and simulates an entire system in fine detail from a single package, and to that end there has been discussion about how to achieve this in the literature. Essentially, there are two approaches that have been suggested: (1) create 1 to 1 mappings from SysML to domain specific languages such that models can be created in SysML or the domain specific modeling tool (Johnson, Paredis et al. 2007; Qamar, Carl During et al. 2009), and (2) create connections from SysML to domain specific modeling tools such that the main parameters or attributes of existing domain specific models can be easily changed in SysML to perform trade studies (Peak, Burkhart et al. 2007; Peak, Burkhart et al. 2007).

Considering 1 to 1 mappings of domain specific languages to SysML essentially gives modelers the freedom to create domain specific models in SysML or the domain specific tool. However, in practice, the only real functionality that is gained by this mapping is the ability to import domain specific models into SysML, as domain specific engineers are more likely to use tools in which they have been primarily trained because that is where they are the most efficient. Consider the example of a CAD engineer. In theory the geometry of the part he creates could be represented by the feature tree which is based on the order in which he performs different geometric operations available in the CAD program. Assuming a 1 to 1 mapping of those operations is available in a SysML library, it is unlikely that the CAD engineer will find it more desirable to create his part by arranging a hierarchy of SysML model entities representing different CAD operations. For the CAD engineer to even consider this course of action, SysML would have to provide a better or at least equal geometric modeling environment compared to what the existing CAD software already supplies, including being intuitive enough for the easy transfer of existing modeling training.

On the other hand, the idea of creating connections between the CAD program and SysML could yield many advantages. For example, assume a CAD model of a standard part has already been created in a domain specific CAD tool and to change the geometry of the part only a few parameters need to be varied. By making connections between SysML and these crucial parameters, it is now possible for the systems engineer to perform detailed trade studies on the part without the need of domain specific knowledge in a CAD program other than the governing parameters.

However, generally speaking, perhaps a better answer to the question of which approach is more favorable is obtained by asking a different question: At what stage in the design process is a modeling effort intended to support? Bearing in mind that SysML is primarily aimed at supporting systems engineering and framing the question in this context it becomes: at what level of system decomposition is the modeling effort designed to support? The general answer would seem to be that early in the design process systems models tend to be simpler, usually involving global system variables to create a general proof of concept, but as the system design is further refined, more sophisticated models are created to make specific design decisions or to perform component optimizations (Peak, Burkhart et al. 2007; Balmelli 2008). In terms of the two above suggested strategies, being able to create models directly in SysML would seem to be more appropriate for simpler models where a custom model authoring environment is not needed, such as basic system governing equations; while creating connections between the main system parameters in SysML to domain specific software models would seem to be more appropriate for more complex models that are most efficient to author in a specific design environment, such as models requiring three dimensional graphical support like the CAD example presented above.

To this end, one of the goals of this research is to create modeling components in SysML to support the systematic engineering of product life cycle networks early in their conception. By creating model components that contain expert knowledge of the different stakeholders in the life cycle networks, systems engineers will be able to explore different designs of these networks earlier in the design process. This will serve to ultimately increase the overall efficiency of the design process by identifying favorable networks early in the design effort.

2.4 Integrating Design and Analysis Models in SysML

There have been many attempts to integrate different design and analysis models and tools with SysML (Huang, Ramamurthy et al. 2007; Johnson, Paredis et al. 2007; Kwon and McGinnis 2007; Peak, Burkhart et al. 2007; Peak, Burkhart et al. 2007; Sameh 2007; Vernadat 2007; Johnson 2008; Mura, Murillo et al. 2008; Qamar, Carl During et al. 2009). As previously discussed there are two main ways to perform this integration, either by 1 to 1 mapping of modeling elements to SysML, or by linking the main parameters of a system model to various elements in SysML. Since the model presented in this work will provide an early estimate of system performance to designers, it is advantageous to create the entire model outside of the model execution environment, thus a 1 to 1 mapping will be used.

The research in (Peak, Burkhart et al. 2007; Peak, Burkhart et al. 2007) describes a method for integrating executable models into SysML by means of Composable Objects (COBs). The COB representation is based on object and constraint graph concepts to gain their modularity and multi-directional capabilities (Peak, Burkhart et al. 2007). In fact, COBs provided the basis for the development of the SysML parametric diagrams (OMG 2007). COBs provide a method for representing knowledge in a way that is readily interpretable by both humans and computers. In an engineering sense, the method works by creating low-level COBs that represent fundamental equations or constraints of a system, such as the governing equations of an individual spring, mass or damper. The equations are represented graphically making them accessible to humans and computers, as well as being systematic and rigorous. Then, by linking these base constraints together, more and more complex objects and systems, such as a spring-mass-damper system, can be formed.

The program ParaMagic, which was created by the authors of (Peak, Burkhart et al. 2007; Peak, Burkhart et al. 2007), provides a framework to realize COBs in the context of SysML parametrics. ParaMagic provides a 1 to 1 mapping of COBs to mathematical solvers such as Mathematica, MATLAB, and Excel. The benefit of using SysML over any of these tools alone is twofold. One, integration with SysML provides a means to model consistency, which is one of the goals of the MBSE approach. Secondly, the graphical nature of SysML parametrics provides a transparency to the modeler greater than that available in any of the above tools alone.

2.5 Electronics Recycling Models

There are essentially three main types of modeling efforts that encompass most of the electronics recycling models that have been created. The three types include Operations Research (OR), Material Flow Analysis (MFA), and Life Cycle Analysis (LCA). Each type of model has its own relative strengths and weaknesses.

2.5.1 Mathematical Programming (MP) Models

The field of OR is focused on the application of information technology, for the purpose of informed decision making. The OR field began in the 1940s out of the World War II. Typically, OR involves creating mathematical models, or formalisms, to understand and structure complex situations in order to predict system behavior and improve system performance. (Heger 2006)

An example of an OR mathematical programming (MP) problem can be seen in Figure 15. Essentially, an objective function is defined (shown at the top of the figure), and is minimized or maximized based on different constraints (following the phrase s.t. or subject to in the figure).

$$
\begin{aligned}
Max\ z = \sum_{k=1}^{K}\sum_{l=1}^{L}((G_{kl}\,R_k) &\quad - \quad (Y_{kl}\,S_{kl})) \\
-\sum_{i=1}^{I}\sum_{l=1}^{L}(C_i + CS_l)X_{il} & \\
\text{s.t.} \sum_{i=1}^{I} X_{il}\,A_{ik}\,T_{kl} \geq G_{kl} &\quad \forall \quad (k,l) \\
M\,Y_{kl} \geq G_{kl} &\quad \forall \quad (k,l) \\
\frac{\sum_{i=1}^{I} X_{il}\,A_{ik}}{\sum_{i=1}^{I} X_{il}} \geq B_{kl}\,Y_{kl} &\quad \forall \quad (k,l) \\
\sum_{l=1}^{L} X_{il} \leq W_i &\quad \forall \quad i \\
Y_{kl} \in [0,1], X_{il} \in R^{+} &
\end{aligned}
$$

Figure 15: Example of an Mathematical Programming Problem Formulation (Reimer, Sodhi et al. 2000)

There have been several such models formulations created for the case of electronics recycling, including (Reimer, Sodhi et al. 2000; Sodhi and Reimer 2001; Chang, Huo et al. 2006; Tsai and Hung 2010). These studies typically identify a network structure, formulate an objective function with constraints based on that structure, identify a method for solving/optimizing the formulation, such as linear programming, and present a hypothetical example of a decision or decisions that their model aims to help make.

There are several notable difficulties in these MP models. Firstly, they can be very inflexible with regard to the structure of the system or decision criteria. Although MP models can work very efficiently and yield meaningful results when the problem is well formulated, changes in the network structure or decision criteria, such as the addition of a stakeholder, can cause the need for complete reformulation. As an example, each of the studies cited above suggest different problem formulations and solution methods, despite the fact they are all modeling relatively similar recycling networks with similar goals. This is not advantageous if the aim of the model is to support preliminary system design, where design changes can be quite frequent. Another difficulty with MP models is the selection of a solver or solution technique. Ideally the choice of a solver or solution technique should yield the same results, especially if the goal is a global optimum; however, in practice the method for achieving solutions can yield very different results because different techniques can be susceptible to various local maximum and minimum in different ways.

Moreover, MP models tend focus on a single objective, which is typically minimizing cost, although there have been attempts to include other criteria and multi-objective models do exist. While cost is a very important metric, other concerns such as social and environmental metrics can also be important.

Lastly, one aspect of MP modeling that shows up in the aforementioned recycling literature, which may either be considered a benefit or detriment depending on one’s point of view, is that the models tend to lack practical, concrete examples. Instead, they often resort to creating fictions companies who have a fictitious decision to make, which could theoretically be resolved using the MP model presented. While this can certainly be a useful exercise, it may prove difficult to implement as the situations are highly idealized.

2.5.2 Life Cycle Assessment (LCA) Models

Life Cycle Assessment (LCA) is a technique to assess the environmental aspects and potential impacts associated with a product, process, or service, by (SAIC 2006):

- Compiling an inventory of relevant energy and material inputs and environmental releases;
- Evaluating the potential environmental impacts associated with identified inputs and releases;
- Interpreting the results to help you make a more informed decision.

The roots of LCA date back to the 1960s and 1970s where firms aimed to quantify the direct and indirect material and energy consumed during product manufacture (Vigon, Tolle et al. 1993). As the methodology advanced the scope of these early assessments was expanded to include the entire product life cycle, as illustrated by Figure 16.

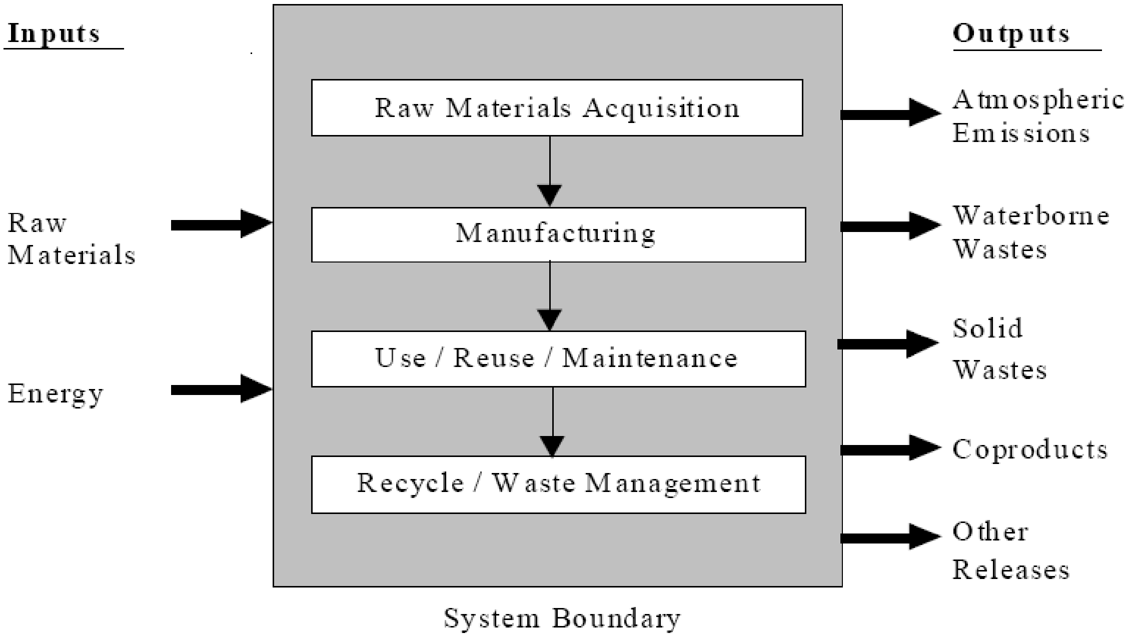


Figure 16: Stages of Life Cycle Assessment (SAIC 2006)

A conventional LCA consists of four main steps (SAIC 2006):

1. Goal Definition and Scoping - Define and describe the product, process or activity. Establish the context in which the assessment is to be made and identify the boundaries and environmental effects to be reviewed for the assessment.
2. Inventory Analysis - Identify and quantify energy, water and materials usage and environmental releases (e.g., air emissions, solid waste disposal, waste water discharges).
3. Impact Assessment - Assess the potential human and ecological effects of energy, water, and material usage and the environmental releases identified in the inventory analysis.

4. Interpretation - Evaluate the results of the inventory analysis and impact assessment to select the preferred product, process or service with a clear understanding of the uncertainty and the assumptions used to generate the results.

There are many examples of LCAs scoping a vast number of products and processes, but perhaps the most relevant to this work is (Socolof, Overly et al. 2001), which spans the life-cycle of CRT and LCD computer displays. The above study follows the structure for an LCA as identified above. The study provides significant insight into a computer display's environmental consequences in all the stages of its life cycle in terms of air, water, and land emissions. Additionally, the study provides some high level insight with respect to material and energy flow at various life cycle stages.

While the theory behind LCA is well intentioned and seemingly logical, many researchers have been critical of its methodology. Two such criticisms found in (Reap, Bras et al. 2003) cite the high cost of performing an LCA and its: sole focus on environmental considerations. Costly LCAs are largely a result of the stringent detail that is required to perform them. It has been suggested that streamlined or abbreviated LCAs be developed to not only reduce the cost, but also to allow LCAs to be performed earlier in the design process to avoid costly design changes that would occur later in the design process.

2.5.3 Material Flow Analysis (MFA) Models

Material flow analysis (MFA) is a systematic assessment of the flows and stocks of materials within a system defined in space and time. It connects the sources, the pathways, and the intermediate and final sinks of a material Because of the law of the conservation of matter, the results of an MFA can be controlled by a simple material balance comparing all inputs, stocks, and outputs of processes. It is this distinct characteristic of MFA that makes the method attractive as a decision-support tool in resource management, waste management, and environmental management.(Brunner and Rechberger 2004) An example of an MFA model can be seen in Figure 17.

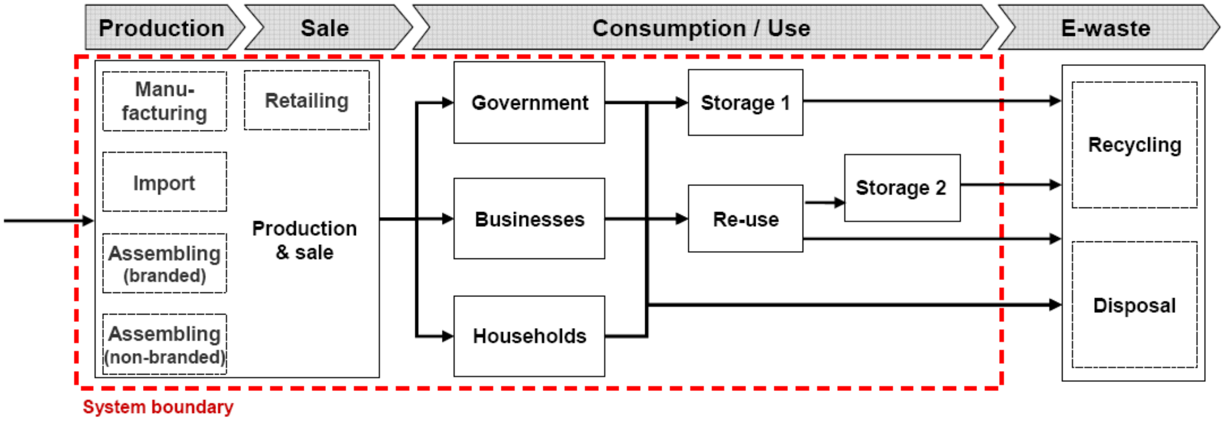


Figure 17: Example of MFA Model

There have been several studies that have investigated electronics recycling with MFA modeling (Streicher-Porte, Widmer et al. 2005; Steubing, Ludwig et al. 2008). Both of these studies are spatially specific to a particular region. Each identifies the local recycling network structure and models the individual stakeholders as mass balances. In both of these studies the “trace” is identified as a personal computer that may or may not include various peripherals. In addition, there is also some effort to identify the computers’ constituent material flows within the network. Using MFA techniques, these studies are able to determine where the largest flows exist, and then make assessments which can include economic, social or environmental considerations.

One of the strong points of MFA modeling is that it is very systematic. Since MFA is based on the physical laws of mass flow, it is very straightforward and objective in its implementation. MFA models are also quite flexible, as new stakeholders and network structure can be modified easily by creating or removing "flows" from the system. In addition, once an MFA model has been created, it can serve to support decision making through the adjustment of transfer coefficients. This allows the decision maker to explore different situational scenarios such as varying stakeholder behavior (Cooper 2009).

However with respect to the difficulties of MFA, a detailed MFA can be difficult to implement from a data gathering perspective. In some cases, especially those involving vested corporate interest, stakeholders are not forthcoming with respect to the movement of products or materials for fear of losing their competitive advantage. In the context of electronics recycling, there is also the unique situation that product or material flow data may be withheld to avoid legal prosecution as mentioned by the authors of (Streicher-Porte, Widmer et al. 2005), where data had to be obtained covertly. This can present danger not only in terms of model fidelity, but also in terms of physical harm coming to the modeler.

2.5.4 Discussion

Each of the aforementioned modeling practices has its own set of advantages and disadvantages. The goal of this study to combine as many as their advantages as possible, and simultaneously minimize their disadvantages.

In the process of researching systems engineering and different modeling techniques, several characteristics of modeling were collected and inferred from the literature:

- Simplicity: A good model is a simplified representation of one aspect of a real system: models are successful because they do not consider all the complexity of the real system (Bahill and Szidarovszky 2009)
- Detail vs Efficiency: At an early stage in the lifecycle, often rough estimations are used; hence the model need not necessarily have a great amount of details in order to be used efficiently (Balmelli 2007; Balmelli 2008)
- Systematic Creation: To perform analysis on a model, there must be data stored formally and systematically (Mura, Murillo et al. 2008)
- Integration and Reuse: To achieve more complex, higher fidelity models, there must be reuse of existing simulation model information and integration of a wide range information from numerous data sources (Kwon and McGinnis 2007)

Table 2: Comparison of Modeling Methodologies in Support of MBSE

Modeling Methodology	Practice 1	Practice 2	Practice 3	Practice 4	Total
MFA	3	2	3	3	11
LCA	2	1	2	2	7
OR	1	3	1	1	6

Bearing these practices in mind, it is arguable that the MFA methodology is the most suited to support a systems engineering modeling effort. Table 2 depicts a lexicographic ordering of the three methodologies with respect to their support of MBSE.

Although this representation is subject to the bias of the author, it nevertheless represents the claim that is justified by the following paragraphs.

With respect to simplicity, MFA is built on the mass balance principle for a trace material or product, thus it provides both a simplified representation of the system and also neglects the complexity of having to trace every material or product through the system, as in an LCA. While the case could be made that OR models typically only focus on one aspect of the system, that being cost, there are many complexities that underlie the monetization of system elements.

The fact that MFA is here regarded as superior to LCA with respect to simplicity is largely a function of a relationship between model detail and efficiency. Although an MFA may lack the model richness of an LCA, the fact that not every emission must be accounted for has the possibility of significantly reducing the data gathering effort which stands to improve modeling efficiency. Thus, looking at these two factors, if the goal of the model is to be support early system design, this slight loss of richness is a necessary trade off to improve modeling efficiency. Overall the OR approach is regarded as superior to LCA and MFA in terms of detail versus efficiency as the OR method does not as heavily rely on data gathering, yet it can still produce interesting insight. This is evident in much of the OR literature, as the absence of tangible data is not an impediment to creating a predictive example.

Continuing to systematic creation, although each methodology presented lends itself to a formal representation, as can be seen in the figures that give examples of them, each does not lend itself to systematic creation. In this respect, MFA is likely the best suited. As was mentioned above, the ease of adding and removing stakeholders by simply adding and removing processes and flows is unmatched by the other two. With respect to OR, though model description is very formal, the formulation of models can depend largely on heuristics which is not favorable from a systematic point of view.

Lastly, MFA also arguably provides the most support for aiding the reuse of information. Once a model is created that describes the flow of a substance with in a system boundary, it is relatively simple to expand that boundary to include more and more outside factors. This cannot be said about LCA, as the expansion of the system boundary can completely change the categories of emissions that the model considers. In terms of an OR formulation, though certain constraints may be reused from problem to problem, the unsystematic creation of formalisms do not lend themselves to reuse.

CHAPTER 3: MODELING LIFE CYCLE NETWORKS IN SYSML

SysML is a graphically based programming language designed for systems engineering. Essentially, SysML acts like a specialized database language. By itself SysML is not executable, but rather it serves to capture the structure and pertinent data of a system. Once the structure has been created and populated with data, SysML can then exchange that information with specialized tools in a formalized manner, such as sending values and equations to a solver or modeling program.

For the purposes of this work SysML will be used to capture the network structure of the stakeholders involved in the lifecycle of electronics waste as it pertains to mass and energy transfer. To make the scope of this work more reasonable for research proposes, only the network structure for LCD computer monitors will be considered.

In SysML entities in a model are represented as blocks, and the relationship between these blocks are represented in diagrams. Although there are many different types of diagrams available in SysML only block definition diagrams (BDD), internal block diagrams (IBD), and parametric diagrams (PAR) are utilized in this work. Before delving too deeply into the structure of the SysML model, it is helpful to think about the structures being modeled. Therefore, the next section details the modeling schema and principles that are used in the modeling effort.

3.1 Modeling Schema

3.1.1 Stakeholders Modeling

To begin it is helpful to think about the lifecycle of a monitor as a system. Inside of this lifecycle system there are many smaller systems which may include entities such as manufacturing systems, use systems, or disposal systems. Inside of these smaller systems there are even more systems, but eventually a point is reached where a boundary must be drawn. Therefore, in this work three layers of system detail are considered: the process level, the facility level and the network level. These levels or layers of detail are shown in Figure 18. The boxes represent the system view or level of detail being taken and following the arrows upward indicates broadening the scope or vantage.

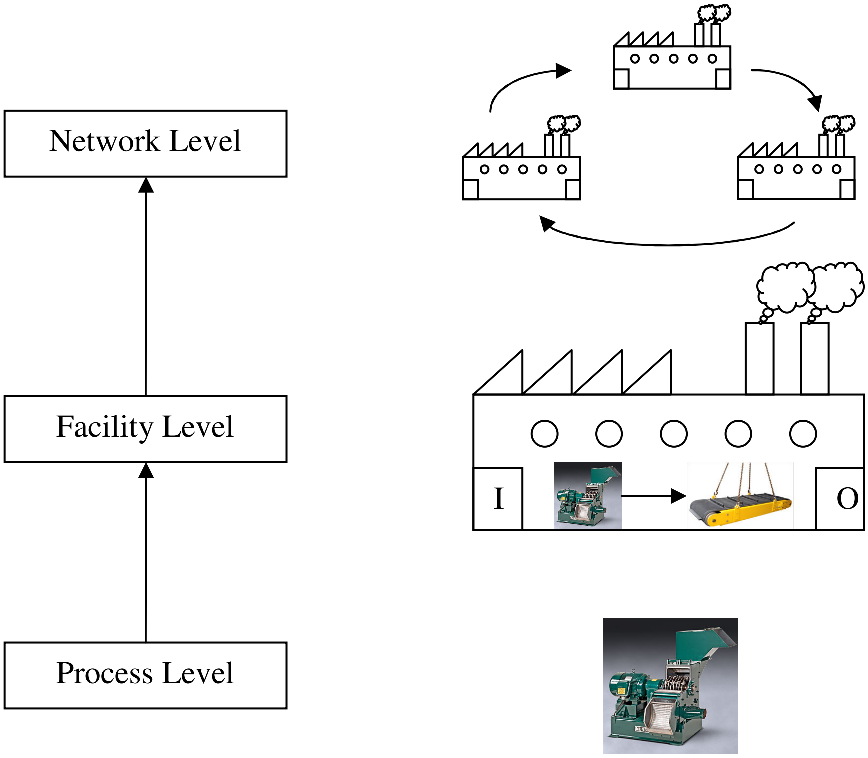


Figure 18: Model Layer Diagram

Beginning at the bottom, the lowest level of mass and energy transfer is assumed to take place at the process level. An example of a process is a hammer mill, where mass in some form enters the hammer mill and mass of a different form, usually much smaller, exits the mill. If the power requirements of the machine are known along with the operating time, then the energy consumed by the machine can be calculated. For the case of a hammer mill there is one input and one output, but as will be discussed later, there can be many inputs and outputs in a single process.

Moving up to the middle level of the spectrum if one were to take a number of processes and group them together, it would be a facility. The facility level serves to aggregate the process flows within a facility. An example of a facility might include several processes such as hammer mill to reduce the size of incoming material, and then a magnetic separator to pull all of the scrap iron out of the incoming material. The input of the facility enters the hammer mill, the output of a hammer mill enters the magnetic separator, and finally the output of the magnetic separator exits the facility. Assuming the operating time of the facility is equivalent to the operating time of the machines in the facility, then the energy consumed by the facility machinery can be calculated and summed to give the total facility energy consumed.

At the top level, as one might guess, when a number of facilities are grouped together it is called a network. The network level serves to capture the interactions between facilities. An example of a network might include the manufacturer of a computer monitor, the user of the computer monitor, and the disposer of the computer monitor. The difference between the facility level and the network level is that the network level does not aggregate the flows between facilities, but rather represents them. In other words it is assumed that there is no level higher than the network level, and that there is only one network. This makes sense from a real world perspective as it is facilities that exchange mass and energy, not networks.

Defining the model in terms of these modular elements is import from the integration and reuse perspective. A modular structure allows others to leverage previous modeling efforts. In other words, once a process or a facility is designed and modeled within this structure that knowledge is captured for future modelers to exploit. For example, if a hammer mill process is designed to go in a mineral processing facility, it is now possible for someone investigating electronics recycling to reuse that hammer mill block in a recycling facility. Thus the knowledge of hammer mill specification is instantly transferred. Ultimately, creating models to be reusable improves model creation efficiency over time as more new models add more knowledge to the pool.

3.1.2 Material Flow Modeling

Just as there are three layers of detail in the stakeholders-model, there are also three levels of detail in the modeling of material flow. At first glance it might seem superfluous to consider three layers of detail in material flow; after all, a kilogram of steel is a kilogram of steel. However, one of the strengths of SysML is the richness it brings to a model. Although a kilogram of steel is a kilogram of steel, a kilogram of steel that has been forged, bent, and welded is not structurally equivalent to the kilogram bar of steel from which it was originally wrought. Therefore, in an effort to capture this structural difference between raw materials and finished product, more layers of detail are needed to model material flow. The layers of detail are shown in Figure 19. The arrows indicate the inheritance of properties from lower levels.

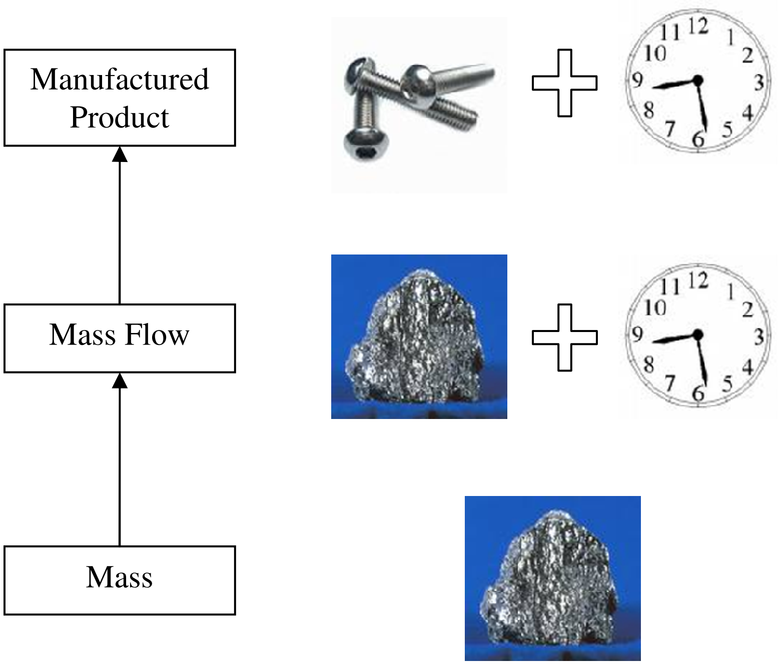


Figure 19: Material Flow Hierarchy

Figure 20 depicts the hierarchy of Figure 19 as a SysML diagram. As a note to experienced SysML users, the inheritance relationship used in the diagram is not in line with the precise definition of inheritance given in the SysML specification. However, within the context of ParaMagic (v16.5), it exploits a feature of the ParaMagic software allowing easy transformation between each type of flow.

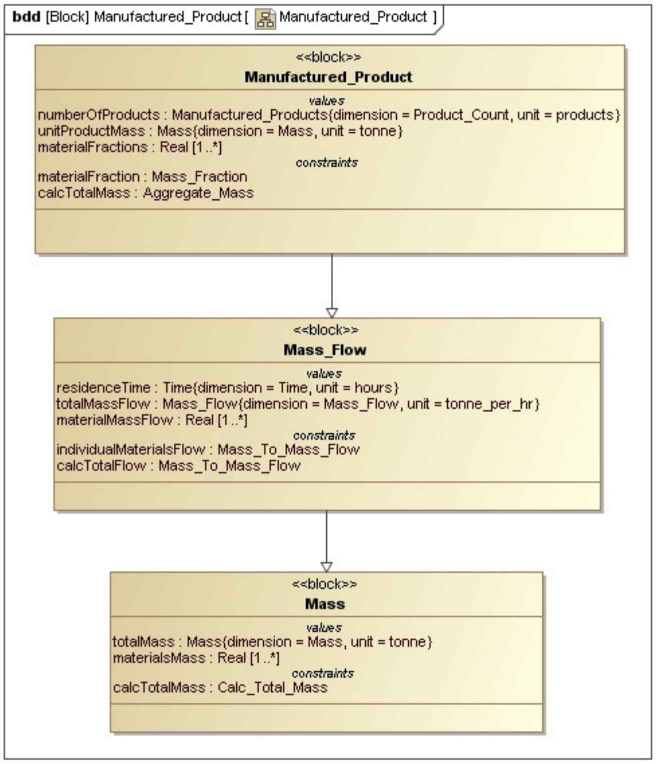


Figure 20: Material Flow Hierarchy in SysML

The most basic level of material flow in this work is that of simply mass. A mass in this model is assumed to be simply a collection of different substances in a vector-like format (materialMass above, value property with multiplicity 1…*), such as steel, aluminum, or plastic, whereby the total mass is computed by the sum of its parts. In other words, as a modeling element, mass has the single property of conservation.

The next layer above mass has all of the properties associated with mass with the added dimension of time. The next level of material flow is mass flow. Mass flow builds on mass using the simple ratio: mass divided by time is equal to mass flow. It is assumed that as a group of substances moves through a process, it stands to reason that the time it takes the group to move through a process is equal. Therefore, the total mass flow can be computed from the sum of its parts, or, in other words, mass flow is conserved.

The top layer of material flow is a manufactured product. A manufactured product flow inherits both the properties of mass and mass flow, but also adds information about an individual product. A manufactured product has several parameters that determine its mass characteristics such as individual unit product mass, the number of products in the flow, and the material fractions associated with the substances in the product. Thus, the total mass of a group of manufactured products can be computed from the product of the total number of products in a flow and the unit product mass. Also, the mass of the constituent substances in a manufactured product can be computed by multiplying the total mass of the products by the material fractions.

The reason for adding the layers of detail to material flow is so that the interactions between processes and facilities in a network have a higher fidelity. For example if one facility sends steel screws to another, then the screws can be described as a manufactured part in the transaction rather than just an exchange of mass. Also, because the layers are related in a formal way, transitioning from one layer to the next is relatively simple by either adding or removing information.

3.1.3 Energy Flow

Continuing with the previous sections' conventions of defining entities in terms of hierarchies, energy, although it ultimately aggregates into a single value, is calculated from several components. One of the goals of this modeling effort is to combine data from many different sources such as machine specifications and life-cycle inventories. This creates a difficulty in that different data sources report data in different forms. For example the common practice in life cycle inventories is to choose a functional unit, which is most likely different from inventory to inventory even for the same product. Therefore, it was necessary to provide the modeler with several different options for calculating energy.

Since energy is calculated from the flow of mass through a process, the method for calculating a process's energy needs to be related to that flow. To achieve this, energy can either be calculated from a specific energy basis (energy consumed per mass processed) or from machine specifications in terms of electrical power and/or combustive power combined with processing speed, number of machines required, time of processing, etc. The hierarchy of these calculations can be seen in Figure 21.

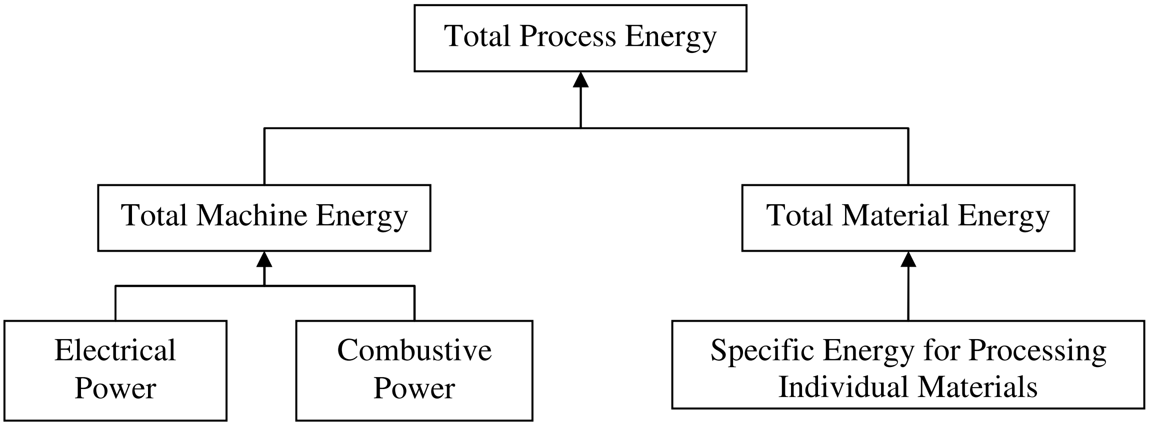


Figure 21: Energy Calculation Hierarchy

At the process level, energy is calculated directly from the incoming mass flow. The SysML parametric diagram that accomplishes this can be seen in Figure 22. At the facility level, energy is aggregated from the energy consumed by the processes contained within the facility. Then finally at the network level, energy is exchanged between facilities, which represents the flow of energy between energy producing facilities and energy consuming facilities that may exist on the power grid. A simplified representation of these interactions is depicted in Figure 23.

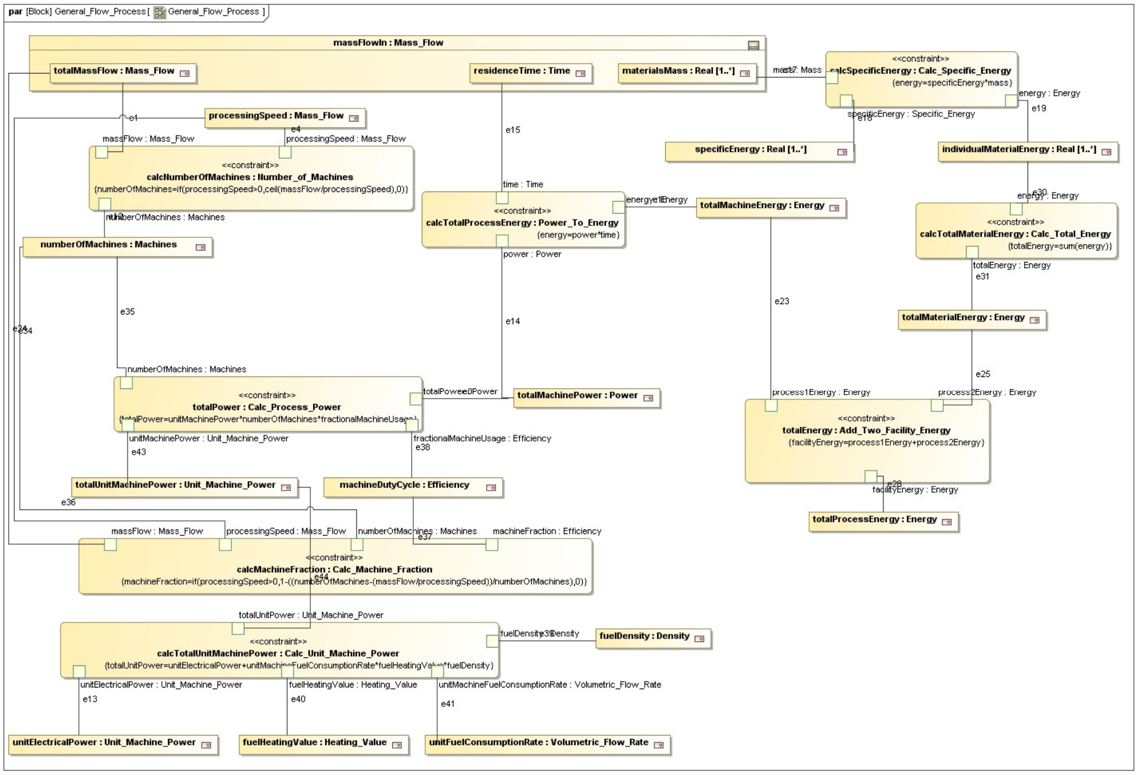


Figure 22: Process Energy Calculation PAR

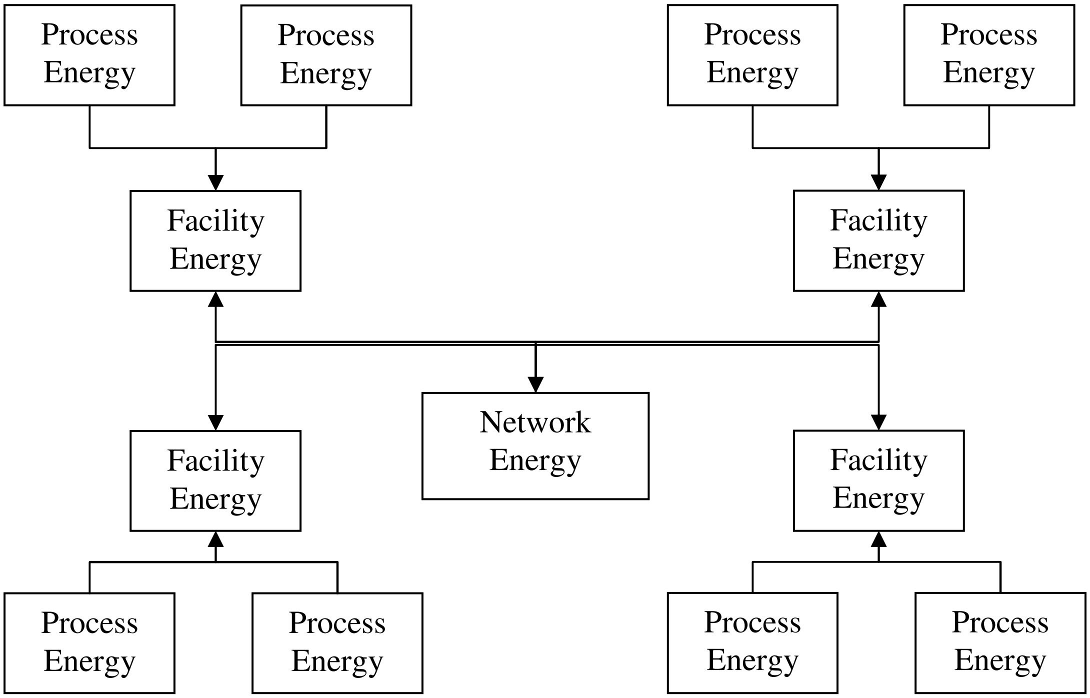


Figure 23: Model Aggregation of Energy

3.2 LCD Glass Manufacturer Example

To illustrate some of the modeling practices above it is useful to actually build a working model of a facility. For illustration purposes, the example facility will be an LCD Glass Manufacturer having one input, two outputs, and one process. The process will be simple as well, having a one input and two outputs.

To begin, it is best view the parts of the manufacturing facility, which are easiest to see in the BDD. Figure 24 shows the BDD for the example facility.

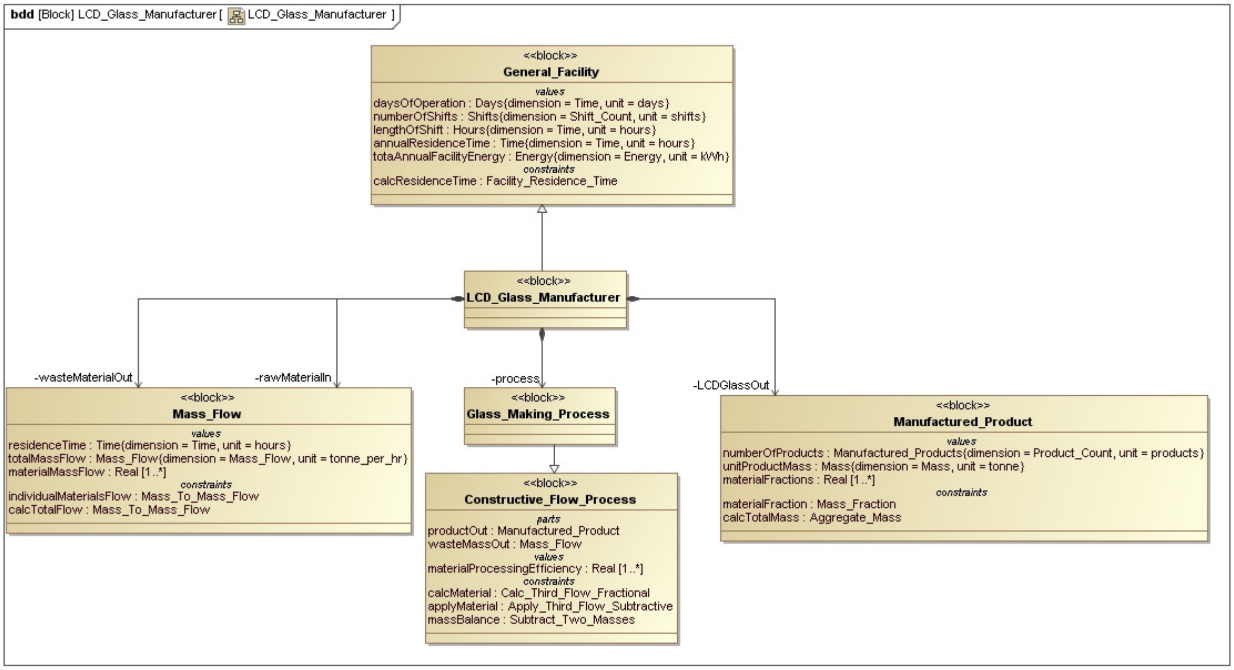


Figure 24: BDD LCD Glass Manufacturer

In the center of the diagram is the Glass Manufacturer Block, which is a specialization of the General Facility Block. The General Facility Block provides several calculations and parameters that are common to many facilities, and is explained in more detail below in 3.2.1. It can be seen from Figure 24 that there are four parts to the Glass Manufacturer: one input (rawMaterialIn), two outputs (wasteMaterialOut, LCDGlassOut), and a single glass making process (process), which is a specialization of a Constructive Flow Process. The Constructive Flow Process provides several calculations and parameters that are common to many processes and is explained in more detail below in 3.2.2. All of the entities are represented by their respective blocks.

To gain an understanding of how these parts interact, it is best to start with the Glass Manufacturer IBDs. The flow of material through a Glass Manufacturer can be seen at the top of Figure 25 and the flow of energy can be seen at the bottom.

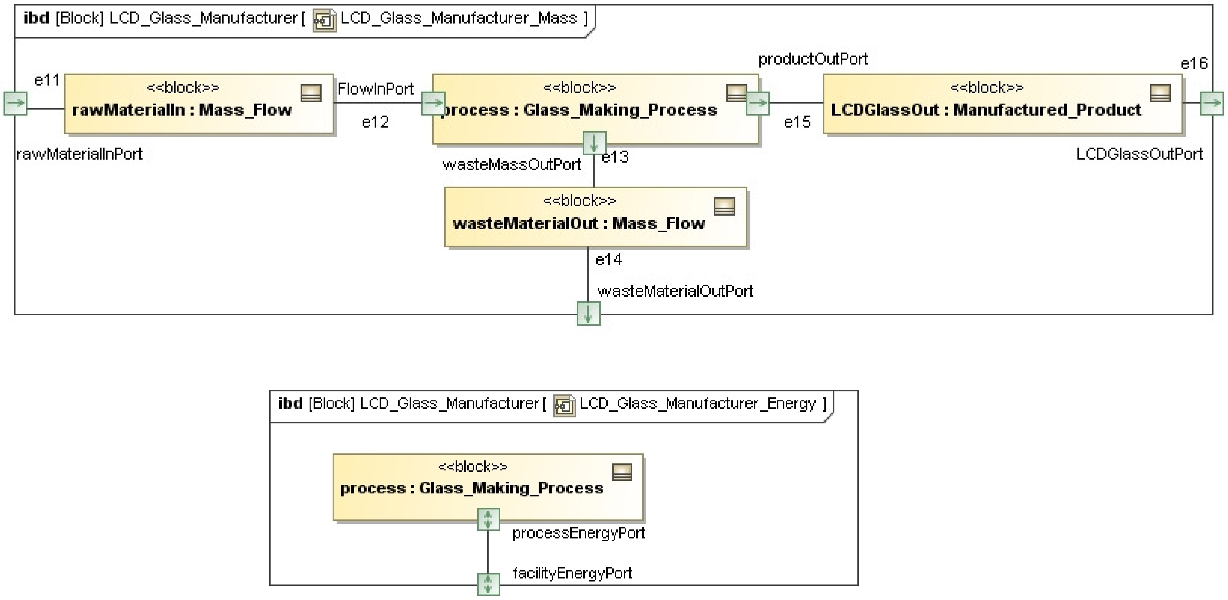


Figure 25: LCD Glass Manufacturer Mass and Energy IBDs

From the material flow IBD it can be seen raw material enters the facility a through a port at the left of the diagram. The flow of raw material is represented by the mass flow block between the two mass flow ports. Once the material enters the glass making process it is divided either into a waste mass flow at the bottom of the diagram, or is transformed into LCD glass at the right of the diagram. Since there is only one process in the facility, the IBD for the energy in a Glass Manufacturer is rather simple. As can be seen in the diagram, energy enters the facility through the facility energy port and flows straight into the glass making process. A notable difference between the mass flow ports and the energy ports is that the energy flow ports are two way while the mass flow ports are one way. This two way port exists because some processes may be energy generating processes which have a negative sign in the instance specification. This convention is necessary because mass flow is represented by a blocks, while energy flow is represented by value types as mentioned earlier in Section 3.1.

With a general idea of the flows through the facility from the IBDs, it is possible to understand the real substance of the model which shows up in the PARs. The flow of material through a glass manufacturer can be seen in the PAR shown in Figure 26.

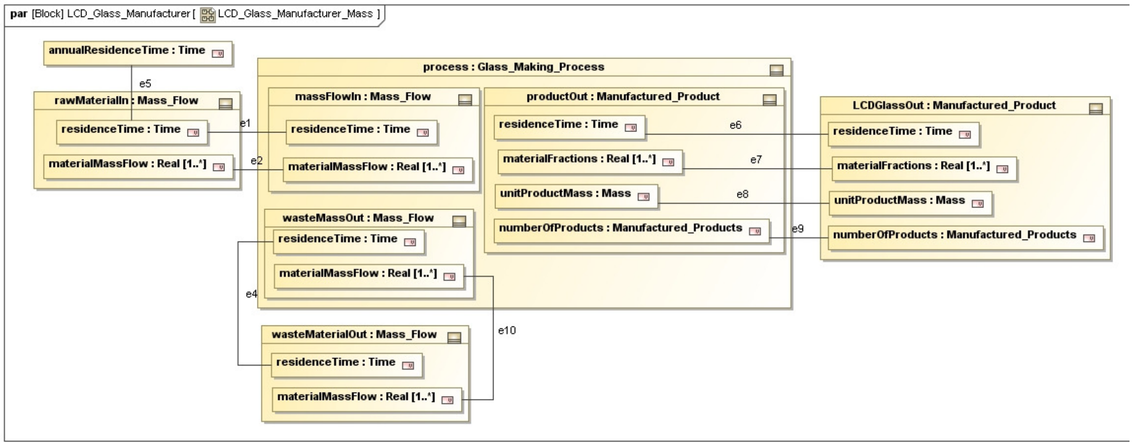


Figure 26: Glass Manufacturer Material Flow PAR

The PAR appears to have a very similar structure to that shown in the IBD in Figure 25. The main difference is that the information flow between blocks is richer. The general flow of the diagram is as follows. The raw material entering the facility is represented by the mass flow block on the left, which corresponds to the block which appeared between flow ports in the IBD. The raw material block gets its time component from the facility as represented by the link between the annualResidenceTime value and the raw material's residenceTime value. The magnitude and assortment of substances entering the facility is represented by raw material's value property materialMassFlow (the vector-like format as mentioned above). The values from the raw materials entering the facility are linked to the input of the glass making process. The internal calculations that take place inside the glass making process block are a combination of calculations inherited from the General Flow Process and Constructive Flow Process Blocks which is described in more detail below in 3.2.2. Essentially though, the raw material that enters the facility is transformed into LCD glass, shown at the right of the diagram, less the material inefficiencies associated with the waste material, shown at the bottom of the diagram.

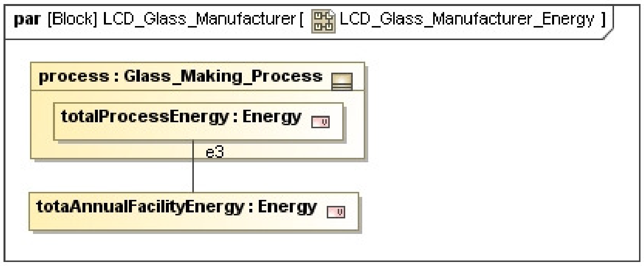


Figure 27: Glass Manufacturer Energy Flow PAR

Figure 27 above represents the energy flow in a glass manufacturing facility. Like the IBD depicting energy flow in Figure 25; because there is only one process in the Glass Manufacturing facility, the energy flow is quite simple. This is because the process energy calculations are handled by the General Flow Process Block. Needless to say however, that energy that is consumed by the single glass making process equates to the total annual facility energy.

Once the structure of the model has been created using PARs, the last step in creating a facility model is to populate the structure with data. This is accomplished by generating an instance structure BDD. Using MagicDraw, which is a development environment supporting SysML, instance structures can be created automatically. Figure

28 shows an instance structure containing the appropriate data to represent a glass manufacturing facility.

With the instance structure created, the SysML model is complete. The model is now ready for external solvers to calculate values for the empty slots in the instance structure. For illustrative purposes, assume that LCD glass is made from 75 percent material 1 and 25 percent material 2. Assume also that a glass making machine processes material at a rate of 1 ton per hour, has a power requirement of 10 kW, and is 95 percent efficient. If a glass manufacturer produces 100,000 units of glass, weighing 0.2 kg each, then how much energy and raw material is consumed by this facility if it operates 16 hours a day, 235 days a year? This is the exact question that can be answered from the model created above, and to help answer this question an external solver called ParaMagic can be used.

The ParaMagic browser window can be seen in Figure 29. It is apparent from the window that the initial conditions stated above are entered in the appropriate variable slots. Also in the window it can be seen that the total annual facility energy is set as a solution target. With givens entered and the target set, ParaMagic is now ready to generate a solution. Figure 30 shows the browser window after a solution has been generated. From the results the answer to the original question is 15.8 tonnes of material 1, 5.3 tonnes of material 2, and 37,600 kWh of energy. Once the solution has been computed, ParaMagic can automatically update the model instance structure. The fully populated instance structure after being solved by an external solver is shown in Figure 31.

bdd [Package] testGlassManu [Instance of the LCD_Glass_Manufacturer]

<<block>>
ICD_Glass_Manufacturer : LCD_Glass_Manufacturer

annualResidenceTime = ""{unit = hours, dimension = Time}
daysOfOperation = "235.0"{unit = days, dimension = Time}
LCDGlassOut = ICD_Glass_Manufacturer.ICDGlassOut
lengthOfShift = "8.0"{unit = hours, dimension = Time}
numberOfShifts = "2.0"{unit = shifts, dimension = Shift_Count}
process = ICD_Glass_Manufacturer.process
rawMaterialIn = ICD_Glass_Manufacturer.rawMaterialIn
totaAnnualFacilityEnergy = ""{unit = kWh, dimension = Energy}
wasteMaterialOut = ICD_Glass_Manufacturer.wasteMaterialOut

<<block>>
ICD_Glass_Manufacturer.process : Glass_Making_Process

individualMaterialEnergy = "", ""
massFlowIn = ICD_Glass_Manufacturer.process.massFlowIn
materialProcessingEfficiency = "0.95"
numberOfMachines = ""{unit = machines, dimension = Machine_Count}
processingSpeed = "1.0"{unit = tonne_per_hr, dimension = Mass_Flow}
productOut = ICD_Glass_Manufacturer.process.productOut
specificEnergy = "0.0"
totalMachineEnergy = ""{unit = kWh, dimension = Energy}
totalMachinePower = ""{unit = kW, dimension = Power}
totalMaterialEnergy = ""{unit = kWh, dimension = Energy}
totalProcessEnergy = ""{unit = kWh, dimension = Energy}
unitMachinePower = "10.0"{unit = kW_per_machine, dimension = Unit_Machine_Power}
wasteMassOut = ICD_Glass_Manufacturer.process.wasteMassOut

<<block>>
ICD_Glass_Manufacturer.process.productOut : Manufactured_Product

materialFractions = "", ""
materialMassFlow = "", ""
materialsMass = "", ""
numberOfProducts = ""{unit = products, dimension = Product_Count}

residenceTime = ""{unit = hours, dimension = Time}
totalMass = ""{unit = tonne, dimension = Mass}
totalMassFlow = ""{unit = tonne_per_hr, dimension = Mass_Flow}

unitProductMass = ""{unit = tonne, dimension = Mass}

<<block>>
ICD_Glass_Manufacturer.process.wasteMassOut : Mass_Flow

materialMassFlow = "", ""

materialsMass = "", ""
residenceTime = ""{unit = hours, dimension = Time}
totalMass = ""{unit = tonne, dimension = Mass}

totalMassFlow = ""{unit = tonne_per_hr, dimension = Mass_Flow}

<<block>>
ICD_Glass_Manufacturer.process.massFlowIn : Mass_Flow

materialMassFlow = "", ""

materialsMass = "", ""
residenceTime = ""{unit = hours, dimension = Time}
totalMass = ""{unit = tonne, dimension = Mass}

totalMassFlow = ""{unit = tonne_per_hr, dimension = Mass_Flow}

<<block>>
ICD_Glass_Manufacturer.ICDGlassOut : Manufactured_Product

materialFractions = "0.75", "0.25"
materialMassFlow = "", ""

materialsMass = "", ""
numberOfProducts = "100.0"{unit = products, dimension = Product_Count}
residenceTime = ""{unit = hours, dimension = Time}
totalMass = ""{unit = tonne, dimension = Mass}
totalMassFlow = ""{unit = tonne_per_hr, dimension = Mass_Flow}

unitProductMass = "1.0"{unit = tonne, dimension = Mass}

<<block>>
ICD_Glass_Manufacturer.wasteMaterialOut : Mass_Flow

materialMassFlow = "", ""

materialsMass = "", ""
residenceTime = ""{unit = hours, dimension = Time}
totalMass = ""{unit = tonne, dimension = Mass}

totalMassFlow = ""{unit = tonne_per_hr, dimension = Mass_Flow}

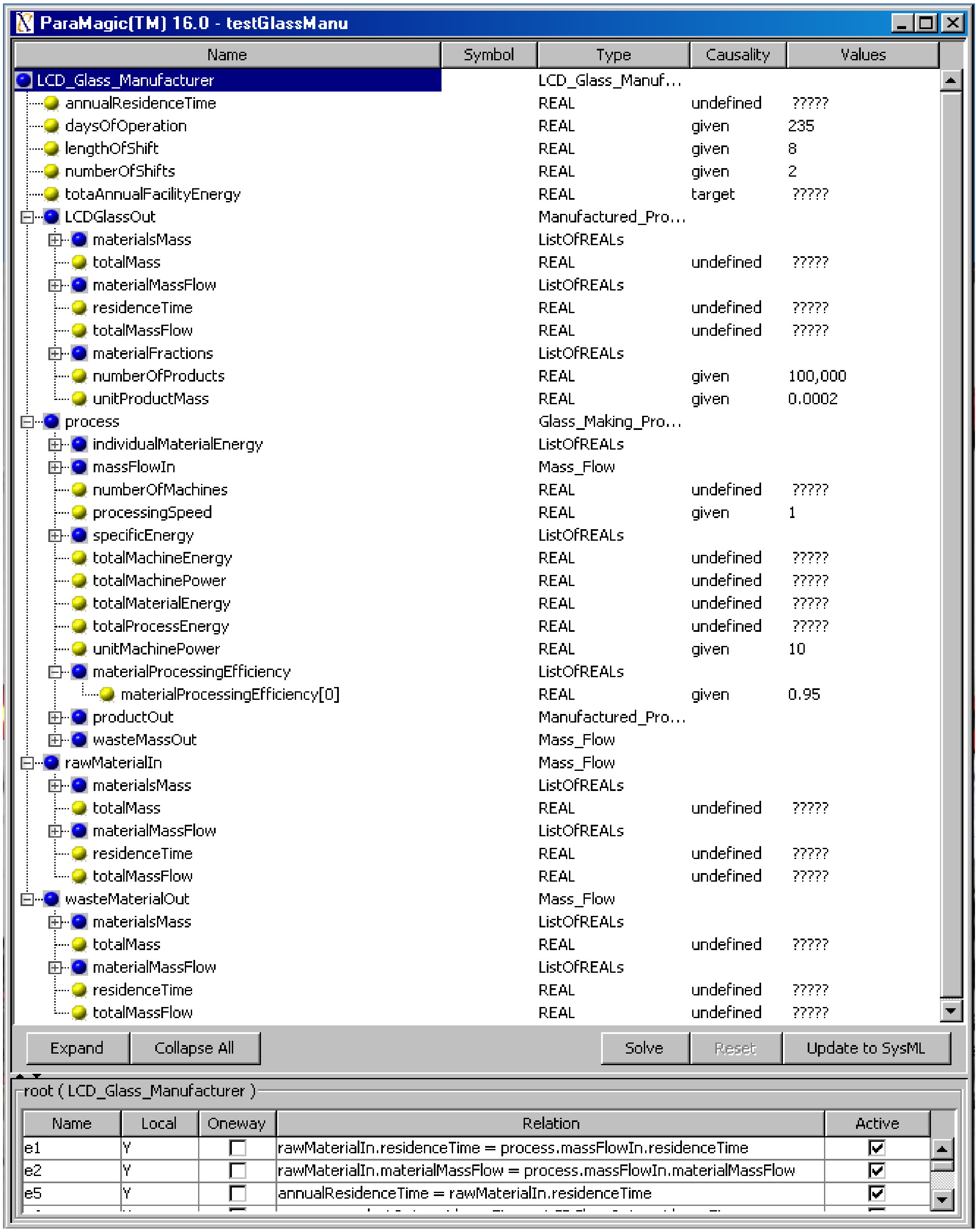
<<block>>
ICD_Glass_Manufacturer.rawMaterialIn : Mass_Flow

materialMassFlow = "", ""
materialsMass = "", ""

residenceTime = ""{unit = hours, dimension = Time}
totalMass = ""{unit = tonne, dimension = Mass}

totalMassFlow = ""{unit = tonne_per_hr, dimension = Mass_Flow}

Figure 28: Partially Populated Glass Manufacturer Facility Instance Structure BDD

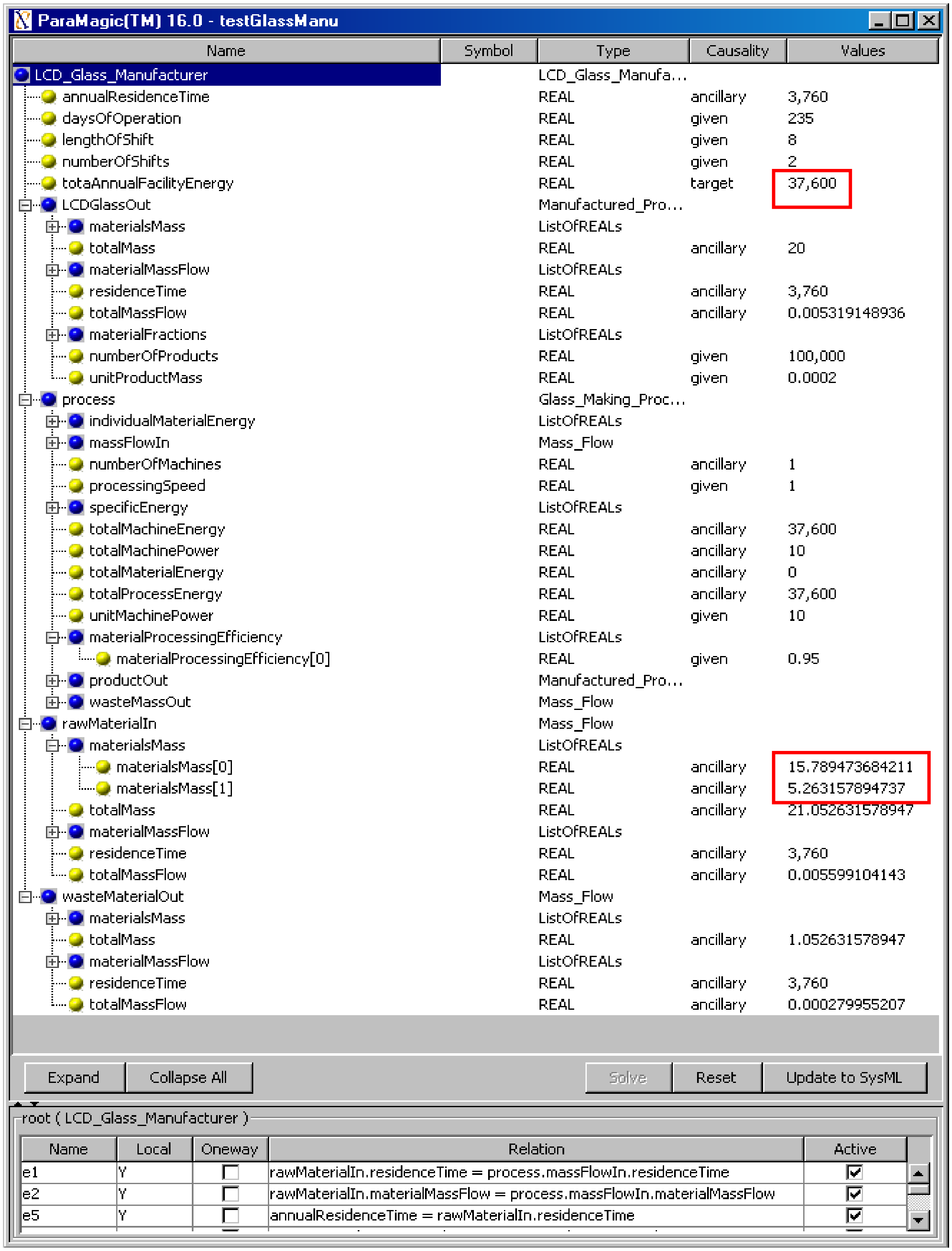


Name	Symbol	Type	Causality	Values
LCD_Glass_Manufacturer		LCD_Glass_Manuf...		
annualResidenceTime		REAL	undefined	?????
daysOfOperation		REAL	given	235
lengthOfShift		REAL	given	8
numberOfShifts		REAL	given	2
totaAnnualFacilityEnergy		REAL	target	?????
LCDGlassOut		Manufactured_Pro...		
materialsMass		ListOfREALs		
totalMass		REAL	undefined	?????
materialMassFlow		ListOfREALs		
residenceTime		REAL	undefined	?????
totalMassFlow		REAL	undefined	?????
materialFractions		ListOfREALs		
numberOfProducts		REAL	given	100,000
unitProductMass		REAL	given	0.0002
process		Glass_Making_Pro...		
individualMaterialEnergy		ListOfREALs		
massFlowIn		Mass_Flow		
numberOfMachines		REAL	undefined	?????
processingSpeed		REAL	given	1
specificEnergy		ListOfREALs		
totalMachineEnergy		REAL	undefined	?????
totalMachinePower		REAL	undefined	?????
totalMaterialEnergy		REAL	undefined	?????
totalProcessEnergy		REAL	undefined	?????
unitMachinePower		REAL	given	10
materialProcessingEfficiency		ListOfREALs		
materialProcessingEfficiency[0]		REAL	given	0.95
productOut		Manufactured_Pro...		
wasteMassOut		Mass_Flow		
rawMaterialIn		Mass_Flow		
materialsMass		ListOfREALs		
totalMass		REAL	undefined	?????
materialMassFlow		ListOfREALs		
residenceTime		REAL	undefined	?????
totalMassFlow		REAL	undefined	?????
wasteMaterialOut		Mass_Flow		
materialsMass		ListOfREALs		
totalMass		REAL	undefined	?????
materialMassFlow		ListOfREALs		
residenceTime		REAL	undefined	?????
totalMassFlow		REAL	undefined	?????

root (LCD_Glass_Manufacturer)

Name	Local	Oneway	Relation	Active
e1	Y	☐	rawMaterialIn.residenceTime = process.massFlowIn.residenceTime	☑
e2	Y	☐	rawMaterialIn.materialMassFlow = process.massFlowIn.materialMassFlow	☑
e5	Y	☐	annualResidenceTime = rawMaterialIn.residenceTime	☑

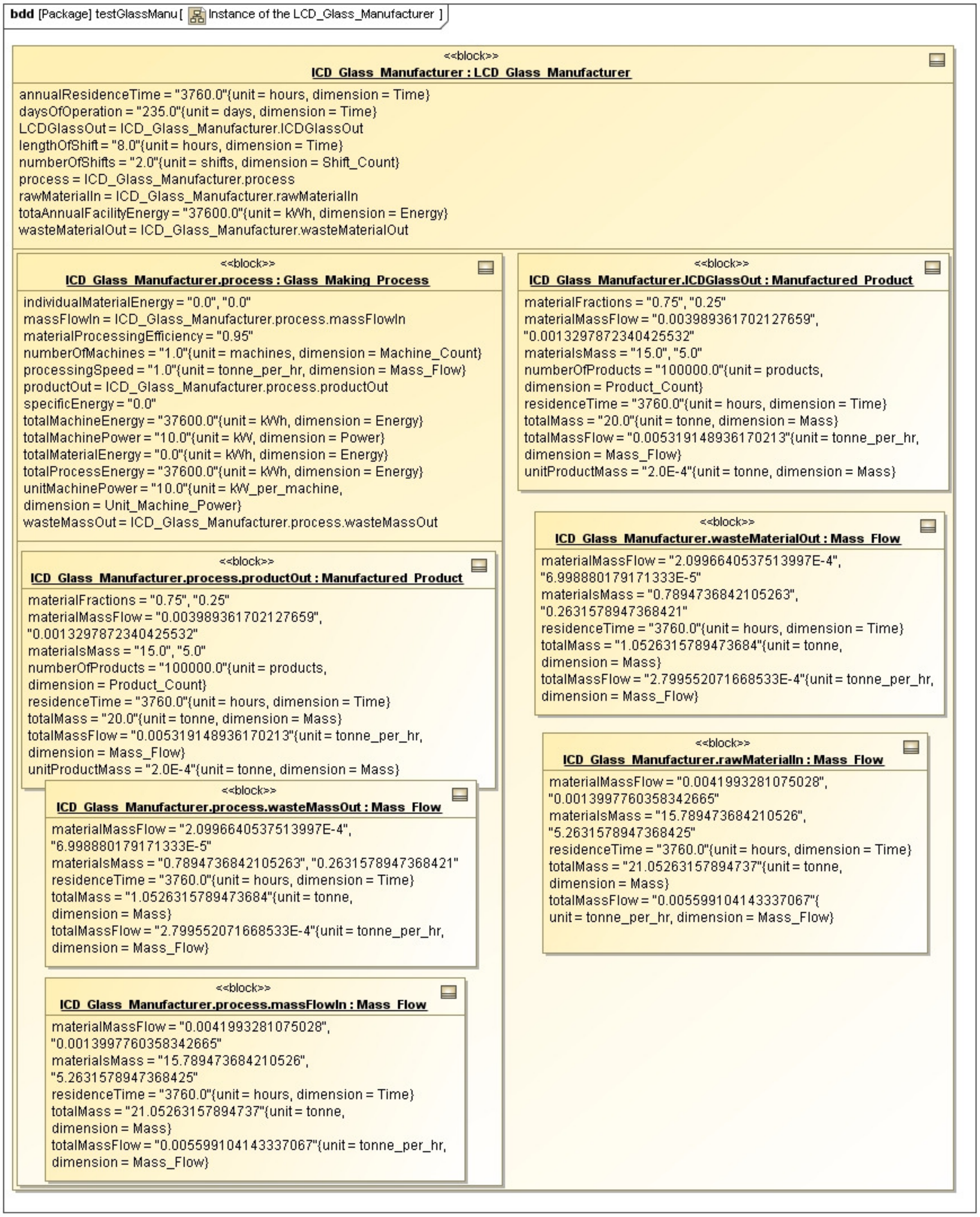
Figure 29: ParaMagic Solver Window Pre-Solution



Name	Symbol	Type	Causality	Values
LCD_Glass_Manufacturer		LCD_Glass_Manufa…		
annualResidenceTime		REAL	ancillary	3,760
daysOfOperation		REAL	given	235
lengthOfShift		REAL	given	8
numberOfShifts		REAL	given	2
totaAnnualFacilityEnergy		REAL	target	37,600
LCDGlassOut		Manufactured_Pro…		
materialsMass		ListOfREALs		
totalMass		REAL	ancillary	20
materialMassFlow		ListOfREALs		
residenceTime		REAL	ancillary	3,760
totalMassFlow		REAL	ancillary	0.005319148936
materialFractions		ListOfREALs		
numberOfProducts		REAL	given	100,000
unitProductMass		REAL	given	0.0002
process		Glass_Making_Proc…		
individualMaterialEnergy		ListOfREALs		
massFlowIn		Mass_Flow		
numberOfMachines		REAL	ancillary	1
processingSpeed		REAL	given	1
specificEnergy		ListOfREALs		
totalMachineEnergy		REAL	ancillary	37,600
totalMachinePower		REAL	ancillary	10
totalMaterialEnergy		REAL	ancillary	0
totalProcessEnergy		REAL	ancillary	37,600
unitMachinePower		REAL	given	10
materialProcessingEfficiency		ListOfREALs		
materialProcessingEfficiency[0]		REAL	given	0.95
productOut		Manufactured_Pro…		
wasteMassOut		Mass_Flow		
rawMaterialIn		Mass_Flow		
materialsMass		ListOfREALs		
materialsMass[0]		REAL	ancillary	15.789473684211
materialsMass[1]		REAL	ancillary	5.263157894737
totalMass		REAL	ancillary	21.052631578947
materialMassFlow		ListOfREALs		
residenceTime		REAL	ancillary	3,760
totalMassFlow		REAL	ancillary	0.005599104143
wasteMaterialOut		Mass_Flow		
materialsMass		ListOfREALs		
totalMass		REAL	ancillary	1.052631578947
materialMassFlow		ListOfREALs		
residenceTime		REAL	ancillary	3,760
totalMassFlow		REAL	ancillary	0.000279955207

Name	Local	Oneway	Relation	Active
e1	Y	☐	rawMaterialIn.residenceTime = process.massFlowIn.residenceTime	☑
e2	Y	☐	rawMaterialIn.materialMassFlow = process.massFlowIn.materialMassFlow	☑
e5	Y	☐	annualResidenceTime = rawMaterialIn.residenceTime	☑

Figure 30: ParaMagic Solver Window Post Solution



```
bdd [Package] testGlassManu [ Instance of the LCD_Glass_Manufacturer ]

<<block>>
ICD_Glass_Manufacturer : LCD_Glass_Manufacturer
annualResidenceTime = "3760.0"{unit = hours, dimension = Time}
daysOfOperation = "235.0"{unit = days, dimension = Time}
LCDGlassOut = ICD_Glass_Manufacturer.ICDGlassOut
lengthOfShift = "8.0"{unit = hours, dimension = Time}
numberOfShifts = "2.0"{unit = shifts, dimension = Shift_Count}
process = ICD_Glass_Manufacturer.process
rawMaterialIn = ICD_Glass_Manufacturer.rawMaterialIn
totaAnnualFacilityEnergy = "37600.0"{unit = kWh, dimension = Energy}
wasteMaterialOut = ICD_Glass_Manufacturer.wasteMaterialOut

<<block>>
ICD_Glass_Manufacturer.process : Glass_Making_Process
individualMaterialEnergy = "0.0", "0.0"
massFlowIn = ICD_Glass_Manufacturer.process.massFlowIn
materialProcessingEfficiency = "0.95"
numberOfMachines = "1.0"{unit = machines, dimension = Machine_Count}
processingSpeed = "1.0"{unit = tonne_per_hr, dimension = Mass_Flow}
productOut = ICD_Glass_Manufacturer.process.productOut
specificEnergy = "0.0"
totalMachineEnergy = "37600.0"{unit = kWh, dimension = Energy}
totalMachinePower = "10.0"{unit = kW, dimension = Power}
totalMaterialEnergy = "0.0"{unit = kWh, dimension = Energy}
totalProcessEnergy = "37600.0"{unit = kWh, dimension = Energy}
unitMachinePower = "10.0"{unit = kW_per_machine,
dimension = Unit_Machine_Power}
wasteMassOut = ICD_Glass_Manufacturer.process.wasteMassOut

<<block>>
ICD_Glass_Manufacturer.process.productOut : Manufactured_Product
materialFractions = "0.75", "0.25"
materialMassFlow = "0.003989361702127659",
"0.0013297872340425532"
materialsMass = "15.0", "5.0"
numberOfProducts = "100000.0"{unit = products,
dimension = Product_Count}
residenceTime = "3760.0"{unit = hours, dimension = Time}
totalMass = "20.0"{unit = tonne, dimension = Mass}
totalMassFlow = "0.005319148936170213"{unit = tonne_per_hr,
dimension = Mass_Flow}
unitProductMass = "2.0E-4"{unit = tonne, dimension = Mass}

<<block>>
ICD_Glass_Manufacturer.process.wasteMassOut : Mass_Flow
materialMassFlow = "2.0996640537513997E-4",
"6.998880179171333E-5"
materialsMass = "0.7894736842105263", "0.2631578947368421"
residenceTime = "3760.0"{unit = hours, dimension = Time}
totalMass = "1.0526315789473684"{unit = tonne,
dimension = Mass}
totalMassFlow = "2.799552071668533E-4"{unit = tonne_per_hr,
dimension = Mass_Flow}

<<block>>
ICD_Glass_Manufacturer.process.massFlowIn : Mass_Flow
materialMassFlow = "0.0041993281075028",
"0.0013997760358342665"
materialsMass = "15.789473684210526",
"5.2631578947368425"
residenceTime = "3760.0"{unit = hours, dimension = Time}
totalMass = "21.05263157894737"{unit = tonne,
dimension = Mass}
totalMassFlow = "0.005599104143337067"{unit = tonne_per_hr,
dimension = Mass_Flow}

<<block>>
ICD_Glass_Manufacturer.ICDGlassOut : Manufactured_Product
materialFractions = "0.75", "0.25"
materialMassFlow = "0.003989361702127659",
"0.0013297872340425532"
materialsMass = "15.0", "5.0"
numberOfProducts = "100000.0"{unit = products,
dimension = Product_Count}
residenceTime = "3760.0"{unit = hours, dimension = Time}
totalMass = "20.0"{unit = tonne, dimension = Mass}
totalMassFlow = "0.005319148936170213"{unit = tonne_per_hr,
dimension = Mass_Flow}
unitProductMass = "2.0E-4"{unit = tonne, dimension = Mass}

<<block>>
ICD_Glass_Manufacturer.wasteMaterialOut : Mass_Flow
materialMassFlow = "2.0996640537513997E-4",
"6.998880179171333E-5"
materialsMass = "0.7894736842105263",
"0.2631578947368421"
residenceTime = "3760.0"{unit = hours, dimension = Time}
totalMass = "1.0526315789473684"{unit = tonne,
dimension = Mass}
totalMassFlow = "2.799552071668533E-4"{unit = tonne_per_hr,
dimension = Mass_Flow}

<<block>>
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materialMassFlow = "0.0041993281075028",
"0.0013997760358342665"
materialsMass = "15.789473684210526",
"5.2631578947368425"
residenceTime = "3760.0"{unit = hours, dimension = Time}
totalMass = "21.05263157894737"{unit = tonne,
dimension = Mass}
totalMassFlow = "0.005599104143337067"{
unit = tonne_per_hr, dimension = Mass_Flow}
```

Figure 31: Fully Populated Glass Manufacturer Instance Structure BDD

3.2.1 General Facility Block

The General Facility Block contains some parameters that are common to most facilities. The parameters include shiftOfLength, numberOfShifts, and daysOfOperation. The product of these three parameters represents the number of hours a facility operates per year (annualResidenceTime). This product is computed in the facility's PAR shown in Figure 32. The General Facility Block also contains a parameter totalAnnualFacilityEnergy which serves to store the aggregated process energy from the various processes contained in a facility.

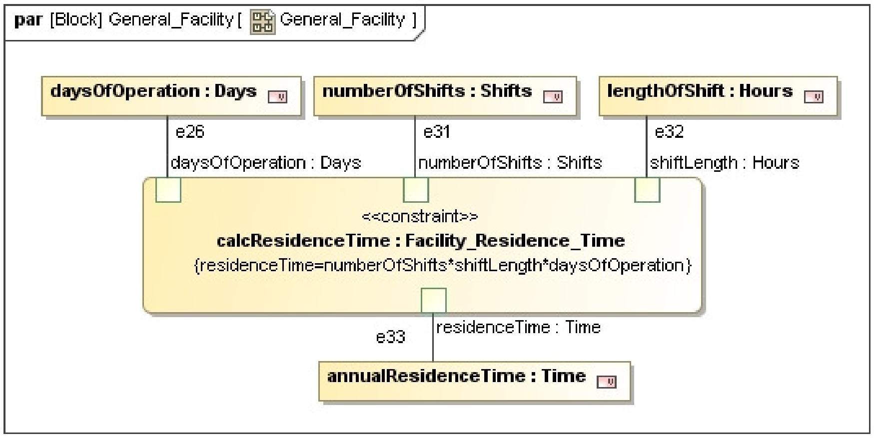


Figure 32: General Facility PAR

3.2.2 General Flow Process Block

Processes are characterized by their input as either a flow processes which have a mass flow as an input, or a product process which has a manufactured product as an input. The General Flow Process Block contains several parameters and calculations that are common to processes having a mass flow as an input; however, there is a nearly identical methodology for processes that have manufactured products as an input. The PAR describing the parameters and calculations can be seen in Figure 22.

Essentially, the General Flow Process Block calculates how much energy is consumed by a process in one of two ways. The energy can be computed based on the number of machines required to process a certain amount of input given a machine's power requirements. However, it is not uncommon for process energy consumption to be reported based on the amount of material processed. In this case, the total energy consumed by a process equal to the product of the specific process energy (energy per unit mass) and the amount of material processed.

From this description alone it is obvious that the General Flow Process Block is a necessary, but not sufficient specification of a process. In addition to specifying the input of a process, the process must also have at least one output. Therefore, there are many further specifications of the General Flow Process Block.

An example of a specialization of the General Flow Process Block is the Constructive Flow Process Block. The Constructive Flow Process Block adds two outputs to the General Flow Process Block: a mass flow to include inefficiencies in the process (wasteMassOut) and a manufactured product (productOut) to represent the desired output of the process. The transformation of the input mass flow into the output mass flow and manufactured product is represented in the PAR shown in Figure 33.

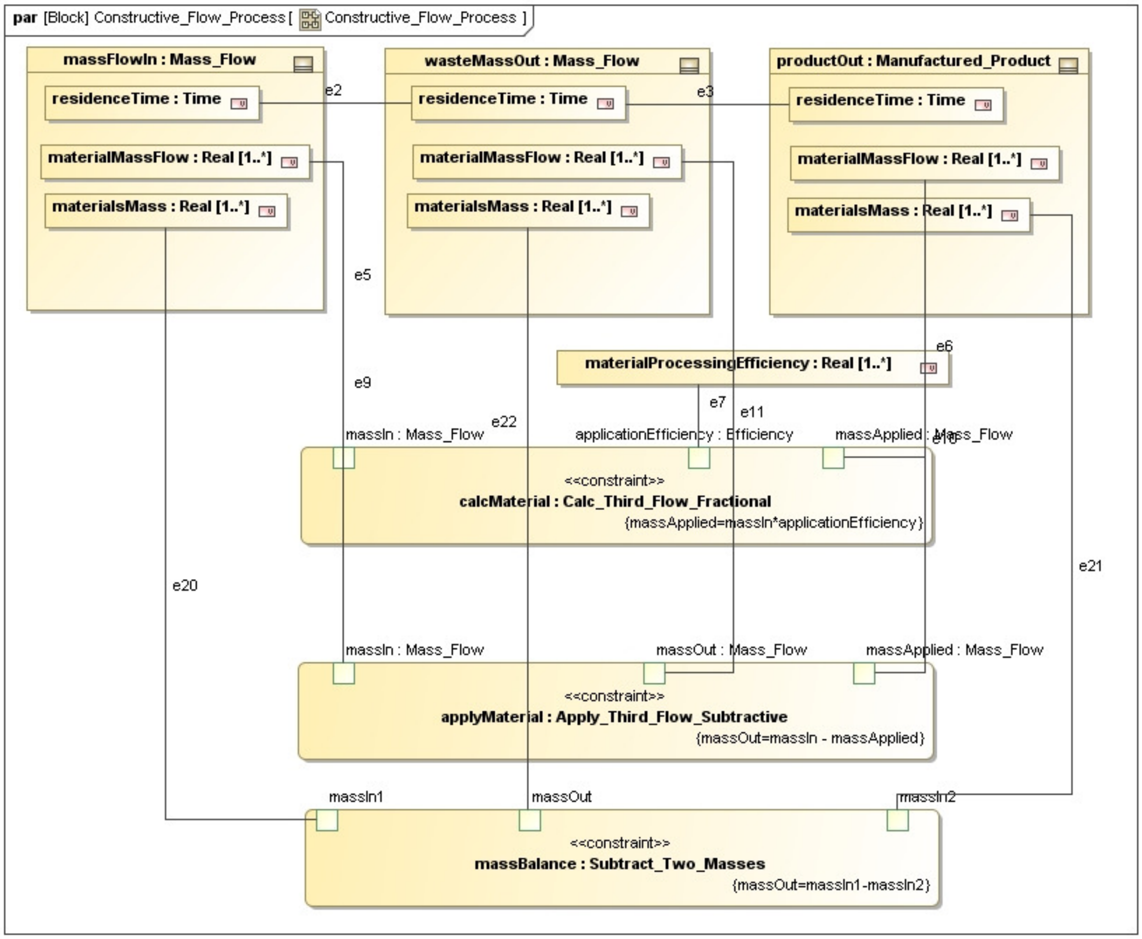


Figure 33: Constructive Flow Process PAR

Essentially, several constraints in the PAR divide the input flow into either a waste stream or into the final product based on some processing efficiency. This method of further specializing the General Flow Process Block can be repeated in a similar fashion to describe a vast number of processes with many different combinations of inputs and outputs. The beauty of this method is that each time a new process needs to be created, all the work of creating the energy calculations can be saved by simply specializing the General Flow Process Block. The BDD in Figure 34 shows several specializations of the General Flow Process Block. The five other specializations in the figure include: Fractional Additive Process which adds a material stream to the incoming flow proportional to the incoming flow but does not result in a manufactured product like the Constructive Process; Conservative process where no material is added or removed from the incoming stream; Fractional Subtractive Process which removes a portion of the incoming material proportional to the incoming flow; Unit Additive Process which adds a fixed amount of material to the incoming flow; and Unit Subtractive Process which subtracts a fixed amount of material from the incoming flow.

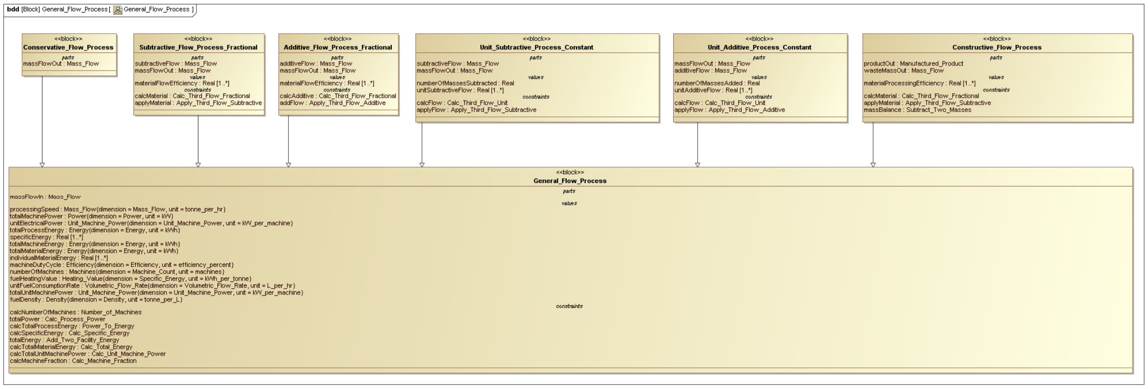


Figure 34: General Flow Process Block Specializations

CHAPTER 4: LIFE CYCLE NETOWRK OF LCD COMPUTER MONITORS

In the previous sections a model of LCD Glass Manufacturing was created, and while this serves as an adequate demonstration of modeling techniques and application, the purpose for creating such a large modeling schema is to apply it to large networks made of many facilities and processes. Therefore, to build on the previous example, the following sections will discuss modeling the life-cycle network in terms of the whole LCD monitor with respect to ferrous and non-ferrous metals, and plastics.

4.1 LCD Monitor Life Cycle

Before delving into each stage of the lifecycle individually, it is worth looking at the entire lifecycle. The entire lifecycle network of an LCD computer monitor can be seen in Figure 35.

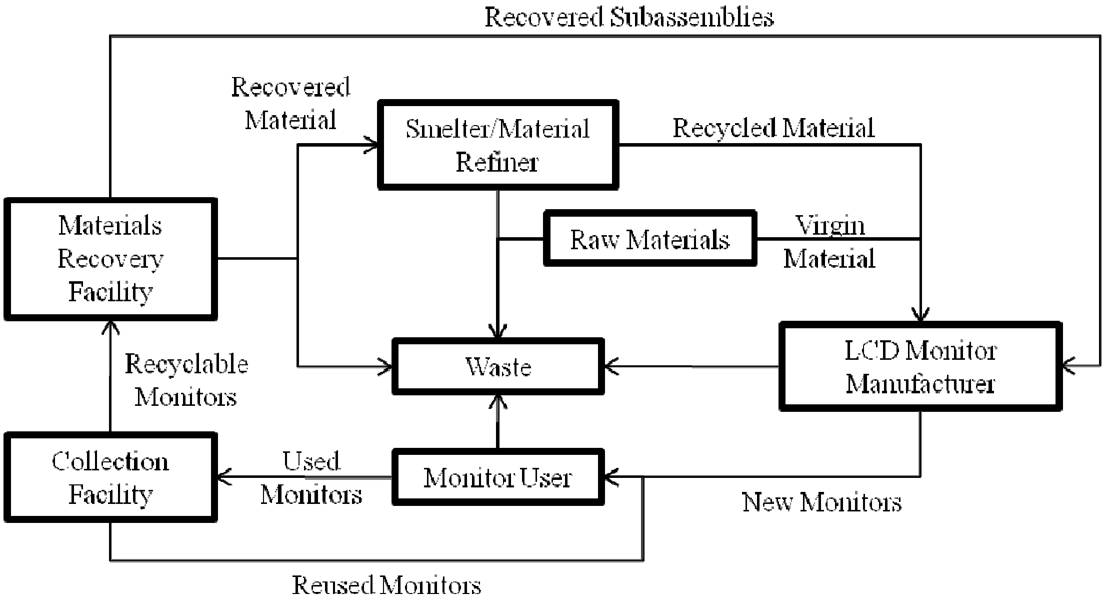


Figure 35: LCD Monitor Life Cycle Network

Beginning from the monitor user, it can be seen new and reused monitors enter the Use Phase. Once the user discards the monitor, it can either flow to the landfill (waste), or it can go to a collection facility. This begins the end of life scenario as described in Section 2.1. At the collection facility, monitors are determined to be either reusable or not reusable. Reusable monitors cycle back to the use phase and offset the production of new monitors, while the remaining monitors are sent to a materials recovery facility for recycling. At the materials recovery facility a portion of the monitors are disassembled and the reusable parts are sent back to the manufacturers to be put into new monitors. The rest of the monitors along with the remains of the disassembly are sent through a series of processes that shred and separate the monitors into its constituent groups, such as ferrous and non-ferrous metals, and plastics. The valuable recovered material is sent to a material refiner, and the low value material becomes waste. The material refiner sends the recovered material through a series of processes to purify the recovered materials into a form that is useable by manufacturers. This stream of recycled materials offsets the production of virgin materials from the raw material supplier. Both the material refiner and the raw material supplier create waste. This stream of materials then flows to the LCD monitor manufacturer where raw materials, remanufactured materials, and recovered subassemblies are processed and combined to create new LCD monitors, which in turn completes the traverse.

The material streams to be examined in this lifecycle network include: ferrous metals, non-ferrous metals, and plastic material. These materials are natural choices as they represent the majority of the value in electronic waste (Cui and Zhang 2008). Any materials that do not fit into these categories are aggregated into the “other” category.

This aggregation was necessary to simplify the model as there are many ancillary materials involved in the LCD monitor lifecycle. For a complete material breakdown of an LCD monitor see the data in APPENDIX C and APPENDIX D. The main consequence of neglecting these ancillary materials is that the impact of their production is neglected. Nevertheless, it is still important to keep track of the "other" category because many processes are dependent on the amount of material flowing through them, thus those processes will be affected by the amount of material in the "other" category.

4.2 Raw Material Refining

All products begin as raw materials that must be extracted from the ground and LCD monitors are no exception. Raw material refining was modeled based on information from the IdeMat database (Version 1.0.1.1). The IdeMat database contains energy and material data that encompasses all the activities needed to transform raw ore into a form usable by a manufacturer. Figure 36 depicts the transformation reported in IdeMat.

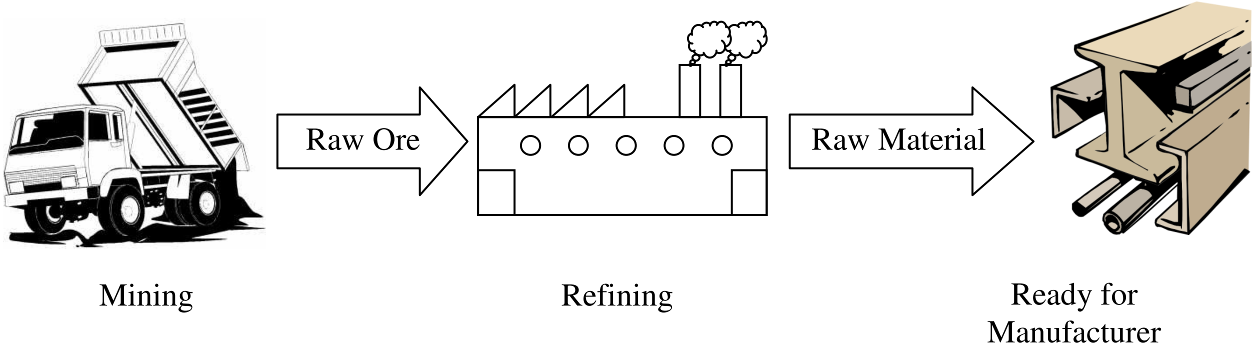


Figure 36: Raw Material Refining

With respect to LCD monitor manufacturing, Table 3 presents the gross amount of energy required to refine a unit of mass for each type of material needed. Standard low carbon steel was chosen for ferrous material, a weighted average of various non-ferrous metals was chosen for the non-ferrous group, and an average of polycarbonate and ABS were chosen for the plastic group. The "other" category contains the materials that do not fit into the three aforementioned groups. The "other" category is assumed to be primarily glass but it also contains the various other chemicals and raw materials, such as ceramics, epoxies, etc, involved in the life cycle in small amounts. Its production energy is chosen as zero first because glass making is considered in another part of the model, thus that energy is accounted for, but also because it is assumed that the "other" materials appear in relatively negligible amounts so their production is neglected. More information on the calculation of the values in Table 3 can be found in Section B.1.

Table 4 shows the material processing efficiency for converting raw, mined material into a product usable by manufacturers. Again in Table 4 since glass manufacturing is considered later in the model and because of the negligible effect of the remaining materials, no inefficiency is accounted for the other category and the material throughput efficiency is 100%.

Table 3: Raw Material Refining Specific Energy by Material (IdeMat V 1.0.1.1 2001)

Material Refining Specific Energy	**IdeMat Value**
Ferrous Metal	1,984 kWh/tonne (7.142 MJ/kg)
Non-Ferrous Metal*	498 kWh/tonne (1.793 MJ/kg)
Plastic*	261 kWh/tonne (0.9396MJ/kg)

Material Refining Specific Energy	**IdeMat Value**
Other	0 kWh/tonne (0 MJ/kg)

* See Section B.1

Table 4: Raw Material Refining Process Efficiency (Mass Throughput) (IdeMat V 1.0.1.1 2001)

Material Refining Efficiency	**IdeMat Value**
Ferrous Metal	32.7 %
Non-Ferrous Metal	1.67 %
Plastic	1.32 %
Other	100 %

To validate the data in Table 3 and Table 4, the American Iron and Steel Institute reported that it requires 12.6 million BTU to manufacture one ton of steel (14.7 MJ/kg) (American Iron and Steel Institute 2005). Since the specific energies in Table 3 are based on the input material rather than the output material, dividing specific energy in Table 3 by the material throughput efficiency in Table 4 yields a value of 21.8 MJ/kg. Similarly for Non-Ferrous metals, it is reported that producing one tonne of aluminum requires 40200 kWh of energy (145 MJ/kg) (U.S. Department of Energy 2007). Recalling that non-ferrous metals are a mix of metals, the value given by IdeMat for aluminum in Section B.1 is 148 MJ/kg. With regard to plastics, a range of energy values is given from 76.2 MJ/kg in (Hischier 2007) to 111.4 MJ/kg in (Boustead 1997) for polycarbonate, which can be compared to the energy value given in Section B.1 of 71.32 MJ/kg. Thus, it can be seen that the values in Table 3 and Table 4 are within an acceptable margin of comparison to other data sources.

4.3 Manufacturing

In Figure 35 above representing the lifecycle network of an LCD computer monitor, the manufacturing stage was shown as a single block. The following sections delve deeper into that block in terms of the manufacturing processes required to make the individual subassemblies associated with an LCD monitor as defined by EcoInvent in (Hischier, Classen et al. 2007). These subassemblies include a backlight, the panel components, and the glass, which combine to form an LCD module subassembly. The LCD module is the main subassembly in the final monitor assembly. The following sections address each stage in the monitor manufacturing process.

4.3.1 LCD Glass Manufacturing

LCD glass manufacturing data was obtained from EcoInvent (Hischier, Classen et al. 2007) and an EPA LCA on LCD computer monitors (Socolof, Overly et al. 2001). The data is available in 0 and APPENDIX D. According to the studies the process of creating an LCD glass assembly requires “preparation and sorting of cullet, melting, forming of LCD flat glass parts, cooling down and palleting until the glass parts are ready.”

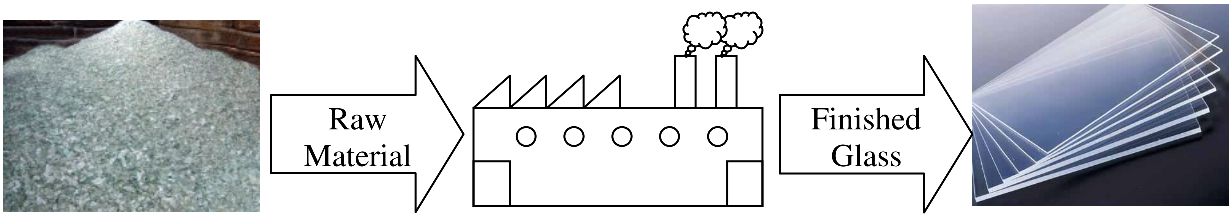


Figure 37: Glass Manufacturer

Specific information as to the machinery required to create glass assemblies was not available in the LCI; however, information on the specific energy of the entire process was calculated based on the material and energy inputs described in the report. Due a lack of more specific information the most conservative estimate for processing efficiency was chosen. The model parameters for the process of manufacturing an LCD glass assembly can be seen in Table 5. The material specifications of an individual LCD glass assembly can be seen in Table 6.

Table 5: LCD Glass Manufacturing Process Parameters (Hischier, Classen et al. 2007)

Model Parameter	**Value**
Specific Energy	418,003 kWh/tonne (1,504 MJ/kg)
Material Processing Efficiency (Mass Throughput)	100 %

Table 6: Manufactured LCD Glass Specifications (Hischier, Classen et al. 2007)

Product Specifications	**Value**
Ferrous Metal Fraction	0 %
Non-Ferrous Metal Fraction	0 %
Plastic Fraction	0 %
Other Fraction	100 %
Product Mass	0.000475 tonne (0.475 kg)

4.3.2 LCD Backlight Manufacturing

An LCD Backlight Assembly is composed of four main parts: a lamp provides the light source, a diffusion system ensures uniform light dispersion, a reflection sheet to reflect the light in the direction of the LCD, and a frame which holds all of these parts in place. Figure 38 shows an exploded view of a backlight assembly.

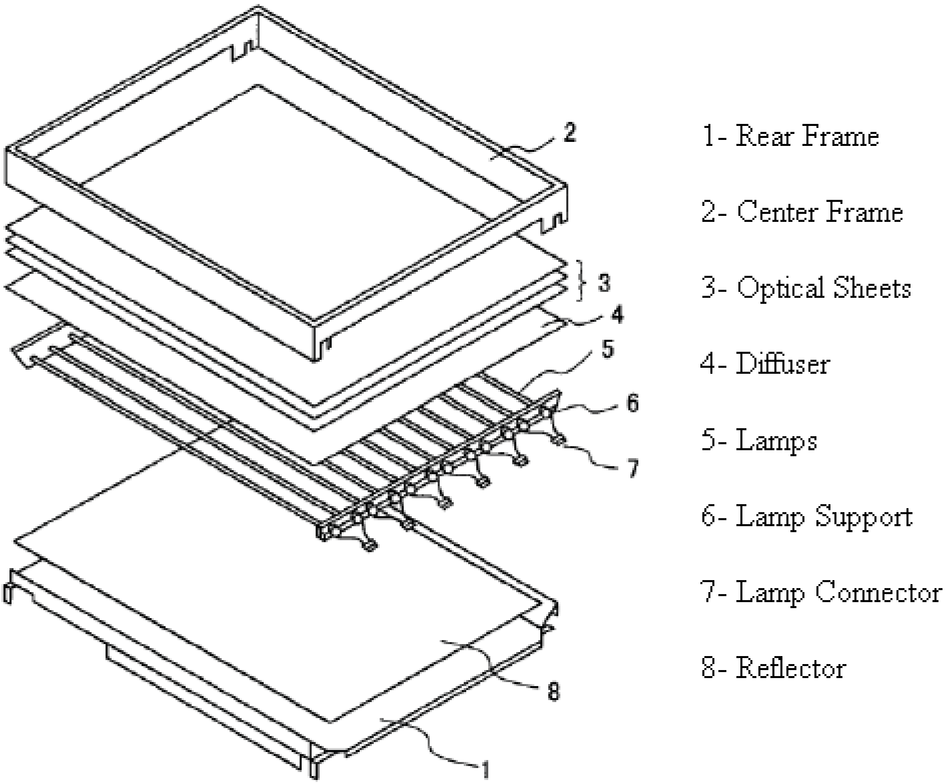


Figure 38: Backlight Assembly (Hischier, Classen et al. 2007)

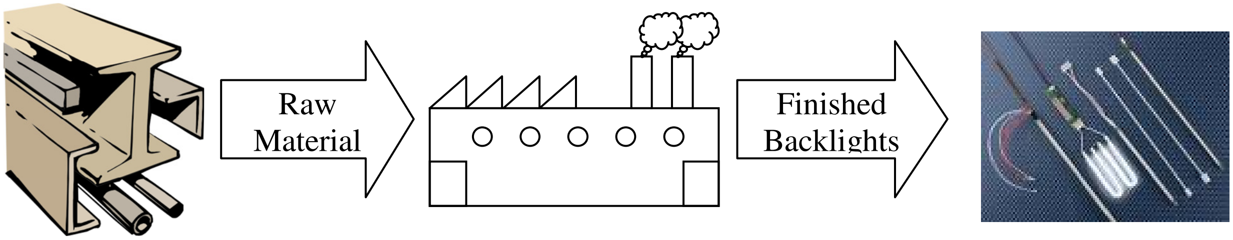


Figure 39: Backlight Manufacturer

Specific information regarding the manufacture of LCD Backlight Assemblies was obtained from EcoInvent (Hischier, Classen et al. 2007) and an EPA LCA on LCD computer monitors (Socolof, Overly et al. 2001). Specific information on the equipment used to manufacture LCD backlights was not available in the studies; however, information on the specific energy of the entire process was calculated based on the material and energy inputs described in the report. Material processing efficiency was also calculated based on the inputs and outputs described in the report. Table 7 describes the model parameters for the manufacture of LCD backlights, while Table 8 describes the backlight's material specifications as relevant to the model.

Table 7: LCD Backlight Manufacturing Process Parameters

Model Parameter	**Value**
Specific Energy	1,227 kWh/tonne (4.417 MJ/kg)
Material Processing Efficiency (Mass Throughput)	68.9 %

Table 8: Manufactured LCD Backlight Specifications

Product Specifications	**Value**
Ferrous Metal Fraction	2.5 %
Non-Ferrous Metal Fraction	3.6744 %
Plastic Fraction	37.4656 %
Other Fraction	56.36 %
Product Mass	0.000689 tonne (0.689 kg)

4.3.3 LCD Panel Component Manufacturing

The LCD Panel Component Assembly consists of the polarizer, color filters, and liquid crystals. A simplified representation is shown in Figure 40, which represents an

LCD seven segment display. A similar assembly for an LCD computer monitor is more complicated; however, it uses similar principles.

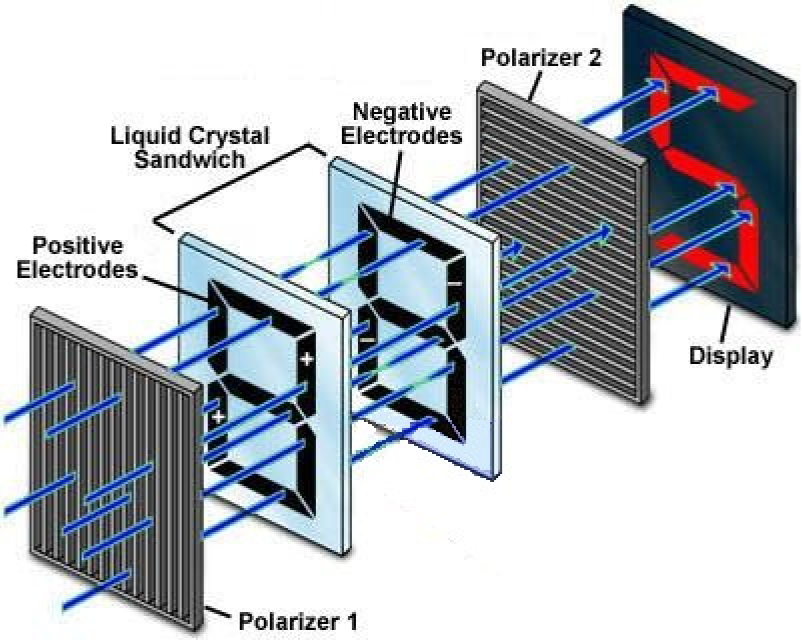


Figure 40: Simplified Panel Components Assembly

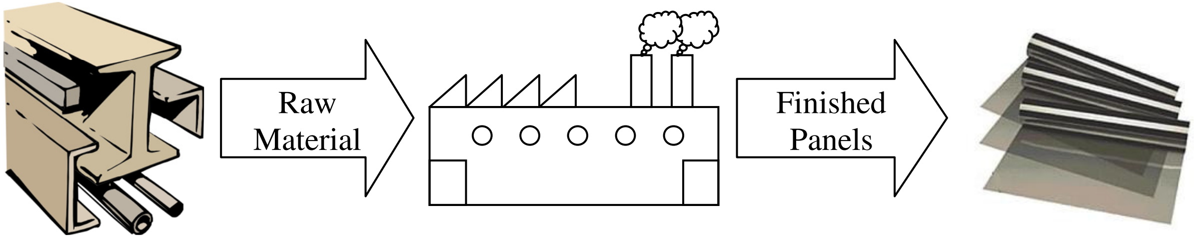


Figure 41: Panel Components Manufacture

The data for the manufacture of the LCD Panel Components was taken from EcoInvent (Hischier, Classen et al. 2007) and an EPA LCA on LCD computer monitors (Socolof, Overly et al. 2001). The data is available in 0 and APPENDIX D. Specific information on the equipment used to manufacture LCD Panel Components was not available in the studies; however, information on the specific energy of the entire process was calculated based on the material and energy inputs described in the report. Material processing efficiency was also calculated based on the inputs and outputs described in the report. Table 9 describes the model parameters for the manufacture of LCD panel components, while Table 10 describes the panel components' material specifications as relevant to this example model.

Table 9: LCD Panel Component Process Parameters

Model Parameter	**Value**
Specific Energy	55,414 kWh/tonne (199.5 MJ/kg)
Material Processing Efficiency (Mass Throughput)	0.2152 %

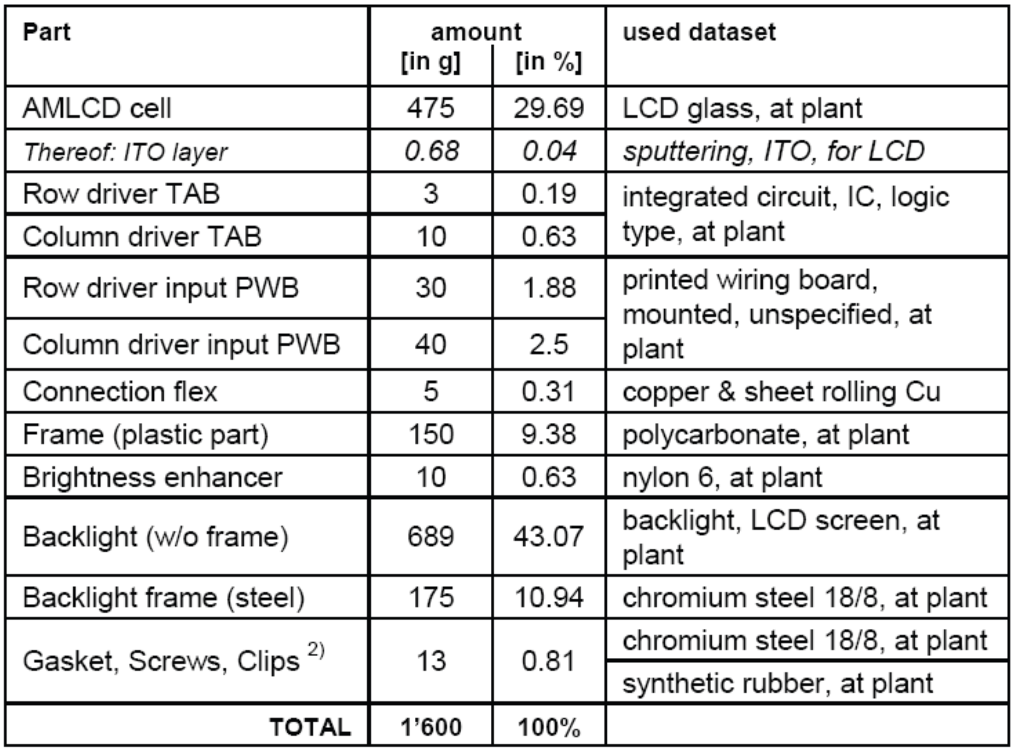
Table 10: Manufactured LCD Panel Component Specifications

Product Specifications	**Value**
Ferrous Metal Fraction	0 %
Non-Ferrous Metal Fraction	0 %
Plastic Fraction	0 %
Other Fraction	100 %
Product Mass	0.00000068 tonne (0.00068 kg)

4.3.4 LCD Module Manufacturing

An LCD module is taken as the assembly of a backlight assembly, a glass assembly, and a panel component assembly as described in the previous sections. In addition to the assemblies, a module also contains a frame, fasteners, connectors and printed wiring boards as detailed in Table 11. A simple representation of LCD module assembly process can be seen in Figure 42.

Table 11: EcoInvent LCD Module Component List



Part	**amount** **[in g]**	 **[in %]**	**used dataset**
AMLCD cell	475	29.69	LCD glass, at plant
Thereof: ITO layer	*0.68*	*0.04*	*sputtering, ITO, for LCD*
Row driver TAB	3	0.19	integrated circuit, IC, logic type, at plant
Column driver TAB	10	0.63	
Row driver input PWB	30	1.88	printed wiring board, mounted, unspecified, at plant
Column driver input PWB	40	2.5	
Connection flex	5	0.31	copper & sheet rolling Cu
Frame (plastic part)	150	9.38	polycarbonate, at plant
Brightness enhancer	10	0.63	nylon 6, at plant
Backlight (w/o frame)	689	43.07	backlight, LCD screen, at plant
Backlight frame (steel)	175	10.94	chromium steel 18/8, at plant
Gasket, Screws, Clips [2)]	13	0.81	chromium steel 18/8, at plant synthetic rubber, at plant
TOTAL	**1’600**	**100%**	

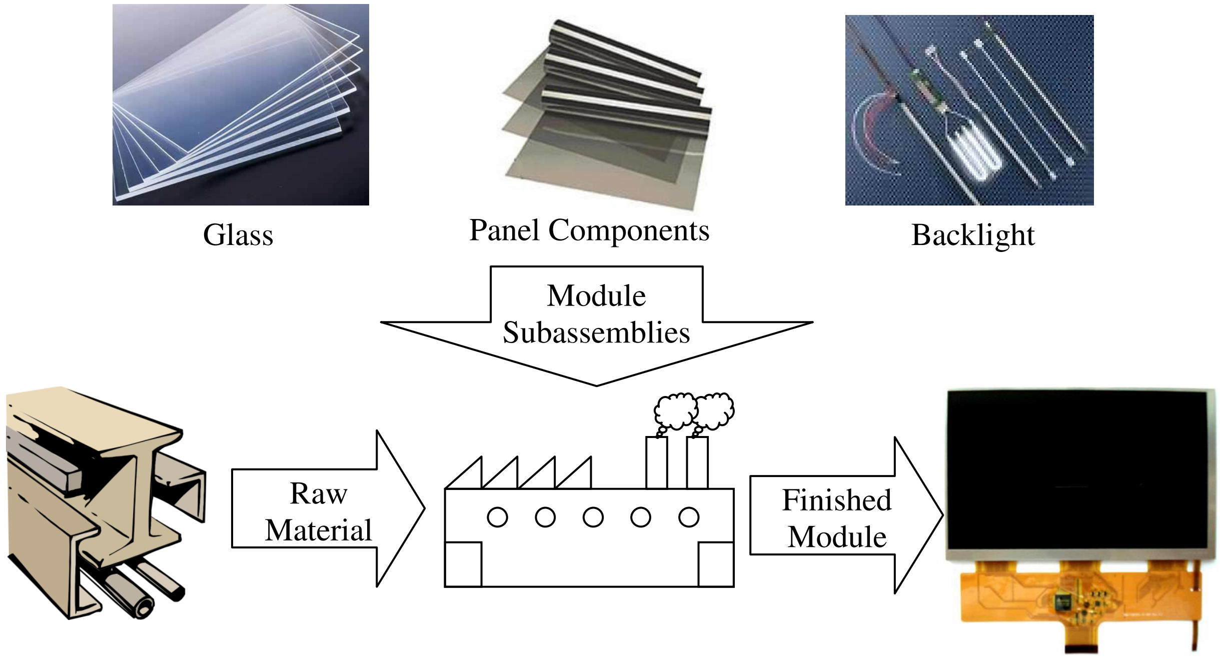


Figure 42: LCD Module Manufacturer

Information on the manufacturing process used to create an LCD module is taken from EcoInvent (Hischier, Classen et al. 2007) and an EPA LCA on LCD computer monitors (Socolof, Overly et al. 2001). The data is available in 0 and APPENDIX D. Specific information on the equipment used to manufacture LCD modules was not available in the studies; however, information on the specific energy of the entire process was calculated based on the material and energy inputs described in the report. Due to lack of more detailed information material processing efficiency was assumed to be the most conservative estimate. Table 12 describes the model parameters for the manufacture of LCD modules, while Table 13 describes the LCD module's material specifications as relevant to the model.

Table 12: LCD Module Manufacturing Process Parameters

Model Parameter	Value
Specific Energy	87,559 kWh/tonne (315.2 MJ/kg)
Material Processing Efficiency (Mass Throughput)	100 %

Table 13: Manufactured LCD Module Specifications

Product Specifications	Value
Ferrous Metal Fraction	12.821 %
Non-Ferrous Metal Fraction	2.187 %
Plastic Fraction	26.122 %
Other Fraction	58.87 %
Product Mass	0.0016 tonne (1.6 kg)

4.3.5 LCD Monitor Manufacturing

An LCD monitor is assumed to be made by assembling an LCD module with a frame, some circuitry, connectors, and hardware. A basic representation of the facility can be seen in Figure 43.

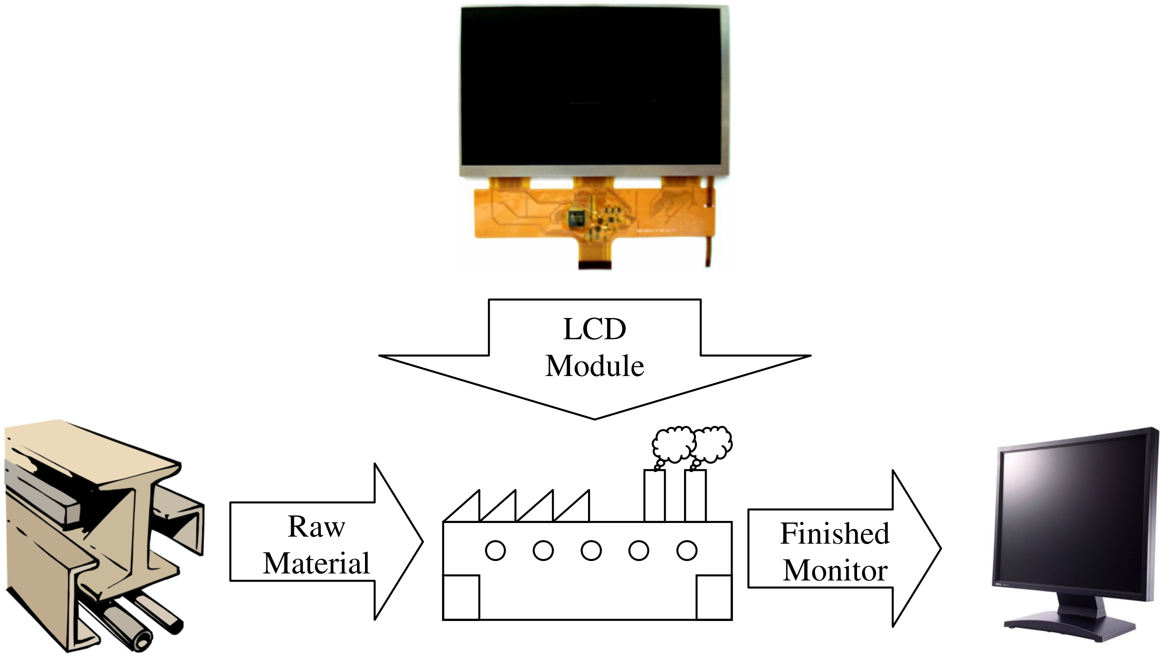


Figure 43: LCD Monitor Manufacturer

Information on the manufacturing process used to create an LCD monitor is taken from EcoInvent (Hischier, Classen et al. 2007) and an EPA LCA on LCD computer monitors (Socolof, Overly et al. 2001). The data is available in 0 and APPENDIX D. Specific information on the equipment used to manufacture LCD monitors was not available in the studies; however, information on the specific energy of the entire process was calculated based on the material and energy inputs described in the report. Due to lack of more detailed information material processing efficiency was assumed to be the most conservative estimate. Table 14 describes the model parameters for the manufacture of LCD monitors, while Table 15 describes the LCD monitor's material specifications as relevant to the model.

Table 14: LCD Monitor Manufacturing Process Parameters

Model Parameter	Value
Specific Energy	9,722 kWh/tonne (35.0 MJ/kg)
Material Processing Efficiency (Mass Throughput)	100 %

Table 15: Manufactured LCD Monitor Specifications

Product Specifications	Value
Ferrous Metal Fraction	44.12 %
Non-Ferrous Metal Fraction	3.00 %
Plastic Fraction	30.98 %
Other Fraction	21.9 %
Product Mass	0.00573 tonne (5.73 kg)

4.3.6 Manufacturing Validation

To validate the manufacturing parameters given above, the energy required to manufacture a single LCD computer monitor can be calculated and compared to other studies. The total energy required to manufacture an LCD computer monitor based on the above parameters is given in the bottom row of Table 16. The last column in the table represents the total energy consumed by each stage in the manufacture of an LCD monitor from the lowest subassembly as defined in the previous sections to final assembly of the monitor. To calculate the total energy per stage, simply divide the specific energy by the material throughput efficiency and then multiply by the mass of each subassembly. The bottom row of the table is the sum of the last column. This value can be compared to an EPA study which reported a total manufacturing energy for a similar LCD computer monitor to be 1440 MJ (Socolof, Overly et al. 2001). Compared to the value in Table 16 of 1486 MJ, the two values are in good agreement.

Table 16: Energy Required to Manufacture an LCD Monitor

Assembly Name	**Specific Energy to Create kWh/tonne (MJ/kg)**	**Material Throughput Efficiency**	**Assembly Mass tonne (kg)**	**Total Creation Energy kWh (MJ)**
Glass Panel	418,003 (1504)	100 %	0.000475 (0.475)	198.6 (715.0)
Backlight	1,227 (4.417)	68.9 %	0.000689 (0.689)	1.227 (4.417)
Panel Components	55,414 (199.5)	0.2152 %	0.00000068 (0.00068)	0.175 (0.630)
LCD Module	87,559 (315.2)	100 %	0.0016 (1.6)	140.1 (504.3)
LCD Monitor	9,722 (35.0)	100 %	0.00573 (5.73)	55.71 (200.5)
			Total	413 (1486)

4.4 Use

Data for the Use Phase of the LCD monitors life is taken from an EPA LCA (Socolof, Overly et al. 2001). For this example model the use was assumed to be “home” use. The average monitor power is based on a full power mode of 0.040 kW and a low power mode of 0.006 kW. The life span of the monitor is assumed to be 3.25 years of which full power mode is used for 522 hr/yr and low power mode is used 793 hr/yr. Combining these assumptions leads to the average monitor usage values in Table 17. The flow of monitors through the use phase can be seen in Figure 44.

The lifespan of 3.25 years was taken as half of the computer’s useful life as defined by (Socolof, Overly et al. 2001). This assumption facilitates the possibility of a secondary use phase; however, although there is the possibility of a secondary use phase, many monitors will either be improperly disposed of into a landfill or stored in homes (Matthews 1997; European Commission DG TREN 2007).

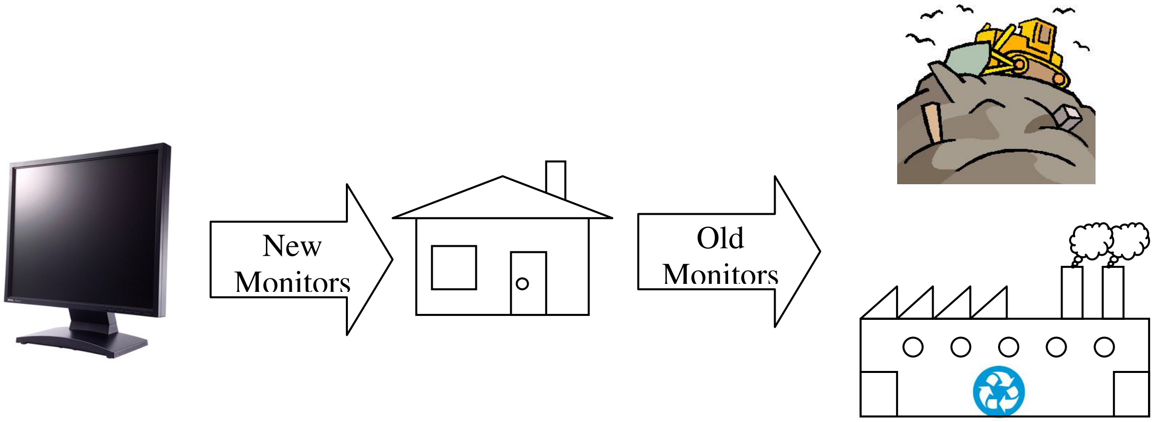


Figure 44: Monitor Use

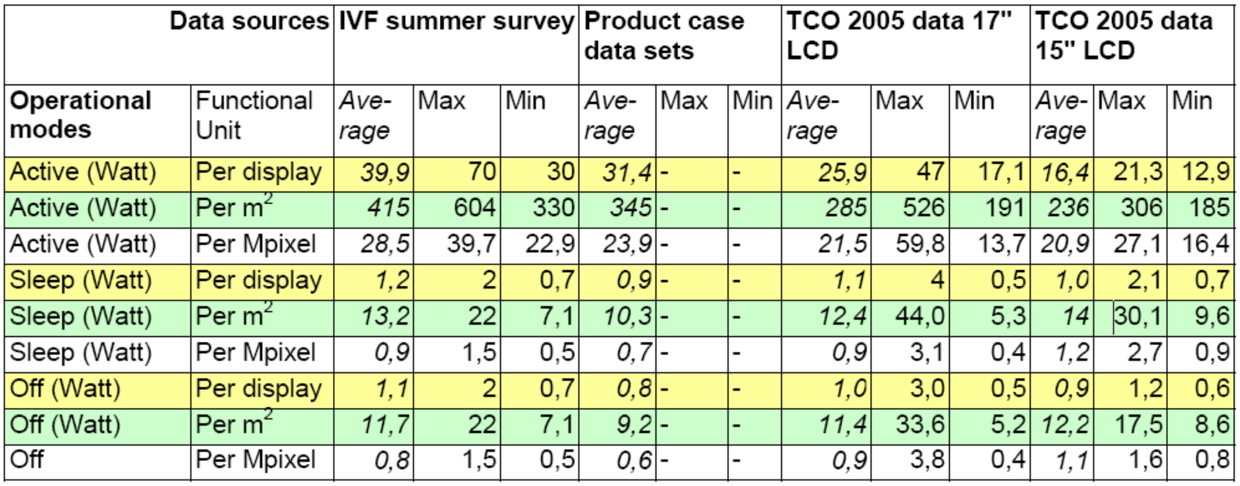
Table 17: LCD Monitor Usage Parameters (Socolof, Overly et al. 2001)

Model Parameter	**Value**
Average Monitor Power	0.0195 kW
Average Monitor Use Over Lifespan	4,273 hr (~0.5 years)

To validate the parameters in Table 17, the values can be compared to those reported by other studies. For example, Table 18 presents LCD computer monitor power estimates from various studies. It is clear from the table that there are several functional units being proposed to estimate power consumption. For simplicity's sake, Table 18 reports that on a per monitor basis the power consumption of an LCD computer monitor is between 0.0171 and 0.047 kW in active mode, and 0.0005 and 0.004 in sleep mode.

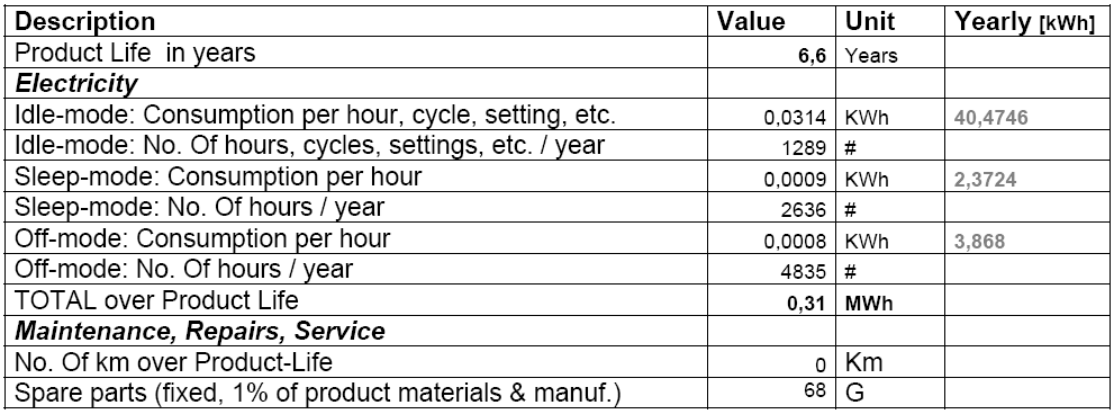
Based on these ranges, the estimates given above are within acceptable agreement. With respect to the usage profiles, the above data can be compared to those given by Table 19. Accounting for the difference in yearly lifespan, the data from (European Commission DG TREN 2007) calculates an annual energy usage of 47 kWh/yr. Using the parameters in Table 17, the annual energy usage of 26 kWh/yr. Overall these values agree relatively well, as it is quite difficult to determine an average usage profile of all LCD computer monitor users.

Table 18: LCD Power Consumption from Various Sources Compiled by (European Commission DG TREN 2007)



	Data sources	**IVF summer survey**			**Product case data sets**			**TCO 2005 data 17" LCD**			**TCO 2005 data 15" LCD**		
Operational modes	Functional Unit	*Ave-rage*	Max	Min	*Ave-rage*	Max	Min	*Ave-rage*	Max	Min	*Ave-rage*	Max	Min
Active (Watt)	Per display	*39,9*	70	30	*31,4*	-	-	*25,9*	47	17,1	*16,4*	21,3	12,9
Active (Watt)	Per m^2	*415*	604	330	*345*	-	-	*285*	526	191	*236*	306	185
Active (Watt)	Per Mpixel	*28,5*	39,7	22,9	*23,9*	-	-	*21,5*	59,8	13,7	*20,9*	27,1	16,4
Sleep (Watt)	Per display	*1,2*	2	0,7	*0,9*	-	-	*1,1*	4	0,5	*1,0*	2,1	0,7
Sleep (Watt)	Per m^2	*13,2*	22	7,1	*10,3*	-	-	*12,4*	44,0	5,3	*14*	30,1	9,6
Sleep (Watt)	Per Mpixel	*0,9*	1,5	0,5	*0,7*	-	-	*0,9*	3,1	0,4	*1,2*	2,7	0,9
Off (Watt)	Per display	*1,1*	2	0,7	*0,8*	-	-	*1,0*	3,0	0,5	*0,9*	1,2	0,6
Off (Watt)	Per m^2	*11,7*	22	7,1	*9,2*	-	-	*11,4*	33,6	5,2	*12,2*	17,5	8,6
Off	Per Mpixel	*0,8*	1,5	0,5	*0,6*	-	-	*0,9*	3,8	0,4	*1,1*	1,6	0,8

Table 19: LCD Power Consumption as Described by (European Commission DG TREN 2007)



Description	**Value**	**Unit**	**Yearly [kWh]**
Product Life in years	**6,6**	Years	
Electricity			
Idle-mode: Consumption per hour, cycle, setting, etc.	0,0314	KWh	40,4746
Idle-mode: No. Of hours, cycles, settings, etc. / year	1289	#	
Sleep-mode: Consumption per hour	0,0009	KWh	2,3724
Sleep-mode: No. Of hours / year	2636	#	
Off-mode: Consumption per hour	0,0008	KWh	3,868
Off-mode: No. Of hours / year	4835	#	
TOTAL over Product Life	**0,31**	**MWh**	
Maintenance, Repairs, Service			
No. Of km over Product-Life	0	Km	
Spare parts (fixed, 1% of product materials & manuf.)	68	G	

4.5 End of Life

4.5.1 Collection Facility

The collection facility serves to sort discarded monitors into reusable and non-reusable monitors. Reusable monitors are sent back to users, while non-reusable monitors are sent to the materials recovery facility. For the purposes of this work, no energy or waste is generated at the collection facility; it merely serves to direct the flow of monitors between the user and the materials recovery facility.

4.5.2 Materials Recovery Facility

Once a computer has reached the end of its useful life and escapes the fate of the landfill, this example model assumes that it must enter a recycling facility. The goal of the recycling facility, or materials recovery facility (MRF), is to harvest any useful subassemblies from the monitor, which can be sent back to the manufacturer, and then process what remains after that harvest into a form that can be more easily converted back into useful materials by a smelter or other appropriate material processor.

The essential flow of material through an MRF can be seen in Figure 45 as described by (Kang and Schoenung 2005). The process begins with computer monitors entering the facility which are then transported about by a front end loader to the disassembly area. There workers disassemble monitors with the assistance of air powered tools. Once the useful assemblies are removed, the remaining monitor pieces are sized reduced into a fine particulate. To ensure the particulate is of the appropriate size a screening operation follows the size reduction. Next the particulate flows through a magnetic separation process to remove ferrous material. The ferrous removal is followed by the removal of non-magnetic, charge conducting materials. In practice this is the removal of non-ferrous metals. The last separation process is carried out by a density separator which removes valuable plastics from the mix. After density separation, the material remaining is a result of the inefficiencies of the previous processes and non-metals that are non-conductive, which are assumed to be sent to the landfill. Each group of separated material passes through a material packaging device known as a baler which prepares the materials for transport to their next destination.

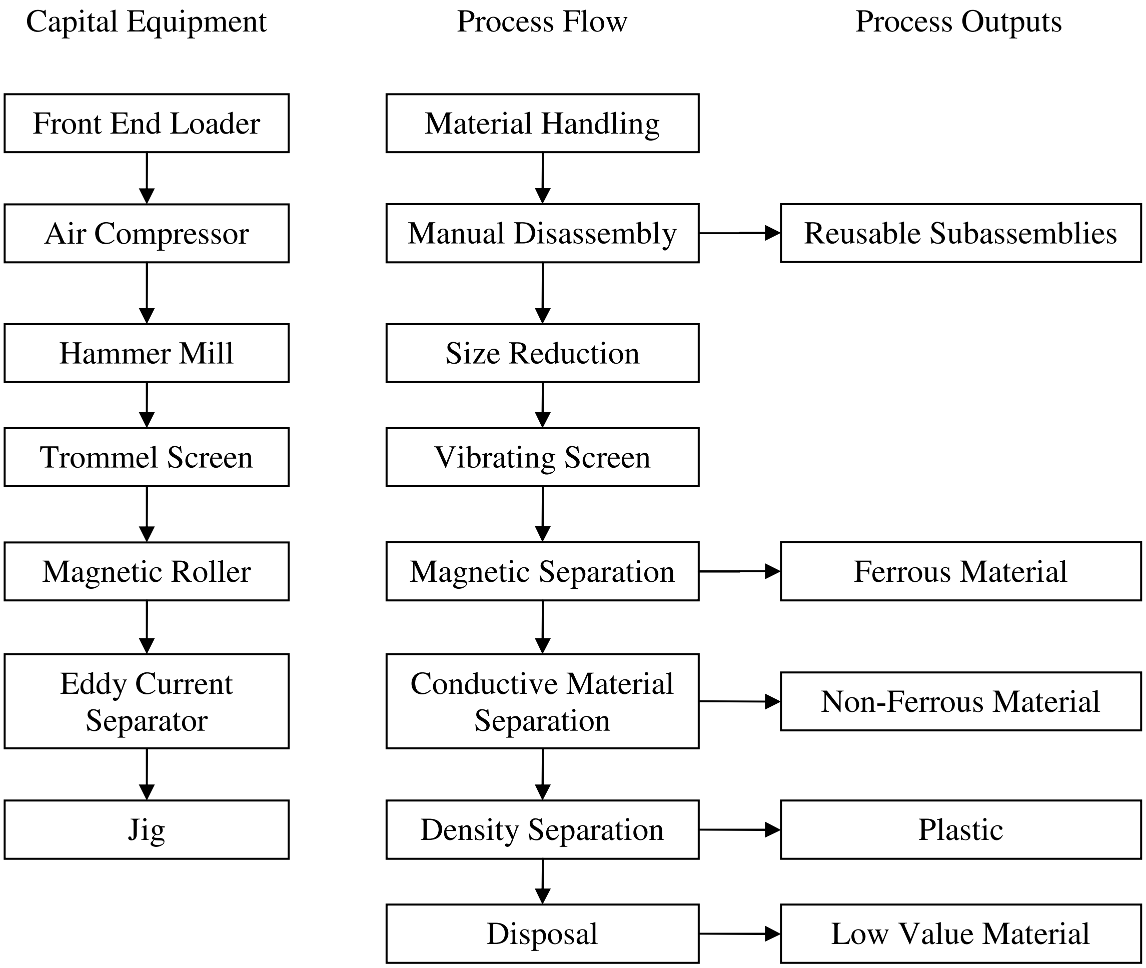


Figure 45: MRF Flow of Operations and Material

A detailed description of technologies that are used in a MRF can be found in APPENDIX A. In Figure 45, an appropriate piece equipment for each process is selected on the left. Looking below in Table 20 through Table 27, the relevant equipment specifications for each machine can be found. The machine specifications are taken from an LCA which was carried out on MRF management (Noon 2009).

Table 20: Front End Loader (Noon 2009)

Model Parameter	Value
Fuel Density	0.000085 tonne/L (0.085 kg/L)
Fuel Heating Value	12,750 kWh/tonne (45.9 MJ/kg)
Fuel Consumption Rate	1.137 L/hr
Processing Speed	1.36 tonne/hr (1360 kg/hr)

Table 21: Manual Disassembly (Air Compressor) (Noon 2009)

Model Parameter	Value
Processing Speed	17.87 tonne/hr (17,870 kg/hr)
Specific Energy	0.726 kWh/tonne (2.613 kJ/kg)
Electrical Power Per Machine	307 kW

Table 22: Hammer Mill (Noon 2009)

Model Parameter	Value
Processing Speed	55 tonne/hr (55,000 kg/hr)
Electrical Power Per Machine	175 kW

Table 23: Trommel Screen (Noon 2009)

Model Parameter	Value
Processing Speed	499 tonne/hr (499,000 kg/hr)
Electrical Power Per Machine	52.7 kW

Table 24: Magnetic Separator (Noon 2009)

Model Parameter	**Value**
Processing Speed	2936 tonne/hr (2,936,000 kg/hr)
Electrical Power Per Machine	0.824 kW

Table 25: Eddy Current Separation (Noon 2009)

Model Parameter	**Value**
Processing Speed	9.99 tonne/hr (9,990 kg/hr)
Electrical Power Per Machine	8.82 kW

Table 26: Density Separator (Noon 2009)

Model Parameter	**Value**
Processing Speed	72.64 tonne/hr (72,640 kg/hr)
Electrical Power Per Machine	8.82 kW

Table 27: Baler (Noon 2009)

Model Parameter	**Value**
Processing Speed	90.8 tonne/hr (90,800 kg/hr)
Electrical Power Per Machine	175.5 kW

4.5.3 Refining of Recovered Materials

A detailed description of refining recovered materials through various mechanical and metallurgical processes can be found in (Cui and Forssberg 2003; Antrekowitsch, Potesser et al. 2006; Veit, Bernardes et al. 2006; Cui and Zhang 2008; Oishi, Yaguchi et al. 2008). Typically the recovered metal particulate is passed through a series of furnaces to remove impurities and refine materials back into virgin materials. An example of this process given by (Antrekowitsch, Potesser et al. 2006) is shown in Figure 47. Plastic particulate normally goes through a series of identifying and characterizing processes to determine and separate polymers (Cui and Forssberg 2003). These processes are followed by pelletizing processes that return the polymers to a useable state for manufacturers. In addition to the recovery of polymers, it is also common practice to include them in the refining of the metal particulate, due to the fact their high caloric value aids in the combustion process (Antrekowitsch, Potesser et al. 2006); however, this process is not included in this work.

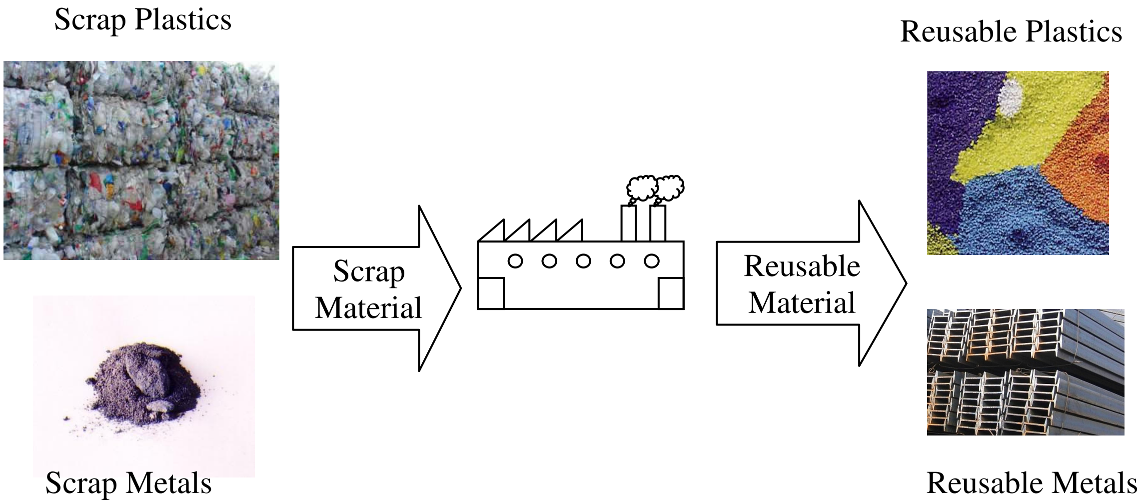


Figure 46: Recovered Material Refiner

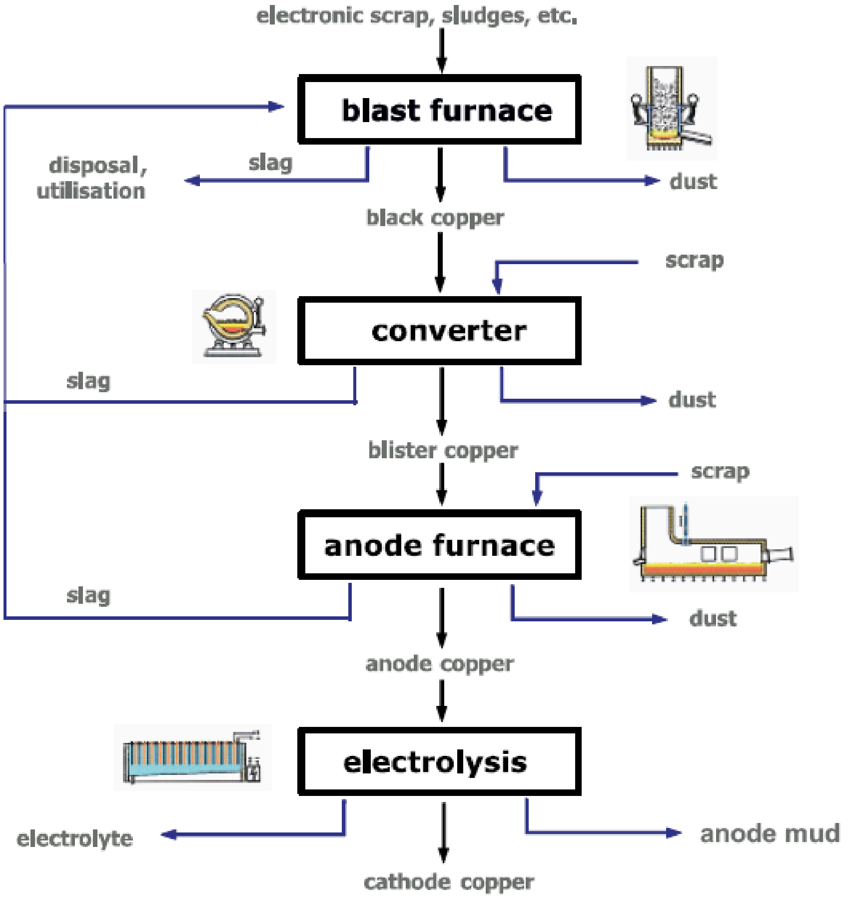


Figure 47: Recovered Material Refining

With respect to the material throughput efficiencies given in Table 29, data was obtained from an LCA given by (Noon 2009). These values represent the fraction of scrap entering a facility that is successfully converted into a reusable form. The energy consumed per unit mass of material entering the facility is given in Table 28. The energy values for the metal refining are obtained from an LCI on an Imperial Blast Furnace from EcoInvent (Sutter 2007). The energy values for plastic refining are based on information from MBA Polymers given by (EPA 2002).

Table 28: Recovered Material Refining Specific Energy by Material

Material Refining Specific Energy	IdeMat Value
Ferrous Metal	1,210 kWh/tonne (4.356 MJ/kg)
Non-Ferrous Metal	1,195 kWh/tonne (4.302 MJ/kg)
Plastic	26.15 kWh/tonne (0.09414 MJ/kg)
Other	0 kWh/tonne (0 MJ/kg)

Table 29: Recovered Material Refining Process Efficiency (Mass Throughput)

Material Refining Efficiency	IdeMat Value
Ferrous Metal	0.84 %
Non-Ferrous Metal	0.83 %
Plastic	0.84 %
Other	0 %

For comparison, accounting for the material throughput efficiency in ferrous material, based on the data in Table 28 and Table 29 the energy per unit mass required to recycle ferrous material is 1440 kWh/tonne (5.184 MJ/kg) (based on energy per unit mass of output rather than on unit mass input). It is estimated that 74% of the energy required to produce a unit mass of steel can be saved by recycling (Oberlin College 2001). Accounting for the material throughput efficiency in the of production raw materials from Table 3 and Table 4 above, the energy per unit mass to produce ferrous material is 6067 kWh/tonne (21.84 MJ/kg). Based on this production energy, a 74% energy savings would result in a recycling estimate of 1577 kWh/tonne (5.667 MJ/kg). This estimate is in good agreement with the data from Table 28 and Table 29.

A similar analysis can be performed for non-ferrous material. Although non-ferrous material is a mix of materials, looking at aluminum for a moment, it is estimated that it takes 5% of the energy to produce a unit mass of aluminum from recycling than it does to produce it from bauxite ore (Waste Online 2005). Based on the data in Table 28 and Table 29 the energy per unit mass required to recycle non-ferrous material is 1440 kWh/tonne (5.184 MJ/kg) (based on energy per unit mass of output rather than on unit mass input). Accounting for the material throughput efficiency in the of production raw materials from Table 3 and Table 4 above, the energy per unit mass to produce non-ferrous material is 29820 kWh/tonne (100.4 MJ/kg). Taking the ratio of recycling energy to raw production energy yields 4.82%, which is in good agreement with the estimate of 5%. Like aluminum, recycling copper takes only a fractional amount of the energy needed to refine the raw ore, approximately 15% (School Science 2010). Compared to 5%, 15% is still within reasonable tolerances. Therefore, since copper and aluminum make up the bulk of the non-ferrous category, as can be seen in Section B.1, the non-ferrous energy and material throughput values are assumed to be reasonable.

Lastly, with respect to plastics, one study found that recycling plastic can save between 59934 and 87877 kJ (59.934 - 87.877 MJ/kg) of energy per kg when plastic is recycled into the same material use (Morris 1996). Taking the parameters for production of raw materials from Table 3 and Table 4, the energy to produce plastic comes out to 19773 kWh/tonne (71.182 MJ/kg) (based on energy per unit mass of output rather than on unit mass input). Subtracting the range of energy saved from the study, the energy to recycle plastics should fall between -4637 and 3125 kWh/tonne (-16.693 – 11.25 MJ/kg). Since this energy is based on adding energy to the plastics to convert them into a usable form (not incineration), negative values are out of the question. However, the 10% estimate by MBA polymers which yielded a recycling energy of 26.1 kWh/tonne (0.09414 MJ/kg), does fall within this range and therefore is a reasonable estimate of the energy to recycle plastic.

4.6 LCD Computer Monitor Model Scenarios

Several example scenarios have been created to demonstrate the capabilities of this example model. The scenarios were created to demonstrate how different choices made throughout the product lifecycle by various stakeholders can affect the overall material and energy footprint of the lifecycle network.

4.6.1 Description of Scenarios

The following sections describe examples of the kinds of trade studies that can be carried out using the modeling methodology in this work. The model scenarios below combine the profiles of the stakeholders described above with some assumptions about their behaviors, which are described below. The result will be a material and energy usage footprint that can be compared to determine what changes should be made in the system to reduce these footprints.

4.6.1.1 Scenario 1

Scenario 1 represents a network with a generous amount of recycling. It assumes that monitor users send only 10% of discarded computers to a landfill and the rest flow to a collection facility. At the collection facility, 15% of the monitors are sent back to the users for a second life. The remaining 85% of computers from the collection facility are sent to a materials recovery facility. Once in the material recovery facility, no computers are disassembled; however, they are all mechanically processed by the MRF operations described in 4.5.2. The assumptions for user discard choices and processing are summarized in Table 30. After the MRF, the processed computers head to a material refiner where they are converted back into materials usable by manufacturers. The refined materials combine with virgin materials to meet the needs of monitor manufacturers, who in turn manufacture monitors to meet the needs of users who discarded their monitors previously. Compared to the general lifecycle in Figure 35, the lifecycle for Scenario 1 can be seen in Figure 48, where the dotted connections and italics represent connections that could exist but are eliminated for this scenario.

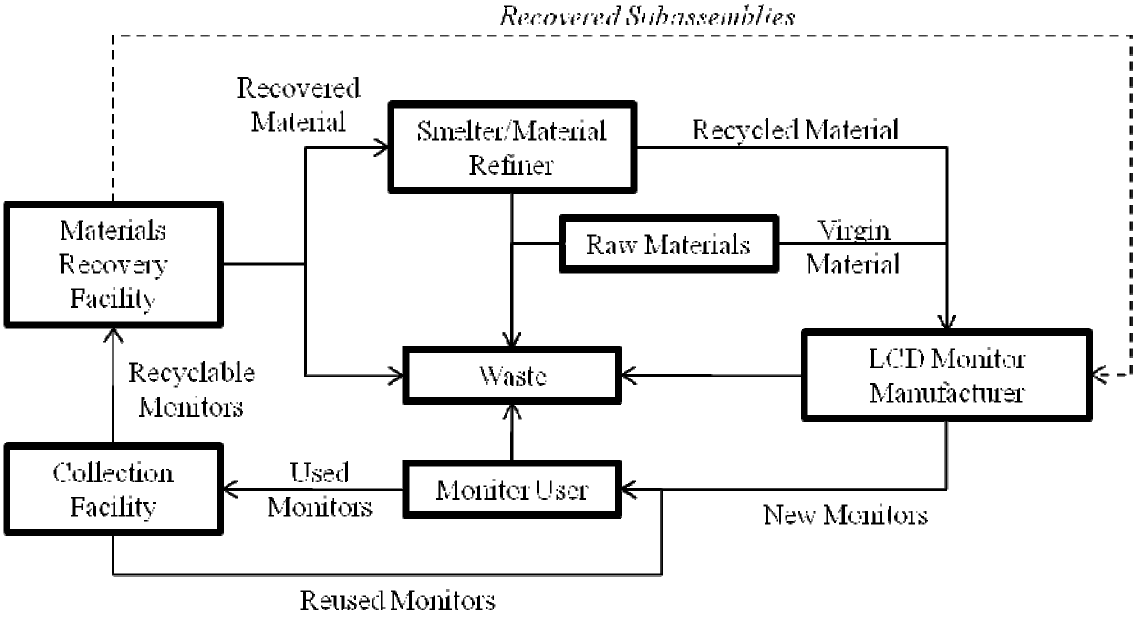


Figure 48: Lifecycle Network of Scenario 1

Table 30: LCD Computer Monitor Example, Scenario 1 Assumptions

Model Parameter	Value
Annual LCD Computer Monitors Discarded (Ai and French December 1, 2008)	350,000
Fraction of Discarded Monitors Landfilled	10%
Fraction of Discarded Monitors Reused	15%
MRF Recycling Operations (Material Recycling)	Yes
MRF Disassembly (Subassembly Reuse)	No

4.6.1.2 Scenario 2

Scenario 2 represents a network similar to that of Scenario 1. It assumes that monitor users send only 10% of discarded computers to a landfill and the rest flow to a collection facility. At the collection facility, 15% of the monitors are sent back to the users for a second life. The remaining 85% of computers from the collection facility are sent to a materials recovery facility. Once in the material recovery facility, the computer monitors are disassembled. It is assumed that 25% of LCD modules, glass panels, and backlights are recovered and sent back to the manufacturer for reuse. The rest of the disassembled monitors are all mechanically processed by the MRF operations described in 4.5.2. The assumptions for user discard choices and processing are summarized in Table 31. After the MRF, the processed computers head to a material refiner where they are converted back into materials usable by manufacturers. The refined materials combine with virgin materials to meet the needs of monitor manufacturers, who in turn manufacture monitors to meet the needs of users who discarded their monitors previously. Compared to the general lifecycle in Figure 35, the lifecycle for Scenario 2 is the same and can be seen in Figure 49.

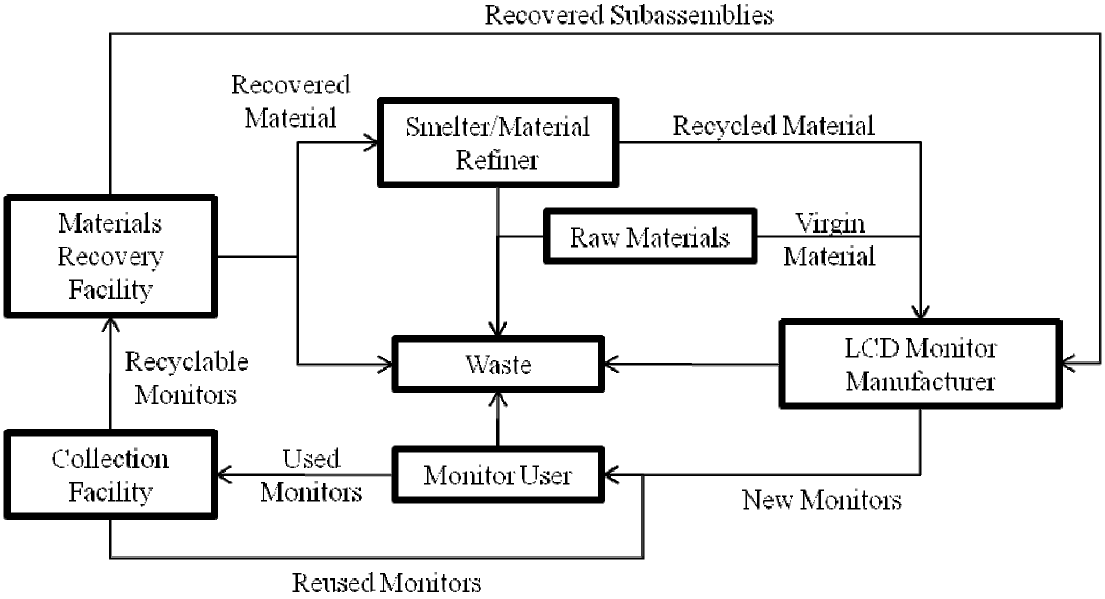


Figure 49: Lifecycle Network of Scenario 2

Table 31: LCD Computer Monitor Example, Scenario 2 Assumptions

Model Parameter	Value
Annual LCD Computer Monitors Discarded*	350000
Fraction of Discarded Monitors Landfilled	10%
Fraction of Discarded Monitors Reused	15%
MRF Recycling Operations (Material Recycling)	Yes
MRF Disassembly (Subassembly Reuse)	Yes**

* (Ai and French December 1, 2008)

**25% of LCD Modules, Backlights, Panel Components, and Glass

4.6.1.3 Scenario 3

Scenario 3 represents a network with non-existent recycling. It assumes that monitor users send all of their discarded computers to a landfill. This breaks all of the cycling loops that could occur later in the monitor's life. Thus the monitor manufacturer must rely solely on virgin materials to produce the monitors needed to replace those discarded by the user. Compared to the general lifecycle in Figure 35, the lifecycle for Scenario 3 can be seen in Figure 49 with dotted lines and italics representing paths and stakeholders that could exist, but do not in this scenario.

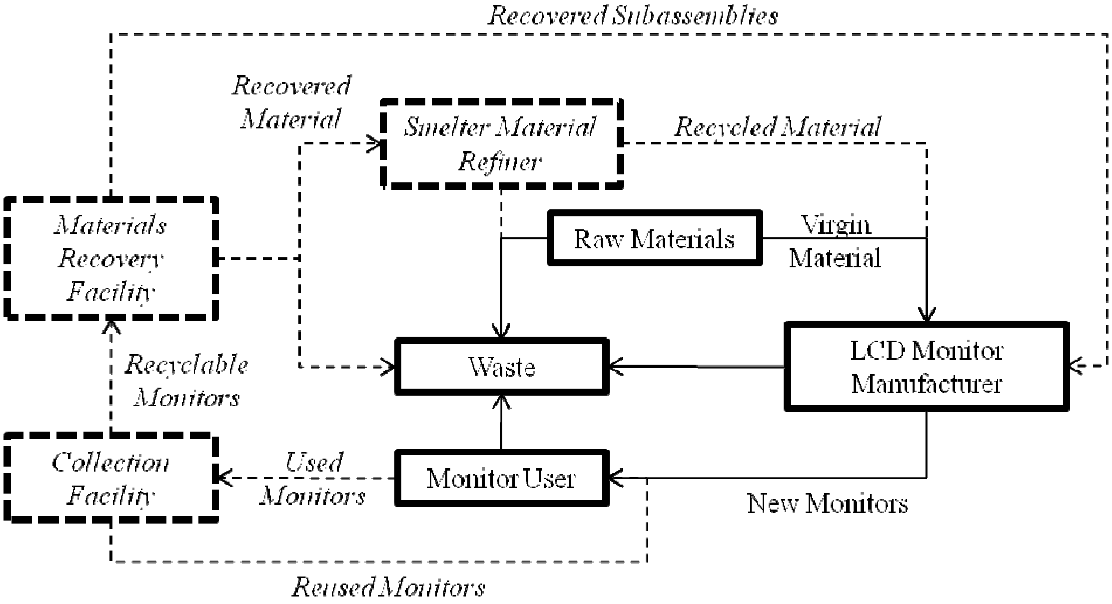


Figure 50: Lifecycle Network of Scenario 3

Table 32: LCD Computer Monitor Example, Scenario 3 Assumptions

Model Parameter	Value
Annual LCD Computer Monitors Discarded*	350,000
Fraction of Discarded Monitors Landfilled	100%
Fraction of Discarded Monitors Reused	0%
MRF Recycling Operations (Material Recycling)	No
MRF Disassembly (Subassembly Reuse)	No

*(Ai and French December 1, 2008)

4.6.1.4 Scenario 4

Scenario 4 represents a network with generous recycling capabilities; however, much of that resource is not taken advantage of. This fact is played out by monitor users, who discard 50% of their computers to a landfill, and send the other 50% to a collection facility. Beyond this fact the rest of the end of life is similar to Scenario 2. Hence, 15% of the discarded monitors are sent back to the monitor users for a second life, while the remaining fraction is sent to an MRF. The MRF disassembles monitors and reclaims 25% of reusable subassemblies. The rest is mechanically and thermally processed by the MRF and the material refiner to be reused by the LCD monitor manufacturer with other raw materials to replace the monitors discarded by the users. These assumptions are summarized in Table 33. Compared to the general lifecycle in Figure 35, the lifecycle for Scenario 4 is the same and can be seen in Figure 51.

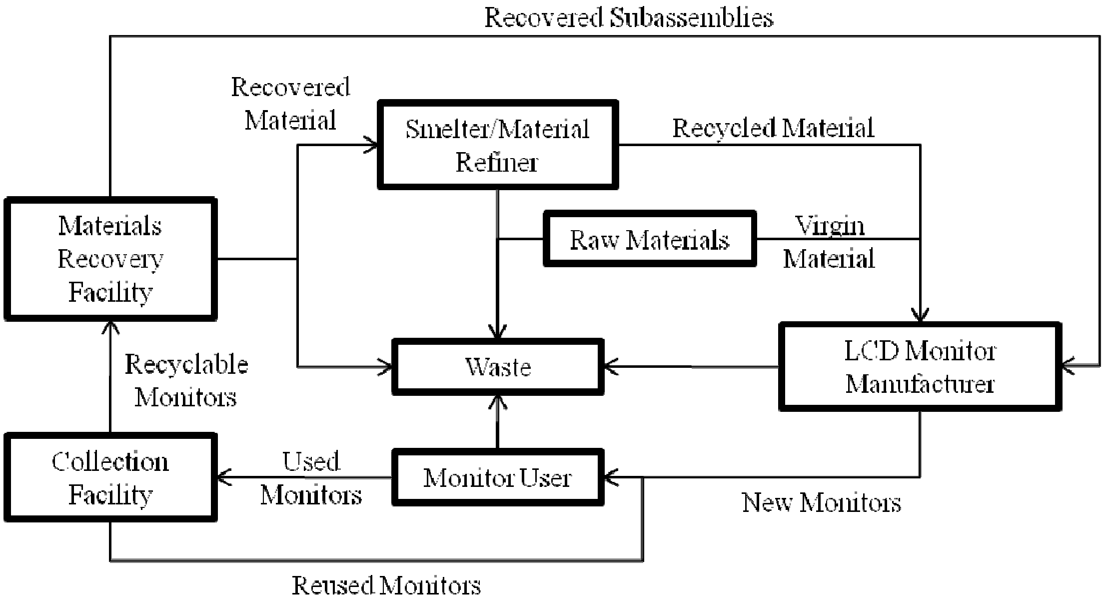


Figure 51: Lifecycle Network of Scenario 4

Table 33: LCD Computer Monitor Example, Scenario 4 Assumptions

Model Parameter	**Value**
Annual LCD Computer Monitors Discarded*	350,000
Fraction of Discarded Monitors Landfilled	50%
Fraction of Discarded Monitors Reused	15%
MRF Recycling Operations (Material Recycling)	Yes
MRF Disassembly (Subassembly Reuse)	Yes**

*(Ai and French December 1, 2008)

**25% of LCD Modules, Backlights, Panel Components, and Glass

4.6.2 Scenario Results

The sections below outline the results of the scenarios described above. The respective scenario parameters can be seen in Table 34.

Table 34: Scenario Parameters

Model Parameter	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual LCD Computer Monitors Discarded*	350,000	350,000	350,000	350,000
Fraction of Discarded Monitors Landfilled	10%	10%	100%	50%
Fraction of Discarded Monitors Reused	15%	15%	0%	15%
MRF Recycling Operations (Material Recycling)	Yes	Yes	No	Yes
MRF Disassembly (Subassembly Reuse)	No	Yes**	No	Yes**

*(Ai and French December 1, 2008)

**25% of LCD Modules, Backlights, Panel Components, and Glass

The material and energy usage footprint is shown for each scenario, respectively. The energy footprint can be described as the total amount of energy consumed by the network. It is calculated by aggregating the energy used by each stakeholder in the network. The material footprint is the amount of material wasted by each stakeholder. Waste is defined as material that is sent to a landfill or storage facility of some kind that effectively removes it from use in the network. Based on these footprints the most favorable network configuration, of the four described, can be determined.

4.6.2.1 Scenario 1

The breakdowns of the total material and energy footprints for Scenario 1 can be seen in Table 35. The figures below the table show the contributing fractions of each stakeholder to the respective footprint in the lifecycle. Since the material footprint is dominated by the raw material refiner as seen in Figure 52, the contributions from the other stakeholders is exploded in Figure 53.

Table 35: Total Energy and Material Footprints Breakdown for Scenario 1

Type	Source	Material Wasted (tonnes)	Fraction of Total Waste	Energy Use (kWh)	Energy Use (MJ)	Fraction of Total Energy
Use	Monitor User	201	0.92%	29,000,000	104,400,000	18.00%
Recycling	Collection Facility	0	0.00%	0	0	0.00%
	MRF	442	2.03%	22,000	79,200	0.01%
	Material Refiner	175	0.81%	870,000	3132,000	0.54%
Manufacturing	LCD Glass Manufacturer	0	0.00%	60,000,000	216,000,000	37.10%
	LCD Backlight Manufacturer	94	0.43%	370,000	1,332,000	0.23%
	LCD Panel Components Manufacturer	95	0.44%	53,00,000	19,080,000	3.27%
	LCD Module Manufacturer	0	0.00%	42,000,000	151,200,000	26.17%
	LCD Monitor Manufacturer	3	0.01%	17,000,000	61,200,000	10.41%
Raw Materials	Raw Material Production	20,759	95.36%	6900000	24,840,000	4.27%
Totals		22,000	100%	162,000,000	583,000,000	100%

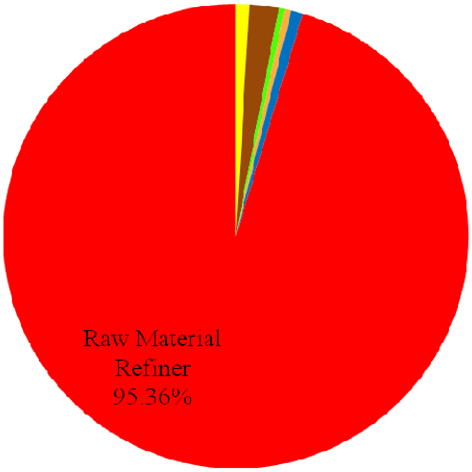


Figure 52: Total Material Footprint of Scenario 1 Breakdown

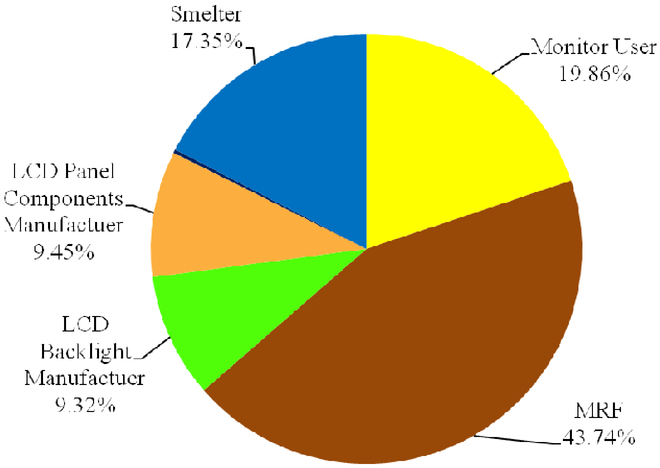


Figure 53: Material Footprint of Scenario 1 Breakdown (No Raw Material Refining)

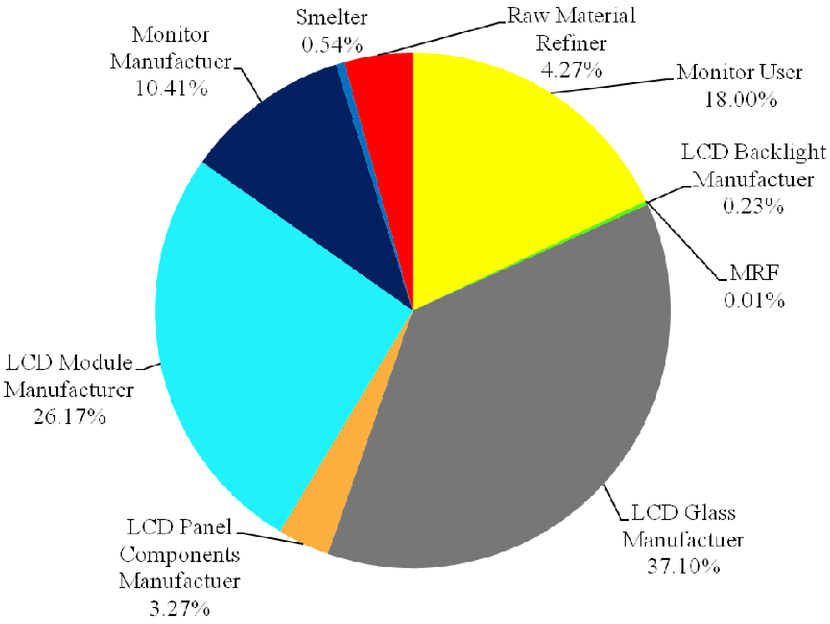


Figure 54: Total Energy Footprint of Scenario 1 Breakdown

4.6.2.2 Scenario 2

The total material and energy footprints for Scenario 2 can be seen in Table 36. The figures below the table show the contributing fractions of each stakeholder to the respective footprint in the lifecycle. Since the material footprint is dominated by the raw material refiner as seen in Figure 55, the contributions from the other stakeholders is exploded in Figure 56.

Table 36: Total Energy and Material Footprints Breakdown for Scenario 2

Type	Source	Material Wasted (tonnes)	Fraction of Total Waste	Energy Use (kWh)	Energy Use (MJ)	Fraction of Total Energy
Use	Monitor User	201	1.05%	29,000,000	104,400,000	23.31%
Recycling	Collection Facility	0	0.00%	0	0	0.00%
	MRF	311	1.63%	49,000	176,400	0.04%
	Material Refiner	167	0.87%	850,000	3,060,000	0.68%
Manufacturing	LCD Glass Manufacturer	0	0.00%	34,000,000	122,400,000	27.33%
	LCD Backlight Manufacturer	53	0.27%	210,000	756,000	0.17%
	LCD Panel Components Manufacturer	74	0.39%	4,100,000	14,760,000	3.30%
	LCD Module Manufacturer	0	0.00%	33,000,000	118,800,000	26.53%
	LCD Monitor Manufacturer	3	0.01%	17,000,000	61,200,000	13.66%
Raw Material	Raw Material Production	18,311	95.78%	6,200,000	22,320,000	4.98%
Totals		19,000	100%	124,000,000	446,000,000	100%

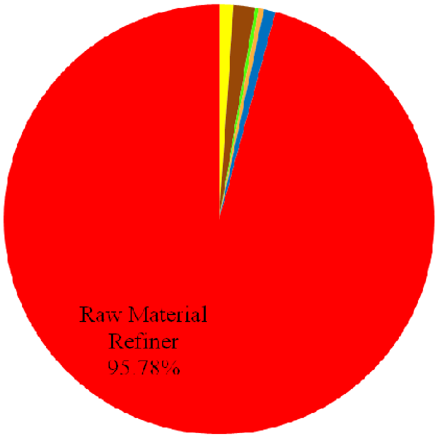


Figure 55: Total Material Footprint of Scenario 2 Breakdown

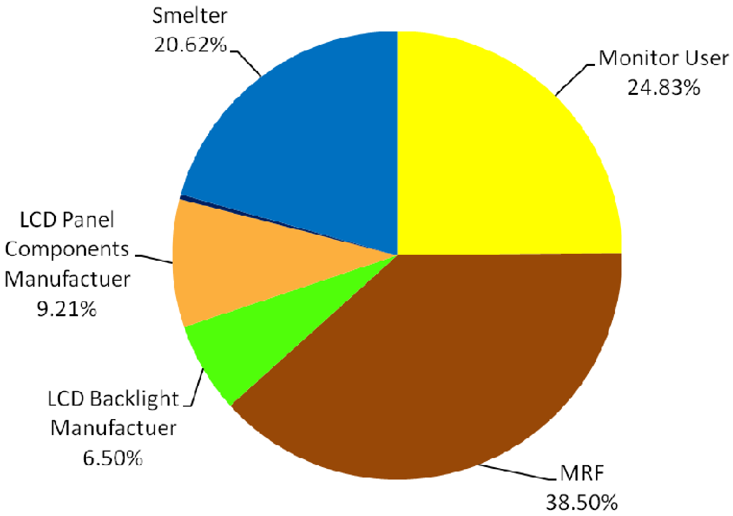


Figure 56: Material Footprint of Scenario 2 Breakdown (No Raw Material Refining)

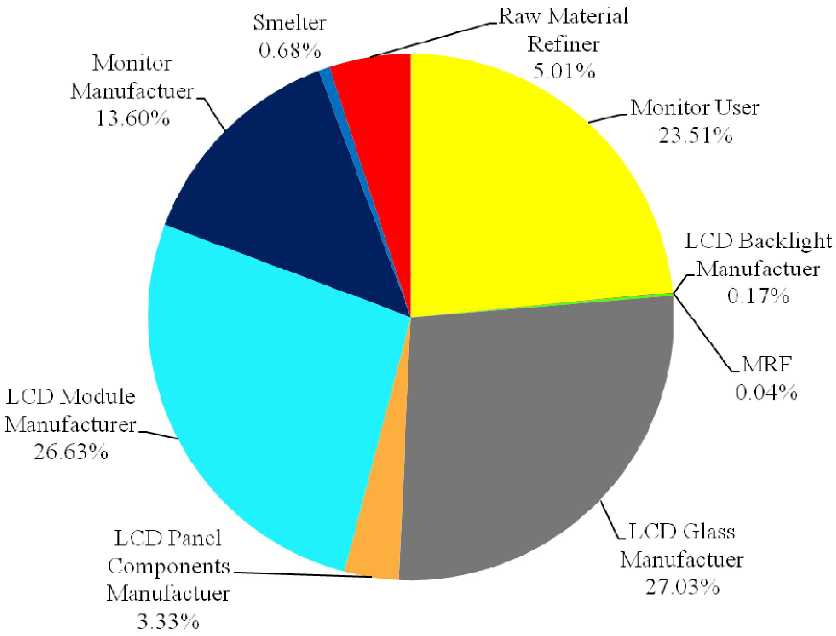


Figure 57: Total Energy Footprint of Scenario 2 Breakdown

4.6.2.3 Scenario 3

The total material and energy footprints for Scenario 3 can be seen in Table 37. The figures above the table show the contributing fractions of each stakeholder to the respective footprint in the lifecycle. Since the material footprint is dominated by the raw material refiner as seen in Figure 58, the contributions from the other stakeholders is exploded in Figure 59.

Table 37: Total Energy and Material Footprints Breakdown for Scenario 3

Type	Source	Material Wasted (tonnes)	Fraction of Total Waste	Energy Use (kWh)	Energy Use (MJ)	Fraction of Total Energy
Use	Monitor User	2,006	3.48%	29,000,000	104,400,000	15.06%
Recycling	Collection Facility	0	0.00%	0	0	0.00%
	MRF	0	0.00%	0	0	0.00%
	Material Refiner	0	0.00%	0	0	0.00%
Manufacturing	LCD Glass Manufacturer	0	0.00%	69,000,000	248,400,000	35.84%
	LCD Backlight Manufacturer	109	0.19%	430,000	1,548,000	0.22%
	LCD Panel Components Manufacturer	110	0.19%	6,100,000	21,960,000	3.17%
	LCD Module Manufacturer	0	0.00%	49,000,000	176,400,000	25.45%
	LCD Monitor Manufacturer	3	0.01%	19,000,000	68,400,000	9.87%
Raw Material	Raw Material Production	55,328	96.13%	20,000,000	72,000,000	10.39%
Totals		58,000	100%	194,000,000	698,000,000	100%

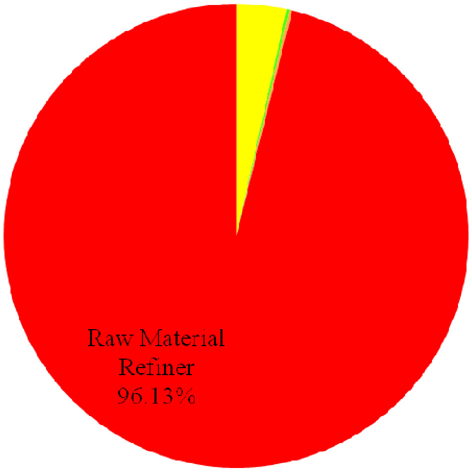


Figure 58: Total Material Footprint of Scenario 3 Breakdown

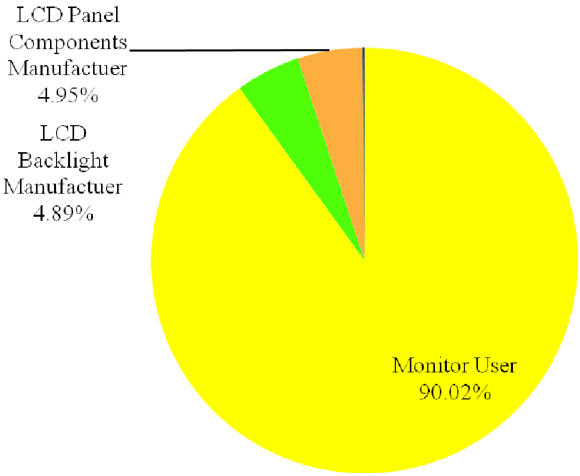


Figure 59: Material Footprint of Scenario 3 Breakdown (No Raw Material Refining)

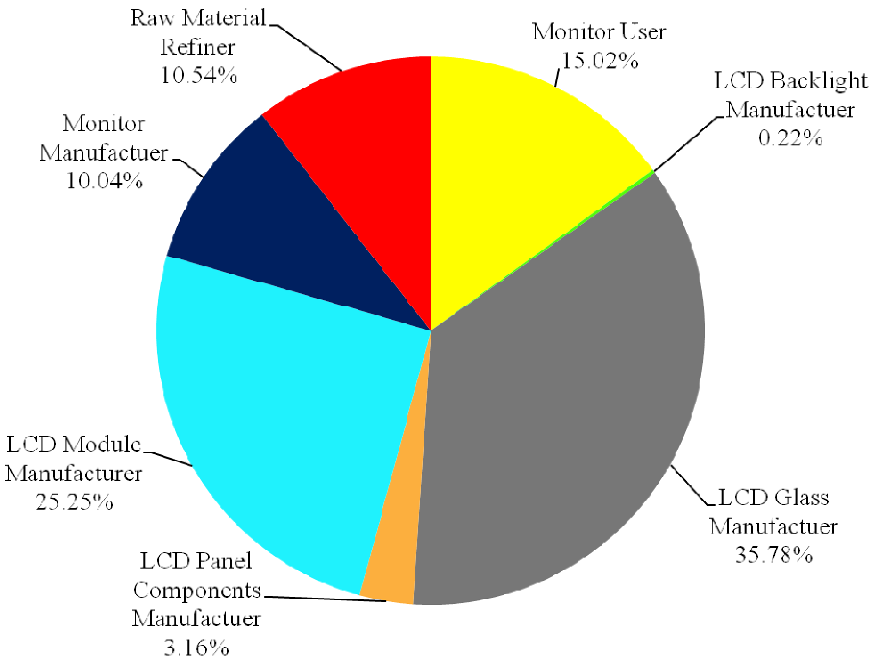


Figure 60: Total Energy Footprint of Scenario 3 Breakdown

4.6.2.4 Scenario 4

The total material and energy footprints for Scenario 4 can be seen in Table 38. The figures above the table show the contributing fractions of each stakeholder to the respective footprint in the lifecycle. Since the material footprint is dominated by the raw material refiner as seen in Figure 61, the contributions from the other stakeholders is exploded in Figure 62.

Table 38: Total Energy and Material Footprints Breakdown for Scenario 4

Type	Source	Material Wasted (tonnes)	Fraction of Total Waste	Energy Use (kWh)	Energy Use (MJ)	Fraction of Total Energy
Use	Monitor User	1,003	2.77%	29,000,000	104,400,000	18.61%
Recycling	Collection Facility	0	0.00%	0	0	0.00%
	MRF	173	0.48%	27,000	97,200	0.02%
	Material Refiner	93	0.26%	470,000	1,692,000	0.30%
Manufacturing	LCD Glass Manufacturer	0	0.00%	50,000,000	180,000,000	32.09%
	LCD Backlight Manufacturer	78	0.21%	310,000	1,116,000	0.20%
	LCD Panel Components Manufacturer	90	0.25%	5,000,000	18,000,000	3.21%
	LCD Module Manufacturer	0	0.00%	40,000,000	144,000,000	25.67%
	LCD Monitor Manufacturer	3	0.01%	18,000,000	64,800,000	11.55%
Raw Material	Raw Material Production	34,763	96.03%	13,000,000	46,800,000	8.34%
Totals		36,000	100%	155,000,000	558,000,000	100%

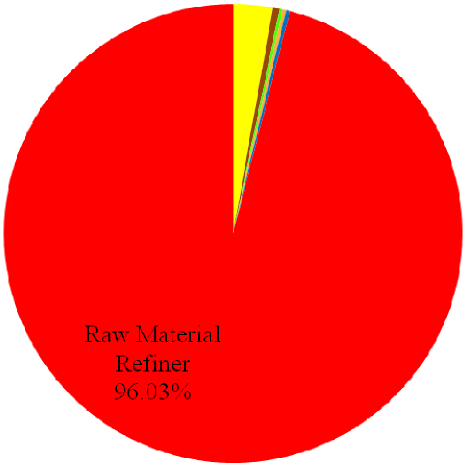


Figure 61: Total Material Footprint of Scenario 4 Breakdown

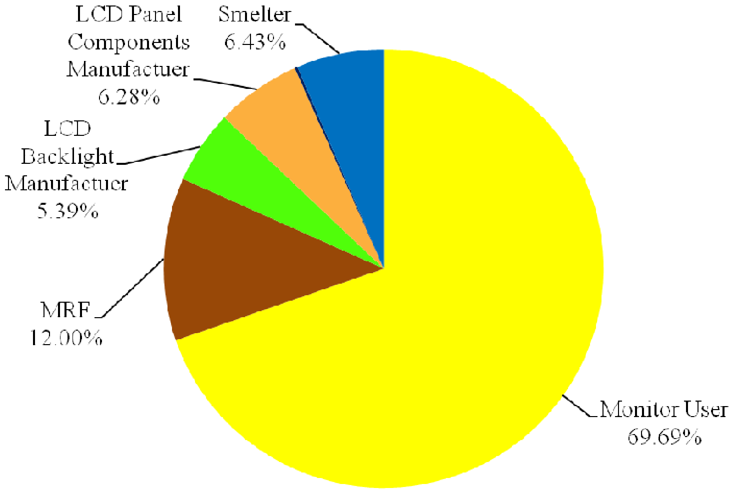


Figure 62: Material Footprint of Scenario 4 Breakdown (No Raw Material Refining)

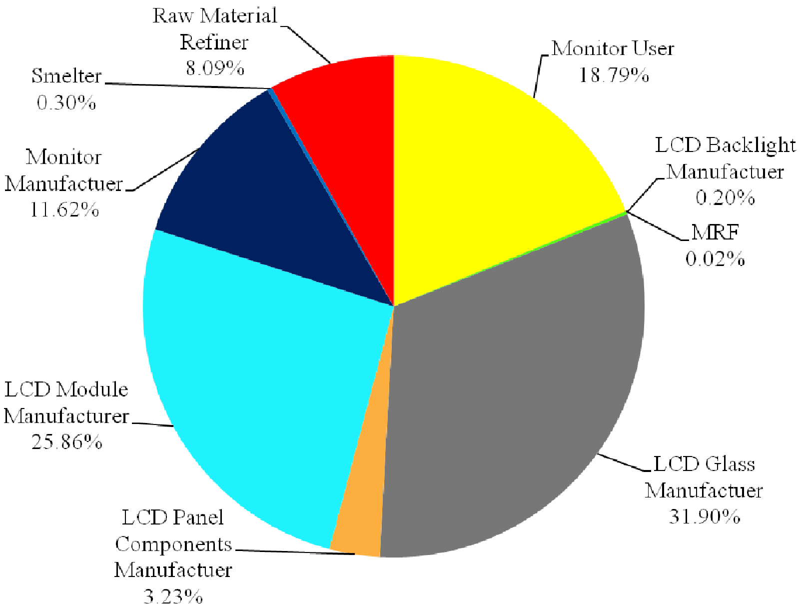


Figure 63: Total Energy Footprint of Scenario 4 Breakdown

4.6.2.5 Comparison of Scenarios

Based on the goal defined earlier to minimize the energy and material usage footprint, it can be seen that Scenario 3 is the most wasteful. The results of the four scenarios are combined and normalized by Scenario 3 in Table 39. Looking at the results in Table 39, a lower number corresponds to a smaller footprint.

Table 39: Energy and Material Usage Footprint Normalized by Scenario 3

Footprint	**Scenario 1**	**Scenario 2**	**Scenario 3**	**Scenario 4**
Material tonnes 10^3 (kg 10^6)	22	19	58	36
Energy kWh 10^6 (MJ 10^8)	162 (5.58)	124 (4.46)	194 (6.98)	155 (5.58)
Material (Normalized)	37.9	32.8	100	62.1
Energy (Normalized)	83.5	63.9	100	79.9

The results in Table 39 are interesting in that as the amount of “cycling” of products and materials increases, the size of the foot print decreases with respect to both energy and material. Cycling refers to the amount materials and products that could be returned back into the system via reuse, recycling, or remanufacturing instead of becoming waste. Recalling Figure 48 through Figure 51, Scenario 3 had the smallest lifecycle network. Scenario 3 only allowed users to discard monitors into a landfill which disallowed any reuse, recycling, or remanufacturing later in the monitor’s life. On the other hand, Scenario 2, which has the lowest footprints, was built with the maximum number of end-of-life options thereby allowing reuse, recycling, and remanufacturing of the monitors.

However, what is also apparent from Table 39 is that in addition to the amount of cycling present in a network, the magnitude of these cycles is also important. For example, Scenario 4 allows reuse, recycling and remanufacturing of computer monitors after they are discarded, but Scenario 1 does not allow remanufacturing (i.e. there is no disassembly at the MRF and therefore no reuse of subassemblies at the manufacturer) and still has a smaller footprint than Scenario 4. This is due to the fact that the magnitude of the end-of-life cycling paths available in Scenario 1, namely that users discard less computers in landfills, are larger than Scenario 4 such that the overall footprints are lower for Scenario 1.

In terms of the material footprints for each scenario, it is evident that there are significant differences in terms of the total footprint. However, when looking at the breakdown of each material usage footprint, it consistent that the raw material refiner dominates in each instance. This fact should be expected as it can be seen from the parameters describing the raw material refiner that its material throughput efficiencies are quite low. Strikingly though, despite these low efficiencies, the material refiner is not consistently the largest consumer of energy. Instead what is evident is that the energy required to manufacture an LCD monitor consistently dominates the energy footprint despite having very high material throughput efficiencies. This fact indicates that it is important to have information about both material throughput and energy consumed, as it is not the case that the biggest waster of material is also the biggest consumer of energy as one might expect.

After the raw material refiner, the next largest waste of material is strongly dependent on the choices made when monitor is discarded. This is expected as the user will be the dominant factor when all of the monitors are sent to a landfill, or the MRF may be the dominant as in Scenario 1 or 2 when it is processing a large amount of monitors.

In terms of the energy breakdown for each scenario, although there is a significant difference between the total amounts of energy consumed, the individual contributor fractions remain roughly the same. Overall the energy breakdown is dominated by manufacturing. This fact supports the earlier conclusions drawn about cycling materials. Or In other words, increasing the amount of cycling reduces the overall energy footprint of a network because relatively large savings in energy upstream result from relatively small expenditures of energy downstream.

4.6.3 MRF Facility Breakdown

One of the strengths of the modeling schema described in Section 3.1 is that in addition to the global material and energy results, it is possible to get local results at the process level. For example, Table 41 and Table 42 present breakdowns of the process energy and the utilized machine capacity for Scenario 1 and Scenario 4. Scenario 1 and 4 provide a good basis for comparison because they have the same basic network paths as seen in Figure 49 and Figure 51; however, the magnitudes of the paths are different.

Table 40: Facility Operation Details

Facility Parameter	**Scenario 2**	**Scenario 4**
Annual Operation Hours	3,760	3,760
Total Annual Material Processed (tonnes)	1,500	850

Table 41: MRF Process Energy Breakdown

Process	**Scenario 2** kWh (MJ 10^3)	**Scenario 4** kWh (MJ 10^3)
Front End Loader	14,000 (50)	7,700 (28)
Manual Disassembly	27,000 (97)	15,000 (54)
Hammer Mill	4,300 (15)	2,400 (8.6)
Trommel Screen	140 (0.5)	80 (0.29)
Magnetic Separation	0.34 (0.0012)	0.21 (0.0076)
Eddy Current Separation	610 (2.2)	340 (1.2)
Density Separation	80 (0.29)	44 (0.16)
Baler	2,000 (7.2)	1,100 (4.0)
Total	49,000 (176)	27,000 (97)

Table 42: Fraction of Machine Operating Capacity Employed

Process	Scenario 2		Scenario 4	
	Number of Machines	Utilized Capacity	Number of Machines	Utilized Capacity
Front End Loader	1	30%	1	17%
Manual Disassembly	1	2.3%	1	1.3%
Hammer Mill	1	0.65%	1	0.36%
Trommel Screen	1	0.072%	1	0.040%
Magnetic Separation	1	0.012%	1	0.0068%
Eddy Current Separation	1	1.8%	1	1.0%
Density Separation	1	0.24%	1	0.13%
Baler	1	0.30%	1	0.17%

From Table 41 it is clear that the most energy dense processes are manual disassembly and the front end loader. It can also be seen from Table 42 that these same processes have the largest fractions of their respective capacities employed. This is interesting in that these processes require the most human interface. A front end loader must have a driver, and manual disassembly obviously requires human attention.

Though what is most obvious from Table 42 is that all of the machines are operating at a relatively low capacity. In other words, the amount of material entering the facility could be more than tripled in the case of Scenario 1 and no new machines would need to be purchased. Or if the facility operator created a better material handing solution that made the front end loader obsolete, then the next highest capacity operation is the manual disassembly, which could handle roughly 40 times more material before needing another machine. Clearly this would increase the annual amount of energy consumed by the facility, but no new capital costs would be incurred. To extrapolate, since the amount of material entering the facility is based on the annual monitor discard rates of Atlanta, it stands to reason that only a few facilities of the size detailed in this work would be needed to service the entire United States. Still, further study and more data collection would be needed to confirm such an extrapolation.

4.7 Lessons Learned from the LCD Monitor Network

This section discusses some ideas that are not necessarily tied directly to the MFA modeling results, but rather thoughtful consideration of some of the economic, policy, and data reporting aspects of the electronics waste problem encountered during the modeling effort.

Looking back at the results from the previous section, it is interesting to note that there are somewhat significant savings that could be gained by making some changes in the life cycle network of LCD monitors. One of the most obvious is the roughly 29 to 70 million kWh of energy that could be saved between the two worst (Scenario 3, 4) and best case scenarios (Scenario 2). Bear in mind that this energy savings was based on the number of monitors discarded annually in the Atlanta metro region, which only represents a small portion of the US market; some have estimated that up to 160,000 computers and televisions are discarded daily in the United States (Silicon Valley Toxics Coalition 2004). A rough estimate of energy cost is 10 cents per kWh (U.S. Energy Information Administration 2010). Thus the question is if anywhere between 2.9 and 7 million dollars could be saved each year (perhaps per day if the entire United States is analyzed), then why are these changes not already being implemented by the stakeholders? Of course it is impossible to speak directly on the behalf of the stakeholders themselves, but the most likely reason is that this savings would be spread out across the entire global network of stakeholders, and considering that the market size of LCD displays is in the 10 to 20 billion dollar range annually (Displaybank 2009), a few million dollars a year is a relatively small incentive

Another possible explanation is that stakeholders in the lifecycle of electronics are not convinced that the business of recycling electronics is profitable. This is borne out by the fact that it takes government legislation such as the WEEE directive in the EU and the California and Washington State electronics bills discussed in Section 2.1 to create incentives (or mandates) encouraging electronics recycling and extended producer responsibility. When the environment is viewed as a free resource to exploit, landfilling electronic waste in the case of electronics recycling, it can be difficult to justify short term expenditures developing knowledge and infrastructure for long term gains. This comes back to the fact that even if there are significant gains to be had by implementing network changes, those gains can only be realized after a new system has been put into place, which will cost time and capital resources that may not have an enticing payback period.

Up to this point, only the cost of energy has been discussed as a savings; however, there is also the value of the wasted material to be considered. There is certainly no doubt that there are valuable materials in electronics waste as discussed in Section 1.1; however, this value is not only difficult to recover but also difficult to quantify. The difficulty of recovering the valuable material has already been discussed in terms of the heterogeneity and complexity of its application, but given that it may be possible to keep 2,500 tonnes of non-ferrous material out of a landfill annually (Scenario 1,2 vs. Scenario 3), or daily based on the previous discussion, what is the value of 2,500 tonnes of non-ferrous material? The difficulty in this question arises from accessing the value of electronics scrap. It is quite simple to ascertain the value of pure metals such as gold, silver, nickel, copper, etc from the London Metals Exchange, but in electronics scrap these precious materials are typically found in small amounts (save copper) per device and moreover they are comingled with many other high and low value materials. This is likely another reason for industry's hesitation at earnestly adopting electronics recycling. In other words, industry is well aware of the high value associated with pure precious materials, in fact they have been reducing the amount found in electronic devices over the years (Cui and Zhang 2008), but the costs associated with recovering these precious materials is not well understood. This is likely due to the fact that there is vested corporate interest in the data and it is not widely publicized, but also because there are many different operations and stakeholders involved in the purification process such as collection facilities, materials recovery facilities, and smelters that make data collection difficult. Therefore in the future, it may be beneficial to carry out an economic analysis of electronics waste in terms of the processes and stakeholders involved, as described in the previous sections, to allow industry to make a more informed and possibly more profitable decision.

Continuing on the topic of wasted resources, it was noted above that electronic device manufacturers have been reducing the amount of precious materials in their products over time. This could have a significant impact on the electronics recycling industry since most of the value derived from electronics waste is obtained by the recovery of precious materials. It would be interesting to see the effects of both increasing and decreasing the amount of precious materials found in devices and observe the recycling industry's response. For example, if all the high value material were removed from electronic devices, as is the current trend, it stands to reason that the industry would collapse or at least cease to become a recycling operation and exist as more of a landfill operation. Though on the other hand, if the amount of precious material in electronic devices was increased, it may have the effect of encouraging growth in the electronics recycling industry as more competition may enter the market to compete for recovery of the precious materials. Interestingly, this may have the effect of increasing manufacturing cost upfront in terms of material costs; however, it may result in decreased pressure on manufacturers to recycle their products as the intrinsic value of recovering materials would encourage the growth of a recycling industry. Though in addition to simply increasing the amount of precious metals in the devices, based on the history of the United States and other developed countries, there would likely need to be increased enforcement of legislation banning illegal export of the devices to third world countries to exploit cheap and unsafe labor practices. Of course testing these hypotheses is outside the scope of this work and more suited to an expert in policy economics, which returns to the introductory discussion of a need to increase the investment in electronics recycling research, but nevertheless they make thought provoking questions here.

CHAPTER 5: DISCUSSION AND CLOSURE

This chapter will examine the results of the previous sections in terms of the research questions proposed in Section 1.4. The discussion begins by addressing Question 1 and Question 2. The discussion closes by revisiting the motivating question of the work.

5.1 SysML and ParaMagic (v16.5) as a Modeling Tool

This section discusses Question 1 proposed in Section 1.4, which is repeated below:

> Question 1: Can ParaMagic be implemented to effectively incorporate executable analysis models in SysML?

After creating the LCD computer monitor lifecycle network model and its many revisions, several of the advantages and disadvantages discussed in Section 2.3 were borne out. The biggest challenge that had to be overcome was creating an executable model. The difficulty in this challenge arose from harnessing SysML's flexibility to create a useful and robust modeling schema that incorporated domain specific knowledge of MFA and COBs. In the LCD computer monitor model, despite the fact that equations and constraints were being constructed in SysML, those equations and constraints had to be parsed into an external solver via ParaMagic. Theoretically, this separation is freeing in that as long as the number of equations is equal to the number of unknowns a system of equations should be solvable and no additional information about the solution process is needed. In practice however, this separation from the solver produced significant difficulties. For example, ParaMagic offers connections to several different external solvers, but probably the most powerful of which is Mathematica. To solve the models given by ParaMagic, Mathematica uses symbolic math. While symbolic math is a very powerful solution technique that can provide significant advantages, not the least of which is the acausal nature of the process, in this particular implementation the solution time of a model grew exponentially with the number of facilities and processes (variables). By the time the final model configuration was prepared, the solving time via Mathematica would well exceed 12 hours for a single scenario. With such large solution times, optimization of the network structure would be for all practical purposes impossible, as 10,000 runs would take approximately 13.5 years. While this statement is not directly a criticism of SysML (more of ParaMagic and Mathematica) it does serve to illustrate the potential pitfalls of flexibility. When a highly sophisticated equation solver is created to solve a wide range of problem formulations, it is expected that solution times will be suboptimal, because of the added operations of packaging and condensing the input formulation into a solvable problem and then selecting the correct solution algorithm. This is likely a difficulty that will be faced by many third party software developers considering SysML.

One very large advantage of SysML came from its ability to support easy model decomposition. This fact was very important in terms of the overall model schema as it allowed modularity. For example general process and facility blocks were constructed which could be inherited and specialized to form specific processes and facilities. Then these processes and facilities could be easily arranged in different structural configurations by making local changes in a diagram. Furthermore, the acausal nature of the solvers employed (despite dramatically increasing solution time) allowed solutions to be driven by the inputs or the outputs of a process or facility. This is a great advantage over models created in tools like Excel, where model decomposition can be very difficult and opaque as the connections between cells can be difficult to track. Also, it can be very difficult to make structural changes to a model in Excel a fact which makes reusing such models difficult; whereas in SysML such changes can be made and viewed easily by dragging and dropping.

With respect to SysML's adherence to data exchange protocols, this advantage was only briefly explored in the course of the research. However, during that brief course it was discovered that parsing SysML files and creating automatic connections to third party software tools can provide a significant impediment. The amount of expertise in computer science and software engineering knowledge should not be underestimated when considering an implementation of SysML.

Therefore, with respect to the question posed at the beginning of this section, ParaMagic can be used to create executable analysis models in SysML. However, as to the effectiveness of such models, ParaMagic and Mathematica become less and less effective as the size of the models increase. This is borne out by the fact that the LCD glass manufacturer example in Section 3.2 can be solved in a matter of minutes, whereas the larger LCD lifecycle network model takes in excess of 12 hours. Thus, for simple models with relatively few variables (≈125 in the LCD glass manufacturer example) ParaMagic and Mathematica is an effective tool, yet for larger models with many variables (≈4680 in LCD computer monitor lifecycle network) ParaMagic and Mathematica can still deliver results given enough time but essentially the effectiveness of the model tends to zero.

5.2 Lifecycle Network of LCD Computer Monitors

In terms of designing a better network for dealing with electronic waste that reduces its energy and material footprint, which is the subject of the second research question, several conclusions can be drawn.

Question 2: What factors in the lifecycle network of LCD computer monitors have the greatest impact in terms of the material and energy usage footprints?

In terms of a lifecycle network, there are two factors: the connections or paths between stakeholders and the stakeholders themselves. Both of these factors are discussed in Section 4.1.

Beginning with the connections between stakeholders, one of the main findings is that the number of the paths available to LCD monitors exiting the use phase needs to be increased. This is based on the assumption that consumers will still want to buy LCD computer monitors, thus necessitating the presence of raw materials and manufacturing. Otherwise the obvious solution with the lowest material and energy use footprint is no monitor at all.

Though if there is still a need for LCD computer monitors, then significant reductions in both energy and material use could be gained by increasing the amount of reuse, recycling, remanufacturing, etc. This was clearly borne out by the savings between Scenario 3 where all monitors were landfilled and Scenario 2 where reuse, recycling, and remanufacturing were present. More generally speaking though, this is the case because recycling, remanufacturing, etc is simply less energy and materially intensive than solely manufacturing new parts and components from virgin material.

However in addition to increasing the number of paths available after use, it must be ensured that more monitors enter such paths rather than merely being stored in basements or landfills. As was learned from Scenario 4 and Scenario 1, even if a materially or energetically favorable path exists for monitors to travel, if no monitors travel those paths then the would-be gains are lost. In other words, even if large investment is poured into sophisticated recycling networks, if stakeholders do not take advantage of such resources then the electronic waste problem will persist. For example this is a common problem with consumers, who either thorough lack of awareness or effort store electronics waste in their homes rather than properly recycling it (Matthews 1997). It is likely this problem will decrease with time as awareness increases, but unlike nature where time forces creatures to travel the path of least resistance, product lifecycles are often subject to irrational human behavior.

In terms of the stakeholders, it was learned that those who waste the most material, are not necessarily the biggest consumers of energy. This fact was borne out by the difference between the production of raw materials and the manufacturing processes involved in creating a monitor. This is likely largely due to the fact that there is significant chemical processing involved in refining raw ore which creates significant material waste, but is not as energy intensive; while product manufacturing often has an emphasis on minimizing material waste yet still remains energy intensive from pressures to produce more units in less time.

Overall, manufacturing was found to be the largest energy consuming phase in the LCD monitor lifecycle network. Generally speaking, this is followed by the use phase, then raw material production, and lastly recycling. In terms of material use, the raw material manufacturer clearly dominates. After raw material production, it is difficult to determine which stakeholder wastes the most as it depends on the stakeholders' decisions. For example if all monitors are discarded into a landfill then it is impossible for recyclers to waste material since they are not being given anything to recycle. These conclusions are similar to those by an LCA performed on computers which found that the pre-manufacturing stage (includes raw material production and part and component manufacture) is the largest impact category (Choi, Shin et al. 2006). The study also found that the product recovery is another key for efficient recycling, which is also discussed above.

5.3 Motivating Research Question

With respect to the motivating research question posed in Section 1.4:

> Can an executable model that overcomes the failings of the document based design approach be created in SysML to evaluate the energy and material usage footprints of LCD computer monitors?

The answer to this question must be a qualified yes. Certainly it must be granted that an executable SysML model was created; notwithstanding the fact that it has a lengthy solution time. Furthermore, the fact that SysML was chosen as a modeling platform inherently overcomes many of the document based design approach limitations. For example since the entire model was constructed in SysML, model validity, traceability, and completeness can be instantly verified. SysML's adherence to data exchange protocols (despite requiring certain expert knowledge) can be extracted and manipulated by third party software and algorithms. The MFA modeling schema that was developed for SysML and ParaMagic can be applied to other product lifecycles beyond computer monitors and electronic waste which increases modularity and reusability. Also, the acausal nature of the methods employed (despite increasing solution time) allows a multidirectional sequence on network design.

With respect to the second half of the question, based on the results from the various scenarios in Section 4.6.2 it must be granted that energy and material usage footprints for LCD computer monitors were evaluated. In addition various conclusions and improvements about the system at large were suggested based on the model results.

APPENDIX A ELECTRONICS RECYCLING TECHNOLOGIES

A.1 Size Reduction

In general size reduction is used in material processing for the following reasons: liberation of valuable or hazardous materials; promotion of a more rapid chemical reaction by increasing the surface area of the material; or to obtain certain treatment, use, or storage material properties (FEMP 2008). Typically in electronics recycling, the reason for size reduction is valuable material liberation. Electronics waste can contain many different valuable materials including: gold, silver, copper, or even platinum group metals. However, these valuable materials are often difficult to reconstitute because they are usually only a small fraction of the total electronics' mass, and they are normally bonded to other materials. Therefore, size reduction is used as a pretreatment to liberate the materials in electronics waste such that the intermingled materials can be separated into pure materials.

Size reduction processes are usually designed to handle either ductile or brittle materials. Ductile materials usually require cutting and shearing to achieve size reduction, while brittle materials require crushing and grinding (Alfred 2001). It is important to align the proper size reduction process to the properties of the feed material to avoid excessive wear. Too much brittle material may cause excessive wear in equipment designed for ductile materials, while ductile materials may damage crushers designed for brittle applications (Alfred 2001). Electronics waste offers a unique challenge in that it can be made of both ductile and brittle materials. For example a printed circuit board contains ductile copper that is encased in a brittle glass ceramic mixture (Mohite 2005). To overcome such a challenge, one technique for reducing the size of brittle/ductile mixtures involves selectively targeting the brittle materials, and then screening to separate the ductile from brittle as brittle materials tend to reduce to smaller sizes than ductile (Alfred 2001).

An important consideration of size reduction is the final particle size. The particle size not only has an effect on the degree of liberation of materials, but also certain separation techniques often require certain particle size range inputs to effectively separate materials. Although the specific particle size to achieve liberation may vary from product to product, research on the liberation of metals in printed circuit boards has shown that 99-96% metal liberation can be achieved at particle sizes less than 3 mm (Eswaraiah, Kavitha et al. 2008). Another study concludes that metals present in electronic scrap can be readily liberated from the composites at particle sizes below 2.0 mm (Zhang and Forssberg 1997). Particle size input to separation processes is discussed in section A.2.

A.1.1 Hammer-mill

Hammer-mills usually consist of a large, fast moving rotor with hammers fixed around the circumference. Input feed enters through a chute and moves toward the anvil as farther material is processed. The anvil is essentially a ledge that provides the fulcrum for the hammers to impact the material. The material remains in the rotor chamber until its size is reduced enough to pass through a grate or screen below the rotor. A diagram of a hammer-mill can be seen in Figure A.1. There are many variations on this theme including: horizontal or vertical rotors and bottom or top mounted screens to name a few. Some hammer-mill systems may be fitted with a dust collector at the output to collect ultra-fine particles.

The chopping action of the mill is most effective when the material is jammed between the hammer and the anvil (Alfred 2001). A secondary size reduction is achieved by repeated bending and shearing of the material until it can pass through the grate/screen. This effect increases with increasing volume (Alfred 2001). One study on hammer-mills describes the comminution of metals as a four stage process (Sander, Schubert et al. 2004):

- Stage 1 occurs adjacent to the anvil, whereby fragments are torn from the feed.
- Stage 2 occurs in flaws created by bending the material, which is influenced by circumferential velocity of the impacting tools causing the flaws to propagate until breakage
- Stage 3 is characterized by further deformation and compaction of the fragments due to impacts. Breakage occurs as a result of gradual crack formation from internal tensile stress.
- Stage 4 consists of further compaction of the fragments until they have the shape of spheres, leaving surface abrasion as the only means of comminution.
- After Stage 4 the materials eventually exit the mill through the grate/screen.

Hammer-mills may be classified based on their power rating. According to (FEMP 2008), electronic scrap falls into the mini-shredder category. Mini-shredders require power up to 260 kW, and can have a capacity up to 10000 tonnes/year (Alfred 2001). The quality of the output in terms of particle size distribution, degree of liberation and bulk density is mainly affected by (FEMP):

- Shape of the anvil and hammers

- Distance from
- anvil to hammers
- hammers to grate/screen
- hammers to side walls
- Aperture of the grate/screen
- Tangential rotor speed
- Degree of wear of the key parts

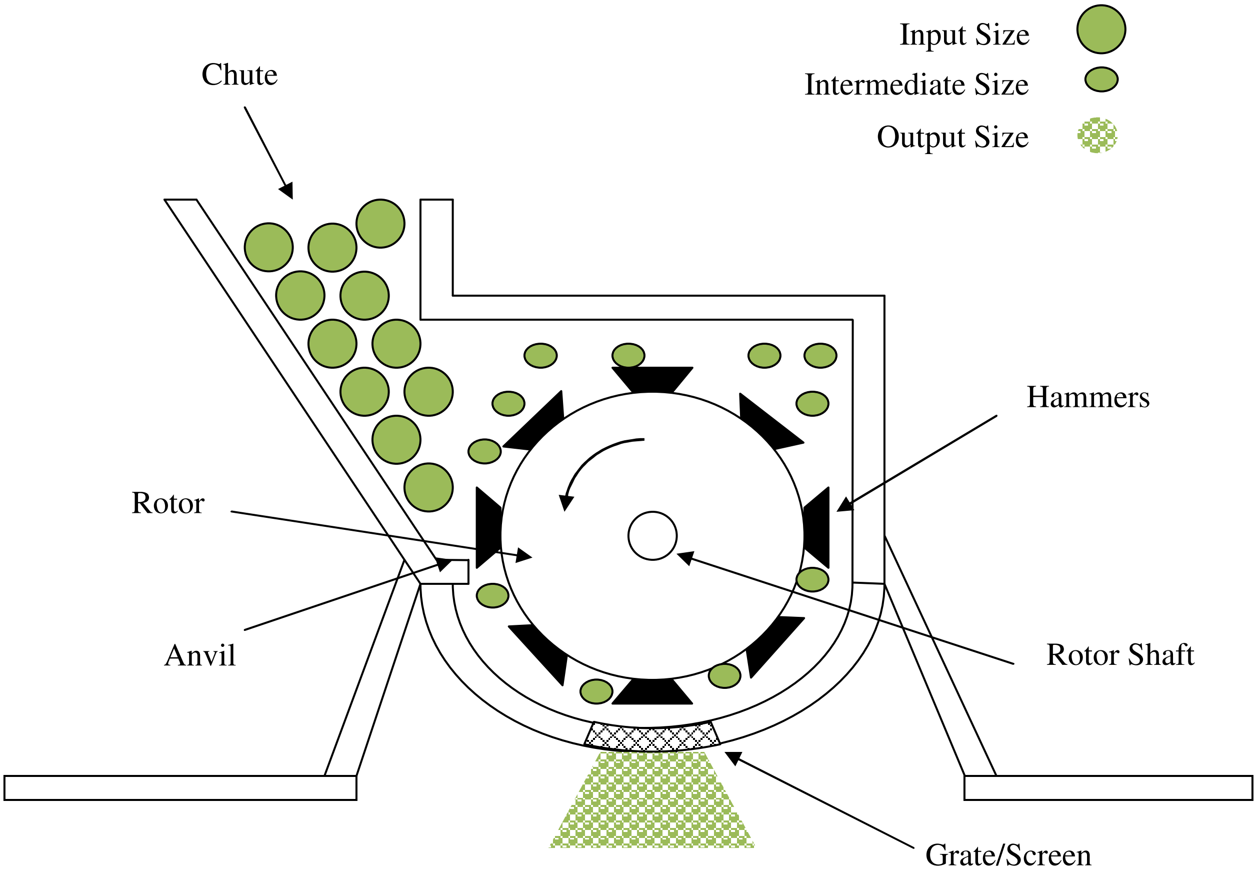


Figure A.1: Hammer-mill Diagram

The shapes of the hammer and the anvil have a direct effect on the size and the shape of mill output. As for hammers, ring shaped impact elements are typically used for electronic scrap (FEMP 2008), similar to the one seen in Figure A.2. Since no material is indestructible, the hammers must be changed periodically to ensure appropriate material size reduction.

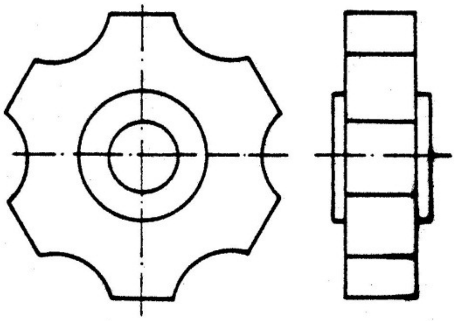


Figure A.2: Hammer Design for Electronic Scrap (Schubert 1984)

There are significant safety concerns when using hammer-mills in any application. Of highest concern is the possibility of dust fires and explosions. Not only is substantial heat generated in the size reduction process, but glowing hot particles resulting from the impact of the hammers can ignite fine dust particles. To protect against this, several precautions should be taken which may include water misting in the rotor chamber, application of an inert gas atmosphere in the rotor chamber, predesigned pressure relief spots in the mill, and pretreatment to ensure no inherently flammable materials are fed into the mill (FEMP 2008).

A.1.2 Ball Milling

Another method of size reduction for electronic waste is ball milling. Ball mills consist of a large drum supported by rotating shafts. As the drum turns impact balls are drawn up the drum’s side either by inertia or lifter bars and subsequently thrown back into the center of the drum whereby gravity causes the balls to fall and smash into the material to be reduced. A diagram of a ball mill can be seen in Figure A.3.

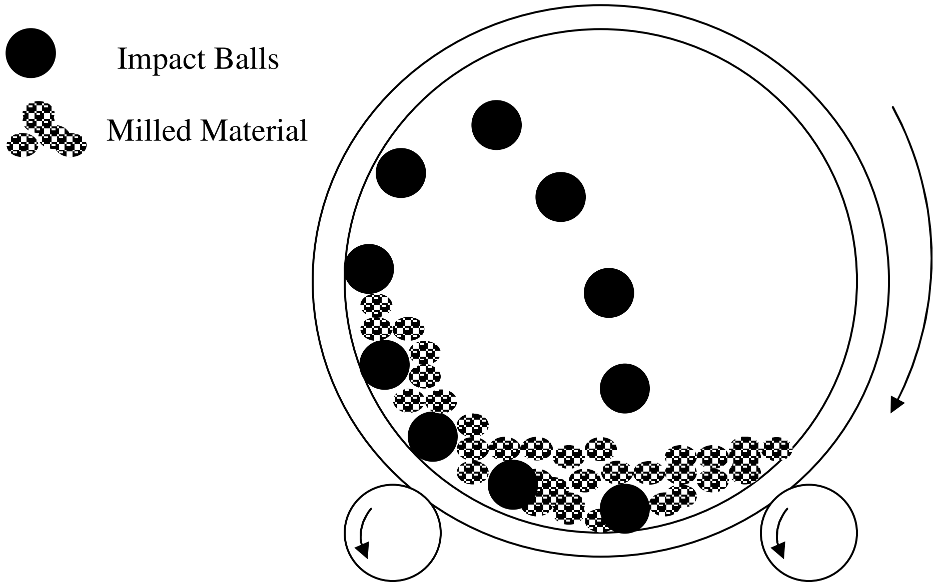


Figure A.3: Ball Mill Diagram

Closed circuit ball milling with high circulating loads, produces a closely sized end product and a high output per unit volume compared with open circuit grinding (Wills 1988). This makes closed circuit ball milling an excellent choice for final size reduction before separation as separation techniques are most effective given a uniform input. The input feed into a ball mill is usually less than 10 mm (Wills 1988). Typical size reduction ranges for a ball mill are in the 20:1 to 200:1 range (FEMP 2008).

The impact balls in a ball mill are made from forged or rolled high-carbon or alloy steel (Wills 1988). Sizing of the balls in the mineral processing industry is carried out by equations resembling:

$$d = kD^{0.5-1} \qquad 1$$

where d is ball diameter, D is the feed size, and k is a constant varying between 35 and 55 (Wills 1988). There is significant wear on the balls and drum liner from continuous impact, and accordingly as time progresses the size of the balls and the integrity of the liner will decrease. However, these problems are solved by regularly adding replacement balls and sieving the older balls from the final output, and by replacing the liner. This solution is not without costs as wear may comprise up to 50% of operational costs (FEMP 2008).

Moisture can play a large role in the effectiveness of size reduction. Dry milling should contain less than 4% water by volume (FEMP 2008). Too much moisture causes bridging between particles that results in agglomeration, and thereby mitigating size reduction effectiveness (FEMP 2008).

A.2 Separation of Materials

A.2.1 Jigging

Jigging is an old method of material separation that is extensively used in mineral processing. Jigging is typically used to concentrate relatively coarse materials from 10 to 3mm (Alfred 2001). A significant advantage of this process is that for fairly closed sized feed, good separation can be achieved at low cost (Alfred 2001).

The operating principle behind jigging is that different density materials will sink at different rates. Typically, a feed is dispersed on a floor that allows water to be pumped through the floor. As the water rises, so does the feed. When the water falls, higher density particles in the feed fall faster than the lower density particles. When this process is repeated, eventually the light and heavy fractions of the feed will separate.

However, significant heterogeneity and high complexity of electronic scrap make it difficult to operate a jigging process. Complicated scrap pieces, particularly wiry materials impede the separation process considerably and can prevent a separation into layers. (Cui and Forssberg 2003)

A.2.2 Shape Separation

Furuuchi *et al.* (Furuuchi and Gotoh 1992) defines four categories of shape separation based on their respective regimes: particle velocity on a tilted plate, the time for particles passing through sieves, adhesion or holding of particles to a solid wall, and settling velocity in a fluid. Each method is fundamentally based on the different behaviors of spherical and non-spherical particles under different stimulus. Different separation techniques are discussed for particle sizes ranging from a few μm to the mm scale.

Tilted plate separation is defined as the most basic and simple shape separation technique. In this method particles tend to be separated according to the flatness of the side view of the moving particle. The shape separation appears applicable particularly for round particles which roll on the plate but not for flat particles which slide on it. Some implementations of this effect are the tilted rotating disk, the tilted rotating cylinder, the tilted vibrating trough, and the tilted chute. The lower limit to the particle size in these shape separators may be a few hundred μm. (Furuuchi and Gotoh 1992)

Shape separation by sieves takes advantage of differences in the length of time it takes for spherical and non-spherical particles to pass through a mesh aperture. As the particle elongation increases the passage time increases because the elongated particle takes a long time to change its orientation and pass through the mesh aperture. The separation efficiency of this method increases with the number of sieves. Implementations of this method include: the tilted vibrating screen, vibrating stacked screens, and the rotating cylindrical sieve. Although this separation method can be applied to a wide range of particle sizes, the lowest limit may exist because of choking particles on the screen; and therefore, the passage rate must be determined experimentally. (Furuuchi and Gotoh 1992)

Particle holding/adhesion methods take advantage of a particle's ability to block an opening. In holding methods, particles stream down onto a perforated rotating drum. The drum contains suction devices that pull the particles such that they adhere to the surface of the drum. The separation criterion occurs as spherical particles better adhere to the drum than non-spherical particles. Therefore, as the drum rotates, non-spherical particles are blown off the drum by an air-jet due to the drag force overcoming the suction force, while spherical particles are brushed off after the non-spherical particles have fallen. This method has been shown to effectively separate glass beads from ores down to 0.354 mm. (Furuuchi and Gotoh 1992)

Settling velocity methods take advantage of the drag force experienced by particles in a fluid. The drag coefficient depends on the particle's shape as well as the particle's Reynolds number. Typically, spherical particles have a lower settling time than non-spherical particles; however, this is not always the case as, in addition to the drag coefficient, the settling velocity is dependent on the mass and projected area of the particle in the settling direction. An implementation of this method involves releasing a stream of particles into a fluid bath moving with some velocity. The bath floor has openings to collect the falling particles. Spherical particles fall quickly into the openings closest to the particle stream, while non-spherical particles are swept into openings farther from the particle stream. In principle, this technique can be used to separate particles of a few μm in size can be separated. (Furuuchi and Gotoh 1992) In applying this method of separation to electronic waste, difficulty could be encountered in overcoming the hydrophobic nature of certain types of electronic waste.

Overall, one difficulty in implementing shape separation as a material separation technique in electronic waste recycling is creating a size reduction process that selectively and consistently creates different particle geometries in different materials. Therefore, to effectively implement shape separation in electronics recycling the particle geometries generated by size reduction techniques must be well understood.

A.2.3 Hydrocyclones

A hydrocyclone is a method of separating materials by their differences in shape, size, density, or a combination of all three factors. A hydrocyclone is a continuously operating classifying device that utilizes centrifugal force to accelerate the settling rate of particles. (Wills 1988) Hydrocyclones have been used extensively by the mineral processing industry.

A diagram of a hydrocyclone is seen in Figure A.4. The hydrocyclone operates by injecting feed mixed with water tangentially into a conical shaped classifier. The high pressure of the input feed creates a vortex or cyclone-like effect in the center of the classifier. The denser or coarse particles fall to the bottom of the cone and exit through the underflow discharge. The less dense or fine particles are swept into the center vortex and exit through the top overflow discharge. The vortex finder extends down into the cone to prevent the coarse particles from exiting with the fine particles. Hydrocyclones can be used to separate materials from 150 to 5 μm, although coarser separations are possible (Wills 1988).

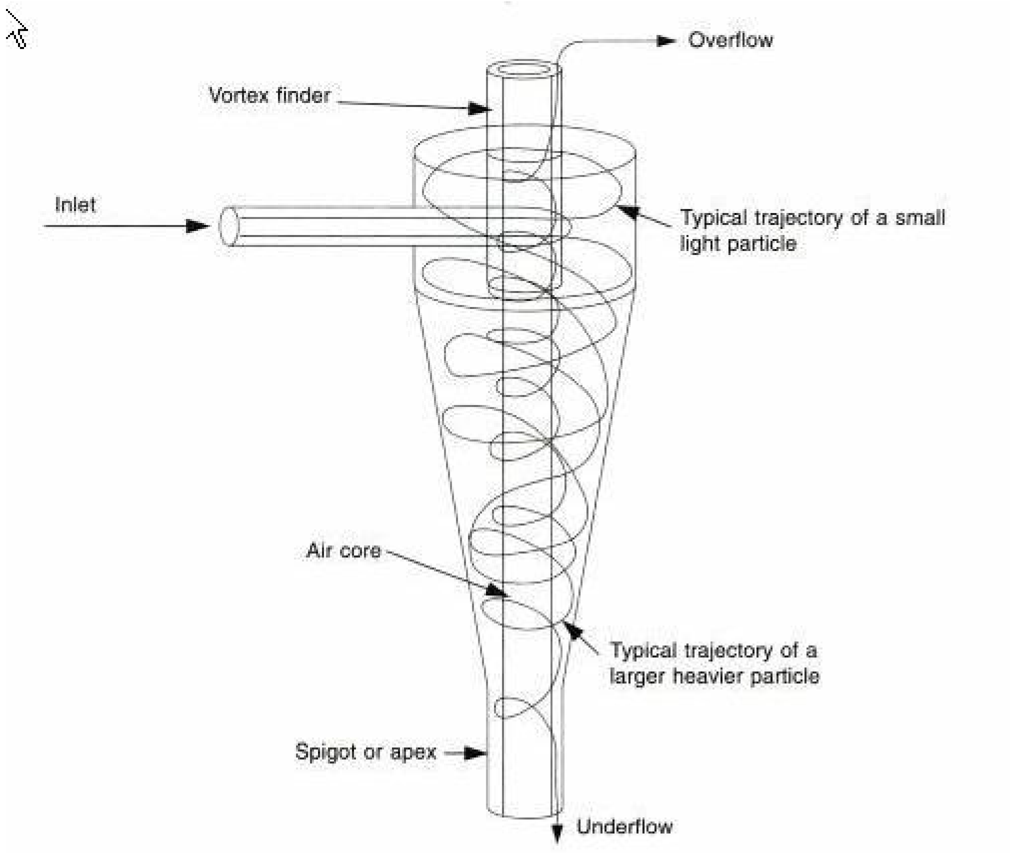


Figure A.4: Hydrocyclone Diagram

There are many ways to calculate the cut point at which particle separation occurs. One such calculation in Bradley *et al.* (Bradley 1965):

$$d_{50} = \frac{14.8{D_c}^{0.46}{D_i}^{0.6}{D_o}^{1.21}e^{0.063V}}{{D_u}^{0.71}h^{0.38}Q^{0.45}(S-L)^{0.5}} \qquad 2$$

where d_{50} is the cut point (µm), D_0 is the overflow diameter (cm), D_i is the inlet diameter (cm), Q is the total flow rate (m^3/hr), S is the specific gravity of the solids and L is the specific gravity of the liquid

A.2.4 Froth Flotation Systems

Froth flotation is regarded as one of the most important techniques in mineral processing. It can be used to separate different materials based on their respective hydrophobic or hydrophilic nature. Flotation separation has traditionally been used to separate copper, lead, and zinc.

A diagram of a flotation cell can be seen in Figure A.5. For froth flotation to work, the material being separated must be to some extent hydrophobic. If this condition is not achieved naturally, then chemical reagents can be employed to induce it. The process begins by inserting the separation mix into a flotation cell. While in the cell, air is pumped into the bottom of the cell via a pipe and agitated to create bubbles. As the bubbles float through the separation mix, the hydrophobic material adheres to the bubble and floats to the surface. Particles must be relatively fine for successful flotation because as they become too big gravitational forces overcome the adhesion to the bubble and the particles fall. Once the target material has floated to the surface, it is critical that a stable froth be maintained to keep the material floating otherwise it will fall when its bubble pops. A stable froth can be achieved by frothing reagents. Finally, with the target material floating on the surface, it can be raked into a collection bin, while the other remaining materials are pumped out from the bottom (Wills 1988)

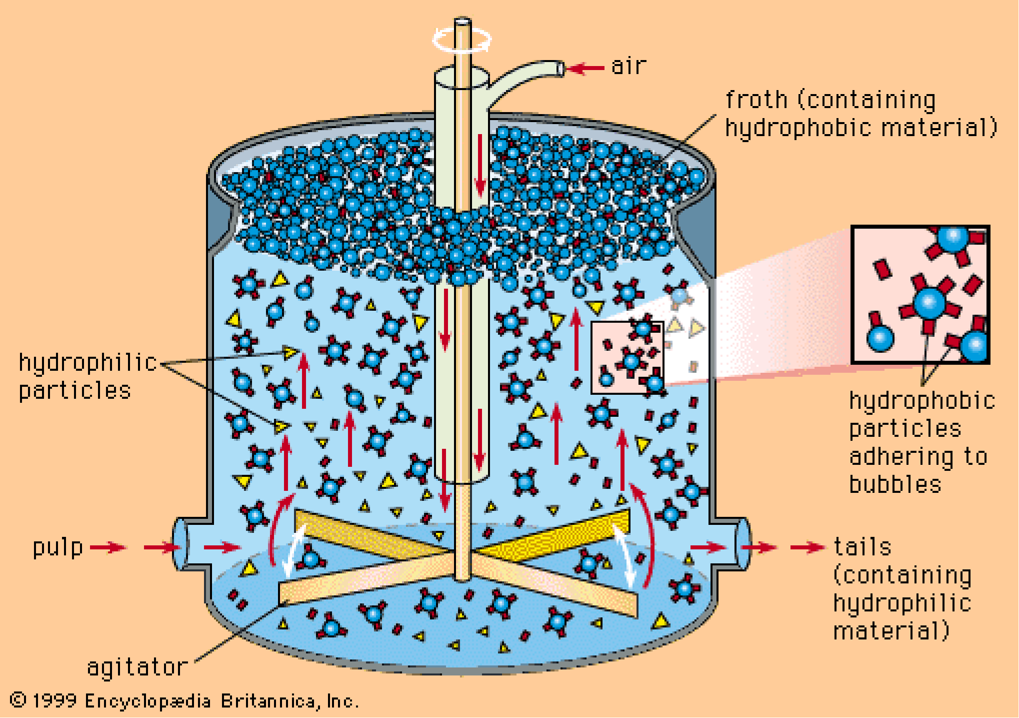


Figure A.5: Floatation Separation Diagram (Encyclopedia Britanica 2008)

One disadvantage to this process is that after floatation separation, the material may need to be dried. Drying can be an expensive and energy intensive process. Also, as mentioned above the particle size must be below a certain threshold for flotation to occur. This suggests that consistently sized particles must be present as two differing materials may have significantly different surface properties, but if one is finely ground and another is super finely ground then they both may float.

A.2.5 Corona Electrostatic Separation

Electrostatic separation is used as a means to separate conducting and non-conducting materials. Typically, the material stream has already been magnetically separated (as discussed in A.2.7), so the material streams are more specifically composed of non-ferrous metal and non-metal materials i.e. aluminum and plastic.

This separation technique requires that there be significant differences in the conductivities of the materials to be separated (Li, Shrivastava et al. 2004). The physical phenomenon behind this technique is corona charging and differentiated discharge leading to different charges of particles, which exerts different forces in different materials (Cui and Forssberg 2003). A diagram of an electrostatic separator, or high tension separator, can be seen in Figure A.6. Essentially, electronic scrap feed falls onto a grounded rotating drum. As the drum rotates, a corona electrode charges the feed. The conducting particles lose their charge as the drum is grounded, but the non-conducting particles retain their charge. Next a deflection electrode attracts conductors which are separated by a splitter plate. Non-conducting particles remain adhered to the drum until they are scraped off by a brush into a collection bin. Particles that are neither strongly conductive nor non-conductive particles are referred to as “middlings” and fall into a collection bin between the conductors and non-conductors. Depending on the application of the separator the deflection electrode may or may not be present (Iuga, Morar et al. 2001).

Traditionally, electrostatic separation has been investigated by the mineral processing industry, but has found uses in electronic recycling separating aluminum and copper from chopped electrical wires and also to remove copper and other precious metals from printed circuit board scrap (Cui and Forssberg 2003). It has also been used to separate materials in automotive recycling (Cui and Forssberg 2003). For this separation technique to be most effective the material stream should contain particle sizes between 0.1 and 5.0 mm, and moreover the electrode system, rotor speed, and moisture content must be appropriately controlled (Cui and Forssberg 2003).

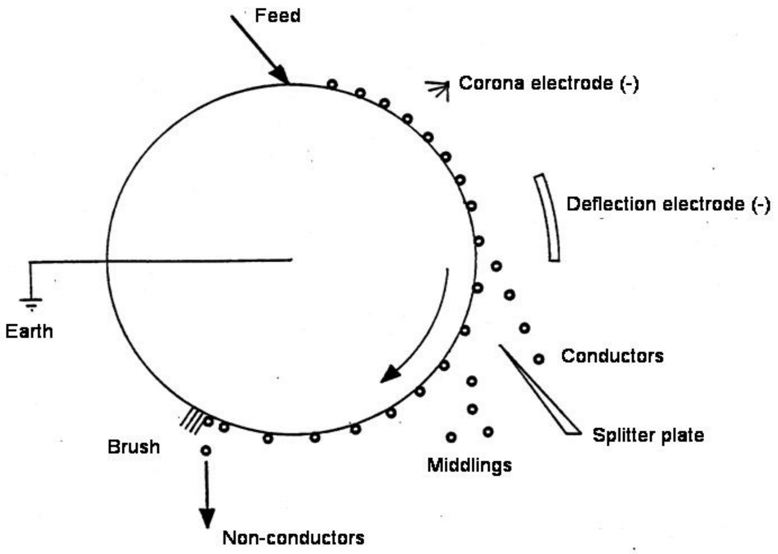


Figure A.6: High Tension Electrostatic Separator (FEMP 2008)

A.2.6 Eddy Current Separation

Eddy current separation is used as a means to separate conducting and non-conducting materials. In some instances, before eddy current separation takes place, the materials will have already been magnetically separated as discussed in A.2.7. Therefore after magnetic separation, eddy current separation often becomes the separation of non-conducting (i.e. plastics, glass, etc.) and non-ferrous (i.e. aluminum, copper, etc.) material streams.

The first industrial eddy current separators were introduced in the 1970s, but it was not until 1978 with the advent of rare earth magnets that the technology began to resemble modern eddy current separators.

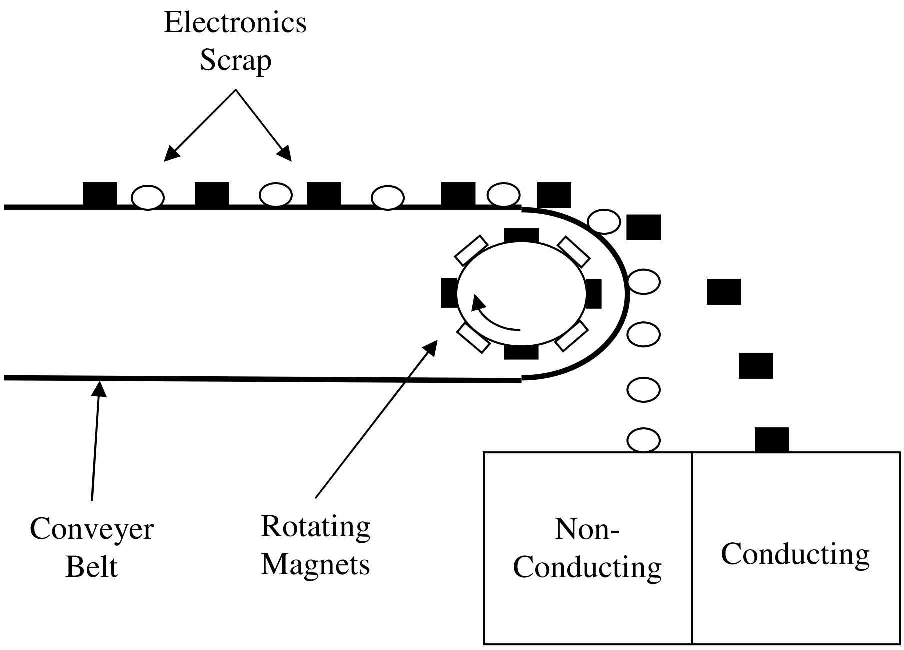


Figure A.7: Eddy Current Separator Operation

The physical phenomenon behind the separation is repulsive forces are exerted in the electrically conductive particles due to the interaction between the alternative magnetic field and the eddy currents induced by the magnetic field (Cui and Forssberg 2003). In other words, electronic scrap is passed over a series of rotating magnets on a conveyer belt. The rotating magnets induce eddy currents inside of the scrap, which in turn creates a magnetic field that opposes the field created by the magnet. Thus the interaction of the two opposing magnetic fields results in non-zero net force in conducting particles thereby accelerating them farther than the non-conducting particles. Figure A.7 shows the operation of a typical eddy current separator.

As mentioned above, eddy current separation is conductivity based. More specifically, to determine how material steams will separate the ratio of conductivity to density should be consulted (Alfred 2001). Table A.1 displays this ratio for some common materials found in electronics. The table below suggests that for equal particle sizes, a magnesium particle will experience twice the acceleration that a silver particle will in a changing magnetic field. It should also be noted from the table that non-conducting particles such as glass and plastic will experience no acceleration.

Table A.1: Ratio of Conductivity to Density for Selected Materials (Alfred 2001)

Material	**σ/ρ (m^2/Ω-kg-10^3)**
Aluminum	14.0
Magnesium	12.9
Copper	6.7
Silver	6.0
Zinc	2.4
Gold	2.1
Brass	1.8
Tin	1.2
Lead	0.45
Stainless Steel	0.18
Glass	0.0
Plastics	0.0

A significant limiting factor for the use of eddy current separation is particle size. When a particle becomes small in comparison to the rotating magnets inducing the eddy currents, the acceleration of that particle will tend to zero (Alfred 2001). For eddy current separation to be effective, the input particle size should be above at least 5 mm, but more practically above 10 mm (Cui and Forssberg 2003). This is significant because it is not uncommon for particles to be ground considerably smaller than these limits.

A.2.7 Magnetic Separation

Magnetic separation is used to separate magnetic (ferrous) materials and non-magnetic (non-ferrous) materials. This is important to electronic recycling because the solder used to attach electronic components to the printed circuit board has traditionally contained lead, which is the hallmark of ferrous materials. Although new solders that do not contain lead are beginning to enter the electronics industry, solder and other components that contain lead can still be found in electronics.

The most widely used piece of magnetic separation equipment for electronic waste is the low intensity drum separator (Cui and Forssberg 2003). In this type of magnetic separator, a large drum rotates over a fixed magnet held inside the drum. The material stream to be separated falls on top of the drum while it is rolling. As the material streams pass over the drum, the magnetic material adheres to the surface of the drum while the non-magnetic material continues to fall. Once the magnetic material moves past the area of the drum covering the magnet, it also falls. Figure A.8 depicts the process of magnetic drum separation.

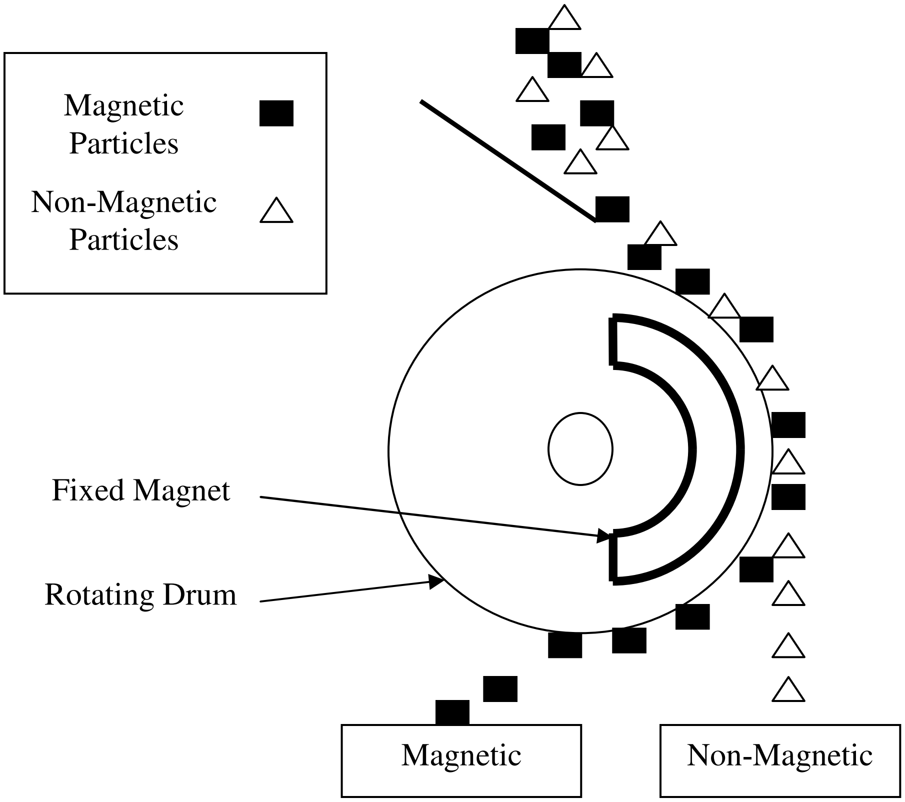


Figure A.8: Magnetic Drum Separation

There are two types of low intensity drum separation: dry and wet. In a magnetic separator many forces act on the particles that include, but are not limited to the force of gravity, the inertial force, the hydrodynamic drag, and surface and inter particles forces (Svoboda and Fujita 2003). Dry separation is typically preferred for finely ground electronic waste because the hydrodynamic drag can be neglected (Svoboda and Fujita 2003) and because of the hydrophobic nature of the material stream. It is beneficial to neglect the hydrodynamic drag because that makes the separation process independent of particle size, as the particle size dependence of the magnetic force and of the force of gravity are equal (Svoboda and Fujita 2003). The choice of magnetic separator is dominated by the distribution of magnetic properties of particles to be separated and the required throughput of the machine (Svoboda and Fujita 2003).

A.2.8 Triboelectric Separation

Triboelectric separation is a means to separate different plastics. Triboelectric separation can distinguish between two resins by simply rubbing them against each other. A triboelectric separator sorts materials on the basis of a surface charge transfer phenomenon.

Table A.2: Triboelectric Range of Polymers (Alfred 2001)

Positive (+)
PA6
PMMA
PS
ABS
PET
PC
PP
HDPE
PVC
Negative (-)

When materials are rubbed against each other, one material becomes positively charged, and the other becomes negatively charged or remains neutral.(Kang and Schoenung 2005) The particles then fall through an electric field and are separated based on their respective charges. The idea to apply this technique was a logical step as almost all plastics are naturally dielectric and thus can be sorted when the proper conditions for frictional charging are met (Dodbiba, Sadaki et al. 2005). The triboelectric range of select polymers can be seen in Table A.2.

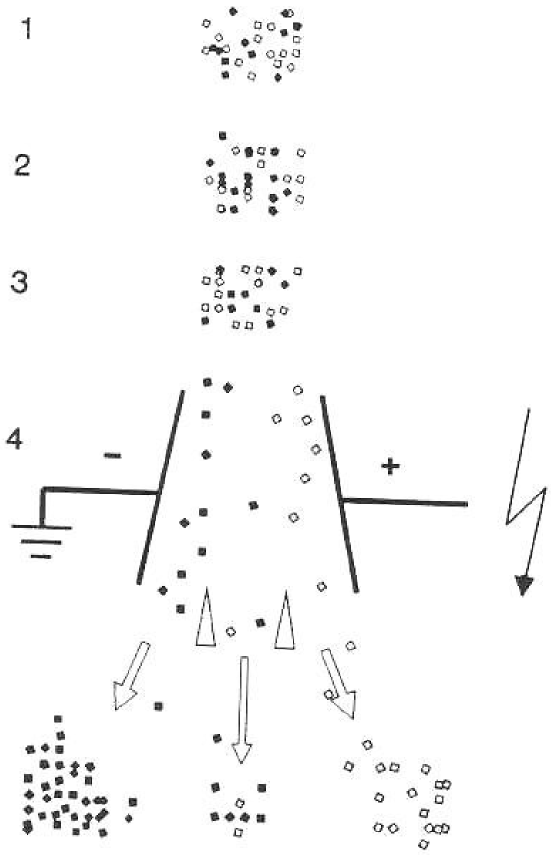


Figure A.9: Triboelectric Separation (Alfred 2001)

Often to obtain appropriate surface charge and ensure significant rubbing, a cyclone is employed. The swirling of particles through a cyclone creates excellent conditions for surface charge transfer. The process of triboelectric separation can be seen in Figure A.9. The process begins (1) with a mixture of polymers. This is followed by a conditioning phases (2). The next step (3) is triboelectric charging. The mixture then falls through a high voltage electric field (4). Finally, the polymers are separated into fractions (5) of more positive and more negative along with the middlings.

Particle size is an important variable in triboelectric separation. If the particle size is much greater than 4-5 mm then they will not be deflected by the electric field; on the other hand, if the particles are too small they tend to collect on the electrode and insulate other particles from the electric field (Kang and Schoenung 2005). Particle sizes between 2-4 mm have been found to produce the highest purity and recovery (Xiao and Laurence III 1999). Other factors that can affect the performance of a triboelectric separator are humidity, surface wetness, and temperature (Xiao and Laurence III 1999),(Dodbiba, Sadaki et al. 2005). A drawback of using triboelectric separation is that only a mixture of two different polymers can be separated or only one polymer can be removed from a mixture at a time (Alfred 2001).

A.2.9 Screening

Since many separation processes require a specific particle size input to achieve maximum material stream separation, screening is a preliminary process employed to ensure correct particle geometry. There are two screening methods that are widely used in the preprocessing of material streams: trommel and vibratory (Wilson, Veasey et al. 1994). Trommel screening involves feeding the material stream into a rotating, perforated drum to allow particles that are either less than or equal to the desired size to pass. Vibratory screening involves feeding the material onto a rapidly agitated mesh that allows particles to pass if their size is less than or equal to the desired size. It is possible to filter out a range of particle sizes by using multiple screens in series filtering the smaller particle sizes first then the larger ones. Trommel screening has a significant advantage of vibratory screening in that it is less susceptible to blinding, which occurs larger particles clog or block the mesh or perforation such that smaller particles cannot pass through (Wilson, Veasey et al. 1994).

A.3 Baling

After a recycler has processed his products, it is a common practice to bale the output. Bailing equipment is used to compact these materials into a finished compact shape or bale. Compacted material is smaller, easier to handle and less costly to transport then loose material. (Beaton 2004) In addition to compacting the material, a baler may also bind the bale with cable or twine to provide supplementary support (American Baler 2010).

APPENDIX B MODEL PARAMETER CALCULATIONS

B.1 Raw Material Refining

The gross material and energy requirements for raw material refining were calculated from the IdeMat database (IdeMat V 1.0.1.1 2001). For ferrous material, a standard low carbon steel was chosen which yielded a gross material requirement of 3.05 kg/kg and a gross energy requirement of 21.85 MJ/kg.

Since the non-ferrous metals category is a mixture of metals, a weighted average of many metals commonly found in electronic scrap was used. Table B.1 shows the material fractions of various non-ferrous metals found in electronic scrap as reported by (Cui and Zhang 2008).

Table B.1: Non-Ferrous Metal Fraction of Various Electronic Scrap

Type of Scrap	**Non-Ferrous Metal Fractions (%)**				
	Cu	**Al**	**Pb**	**Ni**	**Pd**
Electronic	8.5	0.71	3.15	2	0
PC Board	7	14	6	0.85	0.000003
PC Scrap	20	2	2	2	0.00005
E-scrap Sample 1	18.2	19	1.6	0	0
E-scrap Sample 2	16.4	11	1.4	0	0.00002

Table B.2 presents the same information shown in Table B.1, except the fractions have been normalized by the total non-ferrous fractions of the rows. At the bottom of the table the average of each normalized, non-ferrous metal fraction is shown. Those averages were taken as weighting factors to combine the material data shown in

Table B.3 from IdeMat.

Table B.2: Normalized Non-Ferrous Metal Fractions

Type of Scrap	**Normalized Non-Ferrous Metal Fractions (%)**				
	Cu	**Al**	**Pb**	**Ni**	**Pd**
Electronic	0.59	0.049	0.22	0.14	0
PC Board	0.25	0.50	0.22	0.031	1.1E-07
PC Scrap	0.77	0.077	0.077	0.077	1.9E-06
E-scrap Sample 1	0.47	0.49	0.041	0	0
E-scrap Sample 2	0.57	0.38	0.047	0	6.9E-07
Average	0.53	0.30	0.12	0.05	5.5E-07

Table B.3: IdeMat Non-Ferrous Energy and Material Requirements

IdeMat Parameter	**Cu**	**Al**	**Pb**	**Ni**	**Pd**
Gross Energy Requirement (MJ/kg)	94.9	148	29.9	180	292,000
Gross Material Requirement (kg/kg)	3.49	190	2.42	9.12	534,808

The combined result for the non-ferrous metal fraction is 107 MJ/kg for the gross energy requirement and 60 kg/kg for the gross material requirement.

Similar to the non-ferrous metals fraction, the plastic fraction's material refining parameters are taken as a weighted average of plastics commonly found in LCD

Monitors. The common plastics found in LCD monitors are taken to be approximately 50% polycarbonate and 50% ABS. The gross energy requirement of polycarbonate from IdeMat is 76.22 MJ/kg and the gross material requirement is 64.99 kg/kg. The gross energy requirement of ABS from IdeMat is 66.42 MJ/kg and the gross material requirement is 86.22 kg/kg. Taking the average of these values yields a gross energy requirement of 71.32 MJ/kg and a gross material requirement of 75.61 kg/kg for the plastics fraction.

The values in Table 4 are calculated by taking the inverse of the gross material requirement for each material respectively. The values in Table 3 can be calculated by taking the inverse of the gross material requirement for each material category and multiplying by the gross energy requirement.

APPENDIX C EPA PRIMARY INPUTS LCD COMPUTER MONITOR

Table C.1: LCD Primary Material Inputs (kg/unit) (Socolof, Overly et al. 2001)

Material	Upstream	Mfg	Use	EOL	Total	% or Fraction of Total
1,4-butanolide	0	4.06e-04	0	0	4.06E-04	1.12E-06
15" LCD light guide	0	3.74e-01	0	0	3.74E-01	1.03E-03
1-methyl-2-pyrrolidinone	0	4.06e-04	0	0	4.06E-04	1.12E-06
2-(2-butoxyethoxy)-ethanol acetate	0	8.08e-06	0	0	8.08E-06	2.23E-08
3,4,5-trifluorobromobenzene	0	2.64e-04	0	0	2.64E-04	7.29E-07
3,4-difluorobromobenzene	0	3.65e-04	0	0	3.65E-04	1.01E-06
4-4(-propylcyclohexyl)cyclohexanone	0	2.18e-04	0	0	2.18E-04	6.00E-07
4-bromophenol	0	3.27e-04	0	0	3.27E-04	9.00E-07
4-ethylphenol	0	7.00e-05	0	0	7.00E-05	1.93E-07
4-pentylphenol	0	3.42e-04	0	0	3.42E-04	9.43E-07
4-propionylphenol	0	1.94e-04	0	0	1.94E-04	5.36E-07
AlNd	0	2.97e-05	0	0	2.97E-05	8.18E-08
Aluminum (elemental)	0	1.34e-01	0	0	1.34E-01	3.70E-04
Argon	0	3.53e-05	0	0	3.53E-05	9.74E-08
Assembled 15" LCD backlight unit	0	1.48e+00	0	0	1.48E+00	4.07E-03
Assembled LCD monitor	0	0	6.50E+00	0	6.50E+00	1.79%
Backlight lamp (CCFL)	0	1.94e-03	0	0	1.94E-03	5.34E-06
Barium Carbonate	0	1.37e-02	0	0	1.37E-02	3.79E-05
Bauxite (Al2O3, ore)	0	5.09e-01	0	0	5.09E-01	1.40E-03
Cables/wires	0	2.34e-01	0	0	2.34E-01	6.45E-04
Coal, average (in ground)	1.72E+00	8.03E+00	6.69E+01	1.27E-02	7.67E+01	21.15%
Fuel oil #4	0	0	0	-6.18E-02	-6.18E-02	-1.70E-04
Glass, unspecified	0	4.37E-02	0	0	4.37E-02	1.20E-04
Glycol ethers	0	4.06E-04	0	0	4.06E-04	1.12E-06
Indium tin oxide	0	5.26E-04	0	0	5.26E-04	1.45E-06
Iron (Fe, ore)	3.26E+00	0	0	0	3.26E+00	8.98E-03
Iron scrap	4.63E-01	0	0	0	4.63E-01	1.28E-03
LCD front glass (with color filters)	0	1.78E-01	0	0	1.78E-01	4.92E-04
LCD glass	0	4.52E-01	0	0	4.52E-01	1.25E-03
LCD material (confidential)	0	3.11E-04	0	0	3.11E-04	8.56E-07
LCD module	0	1.18E+00	0	0	1.18E+00	3.26E-03
LCD spacers, unspecified	0	1.69E-05	0	0	1.69E-05	4.66E-08
Liquid crystals, for 15" LCD	0	1.24E-03	0	0	1.24E-03	3.43E-06
Mercury	0	3.99E-06	0	0	3.99E-06	1.10E-08
Metals, remaining unspeciated	0	6.81E-04	0	0	6.81E-04	1.88E-06
Mild fiber	0	7.34E-07	0	0	7.34E-07	2.02E-09
Molybdenum	0	1.78E-04	0	0	1.78E-04	4.92E-07
MoW	0	9.09E-04	0	0	9.09E-04	2.51E-06
Natural gas	0	4.22E+00	5.22E+00	-5.75E-02	9.39E+00	2.59%
Natural gas (in ground)	2.29E+02	5.16E+00	0	-1.08E+00	2.33E+02	64.25%
Neon	0	6.31E-05	0	0	6.31E-05	1.74E-07
Petroleum (in ground)	7.09E-01	2.23E+01	1.42E+00	-1.00E+00	2.34E+01	6.45%
Pigment color resist, unspecified	0	3.72E-02	0	0	3.72E-02	1.03E-04
Polarizer	0	4.07E-02	0	0	4.07E-02	1.12E-04
Poly(methyl methacrylate)	0	3.83E-01	0	0	3.83E-01	1.06E-03
Polycarbonate resin	0	5.16E-01	0	0	5.16E-01	1.42E-03
Polyester adhesive	0	6.25E-04	0	0	6.25E-04	1.72E-06
Polyethylene terephthalate	0	5.88E-02	0	0	5.88E-02	1.62E-04

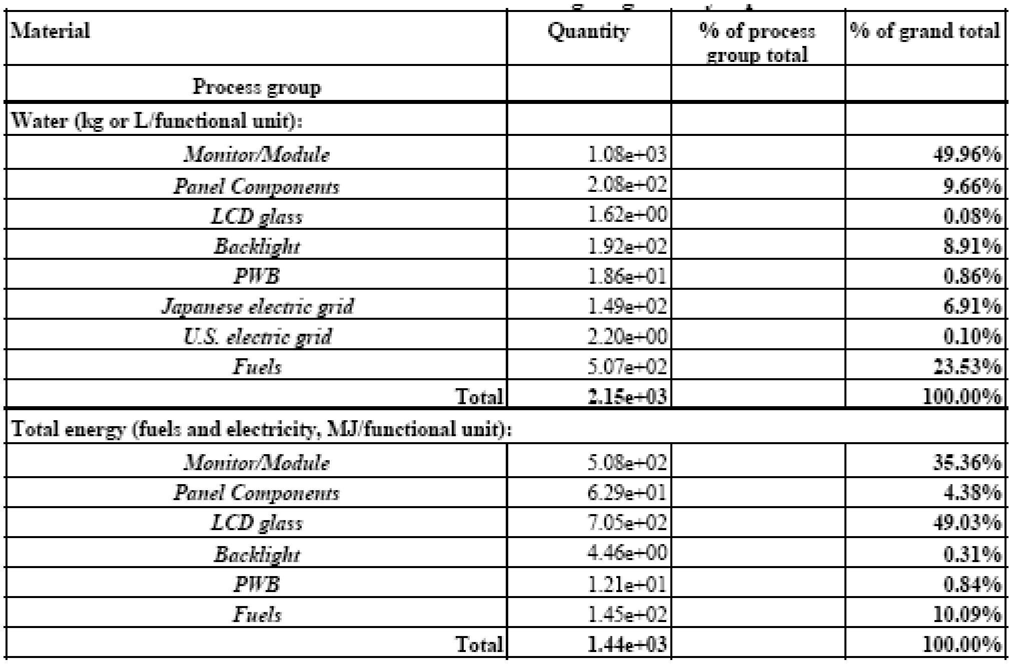
Table C.1: LCD Primary Material Inputs (kg/unit) (Socolof, Overly et al. 2001) (Cont.)

Material	Upstream	Mfg	Use	EOL	Total	% or Fraction of Total
Polyimide alignment layer, unspecified	0	4.86E-04	0	0	4.86E-04	1.34E-06
Polyvinyl alcohol	0	8.61E-03	0	0	8.61E-03	2.37E-05
Potassium Carbonate	0	1.75E-02	0	0	1.75E-02	4.83E-05
PPE	0	3.00E-01	0	0	3.00E-01	8.27E-04
Printed wiring board (PWB)	0	3.74E-01	0	0	3.74E-01	1.03E-03
PWB-laminate	0	3.74E-01	0	0	3.74E-01	1.03E-03
Recycled LCD glass	0	9.54E-02	0	0	9.54E-02	2.63E-04
Rubber, unspecified	0	6.01E-04	0	0	6.01E-04	1.66E-06
Sand	0	1.11E-01	0	0	1.11E-01	3.07E-04
Sodium Carbonate	0	2.26E-02	0	0	2.26E-02	6.23E-05
Solder (60% tin, 40% lead)	0	3.81E-02	0	0	3.81E-02	1.05E-04
Solder (63% tin; 37% lead)	0	2.24E-02	0	0	2.24E-02	6.18E-05
Steel	0	2.53E+00	0	0	2.53E+00	6.97E-03
Strontium Carbonate	0	1.53E-02	0	0	1.53E-02	4.23E-05
Styrene-butadiene copolymers	0	3.62E-01	0	0	3.62E-01	9.97E-04
Titanium	0	1.33E-04	0	0	1.33E-04	3.67E-07
Triallyl isocyanurate	0	1.54E-05	0	0	1.54E-05	4.26E-08
Triphenyl phosphate	0	9.25E-02	0	0	9.25E-02	2.55E-04
Unspecified LCD material	0	1.19E-04	0	0	1.19E-04	3.29E-07
Uranium, yellowcake	0	1.03E-03	1.81E-03	3.4352E-07	2.84E-03	7.84E-06
Zircon Sand	0	1.31E-03	0	0	1.31E-03	3.62E-06
Total primary inputs	2.35E+02	4.97E+01	8.01E+01	-2.19E+00	3.63E+02	100.00%

Table C.2: LCD Utility Inputs

Material	**Quantity**	**% of process group total**	**% of grand total**
Process group			
Fuels (kg/functional unit):			
Monitor/Module			
Fuel oil #4	2.11e-01	4.09%	
Kerosene	2.98e-01	5.77%	
LNG	3.22e+00	62.40%	
Liquified petroleum gas (LPG)	5.83e-01	11.30%	
Natural gas	8.48e-01	16.44%	
Total	**5.16e+00**	95.91%	**20.13%**
Panel Components			
Kerosene	1.68e-01	31.97%	
Natural gas	1.18e-07	<0.01%	
Steam (100 psig)	1.45e-01	27.56%	
Fuel oil #2	4.07e-04	0.08%	
Fuel oil #6	1.25e-01	23.91%	
Natural gas	8.64e-02	16.47%	
Total	**5.25e-01**	68.03%	**2.05%**
LCD glass			
Fuel oil #2	5.38e-02	0.33%	
Liquified petroleum gas (LPG)	1.62e+01	99.33%	
Natural gas	5.63e-02	0.34%	
Total	**1.64e+01**	100.00%	**63.87%**
Backlight			
LNG	4.17e-06	50.00%	
Natural gas	4.17e-06	50.00%	
Total	**8.33e-06**	200.00%	**0.00%**
PWB			
Natural gas	??		**ERR**
Fuels			
Coal, average (in ground)	6.86e-01	19.19%	
Natural gas (in ground)	2.41e+00	67.27%	
Petroleum (in ground)	4.84e-01	13.54%	
Uranium (U, ore)	1.15e-05	<0.01%	
Total	**3.58e+00**	100.00%	**13.96%**
Grand Total	**2.56e+01**		**100.00%**
Electricity (MJ/functional unit):			
Monitor/Module	2.59e+02		**81.80%**
Panel Components	4.64e+01		**14.70%**
LCD glass	2.20e+00		**0.70%**
Backlight	4.46e+00		**1.41%**
PWB	4.43e+00		**1.40%**
Total	**3.16e+02**		**100.00%**

Table C.2: LCD Utility Inputs (Cont.)



Material	Quantity	% of process group total	% of grand total
Process group			
Water (kg or L/functional unit):			
Monitor/Module	1.08e+03		**49.96%**
Panel Components	2.08e+02		**9.66%**
LCD glass	1.62e+00		**0.08%**
Backlight	1.92e+02		**8.91%**
PWB	1.86e+01		**0.86%**
Japanese electric grid	1.49e+02		**6.91%**
U.S. electric grid	2.20e+00		**0.10%**
Fuels	5.07e+02		**23.53%**
Total	**2.15e+03**		**100.00%**
Total energy (fuels and electricity, MJ/functional unit):			
Monitor/Module	5.08e+02		**35.36%**
Panel Components	6.29e+01		**4.38%**
LCD glass	7.05e+02		**49.03%**
Backlight	4.46e+00		**0.31%**
PWB	1.21e+01		**0.84%**
Fuels	1.45e+02		**10.09%**
Total	**1.44e+03**		**100.00%**

APPENDIX D ECOINVENT LCD MONITOR LCI

Table D.1: LCD Glass at Plant

General Flow information							Representation in ecoinvent								Uncertainty information		
Input		Process Name		Output		Remarks	Category	Sub-category	Infra-structure	Location	Modul name in ecoinvent	Mean value	Unit	Source	Type	StDv 95%	General Comment
Water (unspec.)	⇨	LCD glass, at plant					resource	in water			Water, unspecified natural origin	7.50E-03	m3	amount according to Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,12); data from an US-EPA LCA study
barium carbonate	⇨					dataset "barite, at plant" used as a proxy	chemicals	inorganics	No	RER	barite, at plant	5.26E-02	kg	calculated from Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,3); data from an US-EPA LCA study
glass, unspecified	⇨					assumed to be glass cullets from extern	glass	packaging	No	RER	glass, from public collection, unsorted	8.76E-03	kg	calculated from Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,3); data from an US-EPA LCA study
potassium carbonate	⇨						chemicals	inorganics	No	GLO	potassium carbonate, at plant	6.72E-02	kg	calculated from Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,3); data from an US-EPA LCA study
sand	⇨						construction materials	additives	No	DE	silica sand, at plant	4.26E-01	kg	calculated from Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,3); data from an US-EPA LCA study
sodium carbonate	⇨						chemicals	inorganics	No	RER	soda, powder, at plant	8.67E-02	kg	calculated from Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,3); data from an US-EPA LCA study
strontium carbonate	⇨					dataset "copper carbonate, at plan" used as a proxy	chemicals	inorganics	No	RER	copper carbonate, at plant	5.88E-02	kg	calculated from Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,3); data from an US-EPA LCA study
zircon sand	⇨					dataset "zirconum oxide" used as a proxy	chemicals	inorganics	No	AU	zirconium oxide, at plant	9.63E-03	kg	calculated from Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,3); data from an US-EPA LCA study
aluminium oxide	⇨						chemicals	inorganics	No	RER	aluminium oxide, at plant	5.95E-03	kg	calculated from Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,3); data from an US-EPA LCA study
cerium oxide	⇨					dataset "cerium concentratet, 60%cerium oxide, at plant" used as a proxy	chemicals	inorganics	No	CN	cerium concentrate, 60% cerium oxide, at plant	5.84E-04	kg	calculated from Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,3); data from an US-EPA LCA study
chromium oxide	⇨						chemicals	inorganics	No	RER	chromium oxide, flakes, at plant	1.08E-05	kg	calculated from Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,3); data from an US-EPA LCA study
hydrofluoric acid	⇨						chemicals	inorganics	No	GLO	hydrogen fluoride, at plant	1.69E-02	kg	amount according to Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,3); data from an US-EPA LCA study
pumice	⇨					pumice is silicon dioxide - hence dataset "silica sand" used	construction materials	additives	No	DE	silica sand, at plant	1.69E-02	kg	amount according to Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,3); data from an US-EPA LCA study
Water treatment chemicals	⇨			continued ▼		chemicals organic used as proxy	chemicals	organics	No	GLO	chemicals organic, at plant	3.30E-04	kg	estimated, based on CRT panel production	1	1.64	(4,3,3,3,4,5,3); estimation, based on CRT panel glass production

Table D.1: LCD Glass at Plant (Cont.)

General Flow information							Representation in ecoinvent								Uncertainty information		
Input		Process Name		Output		Remarks	Category	Sub-category	Infra-structure	Loca-tion	Modul name in ecoinvent	Mean value	Unit	Source	Type	StDv 95%	General Comment
lubricants polishing, grinding	⇨	LCD glass, at plant		▼ continued		solvents, organic, unspecified used as proxy	chemicals	organics	No	GLO	solvents, organic, unspecified, at plant	2.10E-04	kg	estimated, based on CRT panel production	1	1.64	(4,3,3,3,4,5,3); estimation, based on CRT panel glass production
grinding aid	⇨					chemicals organic used as proxy	chemicals	organics	No	GLO	chemicals organic, at plant	2.64E-03	kg	estimated, based on CRT panel production	1	1.64	(4,3,3,3,4,5,3); estimation, based on CRT panel glass production
technical gas, NH3	⇨					liquid ammonia dataset used as proxy	chemicals	inorganics	No	RER	ammonia, liquid, at regional storehouse	2.00E-03	kg	estimated, based on CRT panel production	1	1.64	(4,3,3,3,4,5,3); estimation, based on CRT panel glass production
technical gas, O2	⇨					m3->kg with a value of 1.337 kg/m3 according to PanGas (2006)	chemicals	inorganics	No	RER	oxygen, liquid, at plant	2.01E-03	kg	estimated, based on CRT panel production	1	1.64	(4,3,3,3,4,5,3); estimation, based on CRT panel glass production
electricity	⇨					5%assumed as US-mix	electricity	supply mix	No	US	electricity, medium voltage, at grid	1.41E-01	kWh	total amount according to Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,2); data from an US-EPA LCA study
electricity	⇨					35%assumed as Japanese mix	electricity	supply mix	No	JP	electricity, medium voltage, at grid	9.90E-01	kWh	total amount according to Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,2); data from an US-EPA LCA study
electricity	⇨					25%assumed as Taiwanese mix (here with Japanese mix as proxy)	electricity	supply mix	No	JP	electricity, medium voltage, at grid	7.07E-01	kWh	total amount according to Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,2); data from an US-EPA LCA study
electricity	⇨					35%assumed as South Korean mix (here with Chinese mix as proxy)	electricity	supply mix	No	CN	electricity, medium voltage, at grid	9.90E-01	kWh	total amount according to Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,2); data from an US-EPA LCA study
natural gas	⇨						natural gas	heating systems	No	RER	heat, natural gas, at industrial furnace >100kW	1.00E+01	MJ	amount according to CRT glass dataset	1	2.03	(3,3,2,3,5,3,1); analogy conclusion - from CRT glass production data
low sulphur oil	⇨					L->MJ with a heating value of 42.6 MJ/kg and a density of 0.86 kg/L according to ecoinvent	oil	heating systems	No	RER	heat, light fuel oil, at industrial furnace 1MW	1.06E+01	MJ	amount according to Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,1); data from an US-EPA LCA study
infrastructure	⇨						glass	packaging	Yes	RER	glass production site	1.25E-10	unit	value for packaging glass production, taken from Hischier (2004)	1	3.33	(1,5,3,3,4,5,9); Estimation from packaging glass production
transportation	⇨			continued ▼			transport systems	road	No	RER	transport, lorry 3.5-16t, fleet average	1.47E-04	tkm	value for packaging glass production, taken from Hischier (2004)	1	2.34	(1,5,3,3,4,5,5); Estimation from packaging glass production

Table D.1: LCD Glass at Plant (Cont.)

General Flow information							Representation in ecoinvent								Uncertainty information		
Input		Process Name		Output		Remarks	Category	Sub-category	Infra-structure	Loca-tion	Modul name in ecoinvent	Mean value	Unit	Source	Type	StDv 95%	General Comment
transportation	⇨	LCD glass, at plant		▼ continued			transport systems	road	No	RER	transport, lorry >16t, fleet average	1.31E-01	tkm	value for packaging glass production, taken from Hischier (2004)	1	2.34	(1,5,3,3,4,5,5); Estimation from packaging glass production
			⇨	Waste Batch (Ba, Pb) (D008 waste)		proxy from ecoinvent used	waste management	municipal incineration	No	CH	disposal, lead in car shredder residue, 0%water, to municipal incineration	3.03E-04	kg	amount according to Socolof et al. (2001)	1	1.52	(1,3,2,3,4,3,6); data from an US-EPA LCA study - approximated with existing waste process
			⇨	Hydrofluoric acid		proxy from ecoinvent used	waste management	hazardous waste incineration	No	CH	disposal, solvents mixture, 16.5%water, to hazardous waste incineration	3.81E-04	kg	amount according to Socolof et al. (2001)	1	1.52	(1,3,2,3,4,3,6); data from an US-EPA LCA study - approximated with existing waste process
			⇨	Chrome debris (D007 waste)		proxy from ecoinvent used	waste management	inert material landfill	No	CH	disposal, inert waste, 5% water, to inert material landfill	3.16E-05	kg	amount according to Socolof et al. (2001)	1	1.52	(1,3,2,3,4,3,6); data from an US-EPA LCA study - approximated with existing waste process
			⇨	Barium debris (D008 waste)		proxy from ecoinvent used	waste management	inert material landfill	No	CH	disposal, inert waste, 5% water, to inert material landfill	4.59E-05	kg	amount according to Socolof et al. (2001)	1	1.52	(1,3,2,3,4,3,6); data from an US-EPA LCA study - approximated with existing waste process
			⇨	Glass to landfill		proxy for glass waste to landfill	waste management	inert material landfill	No	CH	disposal, glass, 0%water, to inert material landfill	5.86E-03	kg	amount according to Socolof et al. (2001)	1	1.52	(1,3,2,3,4,3,6); data from an US-EPA LCA study - approximated with existing waste process
			⇨	waste to landfill		proxy for amount of waste to landfill	waste management	sanitary landfill	No	CH	disposal, municipal solid waste, 22.9%water, to sanitary landfill	6.19E-03	kg	amount according to Socolof et al. (2001)	1	1.52	(1,3,2,3,4,3,6); data from an US-EPA LCA study - approximated with existing waste process
			⇨	waste for further treatment		proxy for amount of waste to further treatment	waste management	hazardous waste incineration	No	CH	disposal, solvents mixture, 16.5%water, to hazardous waste incineration	1.44E-03	kg	amount according to Socolof et al. (2001)	1	1.52	(1,3,2,3,4,3,6); data from an US-EPA LCA study - approximated with existing waste process
			⇨	Waste heat		calculated from the electricity input	air	high population density			Heat, waste	1.02E+01	MJ	calculated as reported in Frischknecht et al. (2004)	1	1.64	(4,3,3,3,4,5,13); Calculated from electricity input
			⇨	chromium, to air			air	high population density			Chromium	2.96E-08	kg	amount according to Socolof et al. (2001)	1	1.51	(1,3,2,3,1,3,31); data from an US-EPA LCA study
continued ▼			⇨	BOD, to water			water	river			BOD5, Biological Oxygen Demand	1.76E-06	kg	amount according to Socolof et al. (2001)	1	1.51	(1,3,2,3,1,3,32); data from an US-EPA LCA study

Table D.1: LCD Glass at Plant (Cont.)

General Flow information							Representation in ecoinvent								Uncertainty information		
Input		Process Name		Output		Remarks	Category	Sub-category	Infrastructure	Location	Modul name in ecoinvent	Mean value	Unit	Source	Type	StDv 95%	General Comment
transportation	⇨	LCD glass, at plant		▼ continued			transport systems	road	No	RER	transport, lorry >16t, fleet average	1.31E-01	tkm	value for packaging glass production, taken from Hischier (2004)	1	2.34	(1,5,3,3,4,5,5); Estimation from packaging glass production
			⇨	Waste Batch (Ba, Pb) (D008 waste)		proxy from ecoinvent used	waste management	municipal incineration	No	CH	disposal, lead in car shredder residue, 0%water, to municipal incineration	3.03E-04	kg	amount according to Socolof et al. (2001)	1	1.52	(1,3,2,3,4,3,6); data from an US-EPA LCA study - approximated with existing waste process
			⇨	Hydrofluoric acid		proxy from ecoinvent used	waste management	hazardous waste incineration	No	CH	disposal, solvents mixture, 16.5%water, to hazardous waste incineration	3.81E-04	kg	amount according to Socolof et al. (2001)	1	1.52	(1,3,2,3,4,3,6); data from an US-EPA LCA study - approximated with existing waste process
			⇨	Chrome debris (D007 waste)		proxy from ecoinvent used	waste management	inert material landfill	No	CH	disposal, inert waste, 5% water, to inert material landfill	3.16E-05	kg	amount according to Socolof et al. (2001)	1	1.52	(1,3,2,3,4,3,6); data from an US-EPA LCA study - approximated with existing waste process
			⇨	Barium debris (D008 waste)		proxy from ecoinvent used	waste management	inert material landfill	No	CH	disposal, inert waste, 5% water, to inert material landfill	4.59E-05	kg	amount according to Socolof et al. (2001)	1	1.52	(1,3,2,3,4,3,6); data from an US-EPA LCA study - approximated with existing waste process
			⇨	Glass to landfill		proxy for glass waste to landfill	waste management	inert material landfill	No	CH	disposal, glass, 0%water, to inert material landfill	5.86E-03	kg	amount according to Socolof et al. (2001)	1	1.52	(1,3,2,3,4,3,6); data from an US-EPA LCA study - approximated with existing waste process
			⇨	waste to landfill		proxy for amount of waste to landfill	waste management	sanitary landfill	No	CH	disposal, municipal solid waste, 22.9%water, to sanitary landfill	6.19E-03	kg	amount according to Socolof et al. (2001)	1	1.52	(1,3,2,3,4,3,6); data from an US-EPA LCA study - approximated with existing waste process
			⇨	waste for further treatment		proxy for amount of waste to further treatment	waste management	hazardous waste incineration	No	CH	disposal, solvents mixture, 16.5%water, to hazardous waste incineration	1.44E-03	kg	amount according to Socolof et al. (2001)	1	1.52	(1,3,2,3,4,3,6); data from an US-EPA LCA study - approximated with existing waste process
			⇨	Waste heat		calculated from the electricity input	air	high population density			Heat, waste	1.02E+01	MJ	calculated as reported in Frischknecht et al. (2004)	1	1.64	(4,3,3,3,4,5,13); Calculated from electricity input
			⇨	chromium, to air			air	high population density			Chromium	2.96E-08	kg	amount according to Socolof et al. (2001)	1	1.51	(1,3,2,3,1,3,31); data from an US-EPA LCA study
continued ▼			⇨	BOD, to water			water	river			BOD5, Biological Oxygen Demand	1.76E-06	kg	amount according to Socolof et al. (2001)	1	1.51	(1,3,2,3,1,3,32); data from an US-EPA LCA study

Table D.1: LCD Glass at Plant (Cont.)

General Flow information							Representation in ecoinvent								Uncertainty information		
Input		Process Name		Output		Remarks	Category	Sub-category	Infra-structure	Loca-tion	Modul name in ecoinvent	Mean value	Unit	Source	Type	StDv 95%	General Comment
▼ continued		LCD glass, at plant	⇨	chloride ions, to water			water	river			Chloride	2.17E-01	kg	amount according to Socolof et al. (2001)	1	1.51	(1,3,2,3,1,3,33); data from an US-EPA LCA study
			⇨	chromium, to water			water	river			Chromium, ion	1.76E-08	kg	amount according to Socolof et al. (2001)	1	1.51	(1,3,2,3,1,3,33); data from an US-EPA LCA study
			⇨	COD, to water			water	river			COD, Chemical Oxygen Demand	1.76E-06	kg	amount according to Socolof et al. (2001)	1	1.51	(1,3,2,3,1,3,32); data from an US-EPA LCA study
			⇨	dissolved solids, to water		as "solids, inorganics" shown here	water	river			Solids, inorganic	7.78E-01	kg	amount according to Socolof et al. (2001)	1	1.51	(1,3,2,3,1,3,33); data from an US-EPA LCA study
			⇨	fluroides, to water			water	river			Fluoride	6.30E-04	kg	amount according to Socolof et al. (2001)	1	1.51	(1,3,2,3,1,3,33); data from an US-EPA LCA study
			⇨	iron, to water			water	river			Iron, ion	5.93E-04	kg	amount according to Socolof et al. (2001)	1	1.81	(1,3,2,3,1,3,37); data from an US-EPA LCA study
			⇨	lead to water			water	river			Lead	9.31E-06	kg	amount according to Socolof et al. (2001)	1	1.81	(1,3,2,3,1,3,37); data from an US-EPA LCA study
			⇨	nickel, to water			water	river			Nickel, ion	1.76E-08	kg	amount according to Socolof et al. (2001)	1	1.81	(1,3,2,3,1,3,37); data from an US-EPA LCA study
			⇨	nitrate, to water			water	river			Nitrate	8.47E-07	kg	amount according to Socolof et al. (2001)	1	1.51	(1,3,2,3,1,3,33); data from an US-EPA LCA study
			⇨	oil & grease, to water			water	river			Oils, unspecified	1.55E-03	kg	amount according to Socolof et al. (2001)	1	3.01	(1,3,2,3,1,3,34); data from an US-EPA LCA study
			⇨	suspended soilds, to water			water	river			Suspended solids, unspecified	1.55E-03	kg	amount according to Socolof et al. (2001)	1	1.51	(1,3,2,3,1,3,33); data from an US-EPA LCA study
			⇨	LCD glass			electronics	component	No	GLO	LCD glass, at plant	1.00E+00	kg				

Table D.2: LCD Module at Plant

General Flow information							Representation in ecoinvent								Uncertainty information		
Input		Process Name		Output		Remarks	Category	Sub-category	Infra-structure	Loca-tion	Modul name in ecoinvent	Mean value	Unit	Source	Type	StDv 95%	General Comment
Glass	⇨	LCD module, at plant				panel glass from CRT used as proxy	electronics	component	No	GLO	LCD glass, at plant	2.97E-01	kg	amount calculated from US-EPA (1998)	1	1.22	(1,3,2,3,1,5,3); calculated from an US-EPA study
ITO layer	⇨						electronics	module	No	RER	sputtering, ITO, for LCD	5.59E-08	m3	amount calculated from Socolof et al. (2001) - see report	1	1.22	(1,3,2,3,1,5,3); calculated from an US-EPA study
row driver TAB	⇨					dataset "integrated circuit, IC, logic type, at plant" used as proxy	electronics	component	No	GLO	integrated circuit, IC, logic type, at plant	1.90E-03	kg	amount according to US-EPA (1998)	1	1.22	(1,3,2,3,1,5,3); calculated from an US-EPA study
Col. driver TAB	⇨					dataset "integrated circuit, IC, logic type, at plant" used as proxy	electronics	component	No	GLO	integrated circuit, IC, logic type, at plant	6.30E-03	kg	amount according to US-EPA (1998)	1	1.22	(1,3,2,3,1,5,3); calculated from an US-EPA study
Row driver input PWB	⇨					dataset "printed wiring board, mounted, unspecified, at plant" used as proxy	electronics	module	No	GLO	printed wiring board, mixed mounted, unspec., solder mix, at plant	1.88E-02	kg	amount according to US-EPA (1998)	1	1.22	(1,3,2,3,1,5,3); calculated from an US-EPA study
Col. driver input PWB	⇨					dataset "printed wiring board, mounted, unspecified, at plant" used as proxy	electronics	module	No	GLO	printed wiring board, mixed mounted, unspec., solder mix, at plant	2.50E-02	kg	amount according to US-EPA (1998)	1	1.22	(1,3,2,3,1,5,3); calculated from an US-EPA study
connection flex	⇨					100%Cu assumed	metals	extraction	No	RER	copper, at regional storage	3.10E-03	kg	amount according to US-EPA (1998)	1	1.22	(1,3,2,3,1,5,3); calculated from an US-EPA study
connection flex, processing	⇨					processing as "sheet rolling" approximated	metals	processing	No	RER	sheet rolling, copper	3.10E-03	kg	amount according to US-EPA (1998)	1	1.22	(1,3,2,3,1,5,3); calculated from an US-EPA study
Frame (plastic part)	⇨						plastics	polymers	No	RER	polycarbonate, at plant	9.38E-02	kg	amount according to US-EPA (1998)	1	1.22	(1,3,2,3,1,5,3); calculated from an US-EPA study
Frame (plastic part processing)	⇨					injection moulding assumed	plastics	processing	No	RER	injection moulding	9.38E-02	kg	amount according to US-EPA (1998)	1	1.22	(1,3,2,3,1,5,3); calculated from an US-EPA study
Brightness enhancer	⇨						plastics	polymers	No	RER	nylon 6, at plant	6.30E-03	kg	amount according to US-EPA (1998)	1	1.22	(1,3,2,3,1,5,3); calculated from an US-EPA study
backlight unit	⇨						electronics	component	No	GLO	backlight, LCD screen, at plant	4.31E-01	kg	amount according to US-EPA (1998)	1	1.22	(1,3,2,3,1,5,3); calculated from an US-EPA study
backlight frame	⇨						metals	extraction	No	RER	chromium steel 18/8, at plant	1.09E-01	kg	amount according to US-EPA (1998)	1	1.22	(1,3,2,3,1,5,3); calculated from an US-EPA study
backlight frame, processing	⇨					section bar rolling assumed	metals	processing	No	RER	section bar rolling, steel	1.09E-01	kg	amount according to US-EPA (1998)	1	1.22	(1,3,2,3,1,5,3); calculated from an US-EPA study
Gasket, screws, clips, etc.	⇨			continued ▼		50%are assumed to be steel	metals	extraction	No	RER	chromium steel 18/8, at plant	4.05E-03	kg	amount according to US-EPA (1998)	1	1.22	(1,3,2,3,1,5,3); calculated from an US-EPA study

Table D.2: LCD Module at Plant (Cont.)

General Flow information							Representation in ecoinvent								Uncertainty information		
Input		Process Name		Output		Remarks	Category	Sub-category	Infra-structure	Loca-tion	Modul name in ecoinvent	Mean value	Unit	Source	Type	StDv 95%	General Comment
Gasket, screws, clips, etc.	⇨	LCD module, at plant		▼ continued		50%are assumed to be rubber & plastics - here as 100% rubber	plastics	polymers	No	RER	synthetic rubber, at plant	4.05E-03	kg	amount according to US-EPA (1998)	1	1.22	(1,3,2,3,1,5,3); calculated from an US-EPA study
production efforts	⇨						electronics	module	No	GLO	assembly, LCD module	1.00E+00	kg	production efforts - data from Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,3); data from an US-EPA LCA study
			⇨	LCD module			electronics	module	No	GLO	LCD module, at plant	1.00E+00	kg				

Table D.3: LCD Module Assembly at Plant

General Flow information							Representation in ecoinvent								Uncertainty information		
Input		Process Name		Output		Remarks	Category	Sub-category	Infra-structure	Loca-tion	Modul name in ecoinvent	Mean value	Unit	Source	Type	StDv 95%	General Comment
Water (unspec.)	⇨	assembly, LCD module					resource	in water			Water, unspecified natural origin	2.81E-01	m3	amount according to Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,12); data from an US-EPA LCA study
Liquid crystal and polarizer	⇨					represented from the dataset "panel components, at plant"	electronics	component	No	GLO	panel components, at plant	2.19E-02	kg	amount estimated from Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,3); data from an US-EPA LCA study
1,4-butanolide	⇨					dataset "chemicals, organic" used as proxy	chemicals	organics	No	GLO	chemicals organic, at plant	2.11E-04	kg	amount according to Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,3); data from an US-EPA LCA study
1-methyl2-pyrrolidinone	⇨						chemicals	organics	No	RER	N-methyl-2-pyrrolidone, at plant	2.11E-04	kg	amount according to Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,3); data from an US-EPA LCA study
2-(2-butoxyethoxy)-ethanol acetate	⇨					dataset "chemicals, organic" used as proxy	chemicals	organics	No	GLO	chemicals organic, at plant	4.21E-06	kg	amount according to Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,3); data from an US-EPA LCA study
Glycon ethers	⇨					dataset "ethylene glycol" used as proxy	chemicals	organics	No	RER	ethylene glycol, at plant	2.11E-04	kg	amount according to Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,3); data from an US-EPA LCA study
Mild fiber	⇨					dataset "glass fiber" used as proxy	glass	construction	No	RER	glass fibre, at plant	3.82E-07	kg	amount according to Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,3); data from an US-EPA LCA study
polyimide alignment layer, unspecified	⇨					dataset "polycarbonate" uased as proxy	plastics	polymers	No	RER	polycarbonate, at plant	2.53E-04	kg	amount according to Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,3); data from an US-EPA LCA study
triallyl isocyanurate	⇨					dataset "toluene diisocyanate" used as proxy	plastics	monomers	No	RER	toluene diisocyanate, at plant	8.02E-06	kg	amount according to Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,3); data from an US-EPA LCA study
triphenyl phosphate	⇨					dataset "sodium phosphate" used as proxy	chemicals	inorganics	No	RER	sodium phosphate, at plant	4.82E-02	kg	amount according to Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,3); data from an US-EPA LCA study
acetic acid	⇨						chemicals	organics	No	RER	acetic acid, 98% in H2O, at plant	1.67E-03	kg	amount according to Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,3); data from an US-EPA LCA study
acetoene	⇨						chemicals	organics	No	RER	acetone, liquid, at plant	2.68E-03	kg	amount according to Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,3); data from an US-EPA LCA study
aluminium sulphate	⇨						chemicals	inorganics	No	RER	aluminium sulphate, powder, at plant	2.73E-02	kg	amount according to Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,3); data from an US-EPA LCA study
ammonia & ammonium containing substances	⇨			continued ▼		data of ammonia, ammonium bifluoride, ammonium fluoride and ammonium hydroxide	chemicals	inorganics	No	RER	ammonia, liquid, at regional storehouse	7.62E-03	kg	amount according to Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,3); data from an US-EPA LCA study

Table D.3: LCD Module Assembly at Plant (Cont.)

General Flow information							Representation in ecoinvent								Uncertainty information		
Input		Process Name		Output		Remarks	Category	Sub-category	Infrastructure	Location	Modul name in ecoinvent	Mean value	Unit	Source	Type	StDv 95%	General Comment
argon	➪	assembly, LCD module		▼ continued			chemicals	inorganics	No	RER	argon, crude, liquid, at plant	2.05E-03	kg	amount according to Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,3); data from an US-EPA LCA study
calcium hydroxide	➪						construction materials	binder	No	CH	lime, hydrated, packed, at plant	3.62E-02	kg	amount according to Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,3); data from an US-EPA LCA study
carbon dioxide	➪						chemicals	inorganics	No	RER	carbon dioxide liquid, at plant	9.74E-06	kg	amount according to Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,3); data from an US-EPA LCA study
chlorine	➪						chemicals	inorganics	No	RER	chlorine, liquid, production mix, at plant	4.04E-03	kg	amount according to Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,3); data from an US-EPA LCA study
cyclohexane	➪						chemicals	organics	No	RER	cyclohexanol, at plant	5.29E-06	kg	amount according to Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,3); data from an US-EPA LCA study
dimethylsulfoxide	➪						chemicals	organics	No	RER	dimethyl sulfoxide, at plant	1.73E-02	kg	amount according to Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,3); data from an US-EPA LCA study
ethanol	➪						chemicals	organics	No	RER	ethanol from ethylene, at plant	3.52E-03	kg	amount according to Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,3); data from an US-EPA LCA study
hydrochloric acid	➪						chemicals	inorganics	No	RER	hydrochloric acid, 30% in H2O, at plant	1.12E-02	kg	amount according to Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,3); data from an US-EPA LCA study
hydrofluoric acid	➪						chemicals	inorganics	No	GLO	hydrogen fluoride, at plant	1.10E-03	kg	amount according to Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,3); data from an US-EPA LCA study
hydrogen	➪						chemicals	inorganics	No	RER	hydrogen, liquid, at plant	1.16E-01	kg	amount according to Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,3); data from an US-EPA LCA study
hydrogen peroxide	➪						chemicals	inorganics	No	RER	hydrogen peroxide, 50% in H2O, at plant	3.83E-05	kg	amount according to Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,3); data from an US-EPA LCA study
isopropyl alcohol	➪						chemicals	organics	No	RER	isopropanol, at plant	9.09E-02	kg	amount according to Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,3); data from an US-EPA LCA study
krypton	➪						chemicals	inorganics	No	CH	krypton, gaseous, at regional storage	6.72E-06	kg	amount according to Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,3); data from an US-EPA LCA study
methyl ethyl ketone	➪			continued ▼			chemicals	organics	No	RER	methyl ethyl ketone, at plant	1.91E-06	kg	amount according to Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,3); data from an US-EPA LCA study

Table D.3: LCD Module Assembly at Plant (Cont.)

General Flow information							Representation in ecoinvent								Uncertainty information		
Input		Process Name		Output		Remarks	Category	Sub-category	Infra-structure	Loca-tion	Modul name in ecoinvent	Mean value	Unit	Source	Type	StDv 95%	General Comment
nitric acid	⇨	assembly, LCD module		▼ continued			chemicals	inorganics	No	RER	nitric acid, 50%in H2O, at plant	3.23E-03	kg	amount according to Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,3); data from an US-EPA LCA study
nitrogen	⇨						chemicals	inorganics	No	RER	nitrogen, liquid, at plant	1.54E+00	kg	amount according to Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,3); data from an US-EPA LCA study
oxygen	⇨						chemicals	inorganics	No	RER	oxygen, liquid, at plant	2.02E-03	kg	amount according to Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,3); data from an US-EPA LCA study
phosphoric acid	⇨						chemicals	inorganics	No	RER	phosphoric acid, industrial grade, 85%in H2O, at plant	1.03E-02	kg	amount according to Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,3); data from an US-EPA LCA study
proplyene glycol	⇨						chemicals	organics	No	RER	propylene glycol, liquid, at plant	5.22E-03	kg	amount according to Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,3); data from an US-EPA LCA study
sodium hydroxide	⇨						chemicals	inorganics	No	RER	sodium hydroxide, 50%in H2O, production mix, at plant	9.35E-02	kg	amount according to Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,3); data from an US-EPA LCA study
sulfuric acid	⇨						chemicals	inorganics	No	RER	sulphuric acid, liquid, at plant	5.96E-02	kg	amount according to Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,3); data from an US-EPA LCA study
xylene (mixed)	⇨						chemicals	organics	No	RER	xylene, at plant	4.09E-04	kg	amount according to Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,3); data from an US-EPA LCA study
various organic chemicals	⇨					all those chemicals not separately mentioned here (all information from Socolof et al. (2001))	chemicals	organics	No	GLO	chemicals organic, at plant	1.57E-01	kg	amount according to Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,3); data from an US-EPA LCA study
fuel oil #4	⇨					light fuel oil used as proxy	oil	heating systems	No	RER	heat, light fuel oil, at industrial furnace 1MW	2.34E+00	MJ	amount according to Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,1); data from an US-EPA LCA study
kerosene	⇨					light fuel oil used as proxy	oil	heating systems	No	RER	heat, light fuel oil, at industrial furnace 1MW	3.31E+00	MJ	amount according to Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,1); data from an US-EPA LCA study
LNG	⇨					natural gas as proxy used	natural gas	heating systems	No	RER	heat, natural gas, at industrial furnace >100kW	3.81E+01	MJ	amount according to Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,1); data from an US-EPA LCA study
Liquified petroleum gas (LPG)	⇨					light fuel oil used as proxy	oil	heating systems	No	RER	heat, light fuel oil, at industrial furnace 1MW	6.47E+00	MJ	amount according to Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,1); data from an US-EPA LCA study
Natural gas	⇨			continued ▼			natural gas	heating systems	No	RER	heat, natural gas, at industrial furnace >100kW	1.00E+01	MJ	amount according to Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,1); data from an US-EPA LCA study

Table D.3: LCD Module Assembly at Plant (Cont.)

General Flow information							Representation in ecoinvent								Uncertainty information		
Input		Process Name		Output		Remarks	Category	Sub-category	Infra-structure	Loca-tion	Modul name in ecoinvent	Mean value	Unit	Source	Type	StDv 95%	General Comment
electricity	⇨	assembly, LCD module		▼ continued		33%as Chinese electricity mix (used as proxy for South Korean production)	electricity	supply mix	No	CN	electricity, medium voltage, at grid	6.18E+00	kWh	total amount according to Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,2); data from an US-EPA LCA study
electricity	⇨					67%as Japanese electricity mix (used as proxy for Taiwanese production)	electricity	supply mix	No	JP	electricity, medium voltage, at grid	1.26E+01	kWh	total amount according to Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,2); data from an US-EPA LCA study
infrastructure	⇨						electronics	component	Yes	GLO	electronic component production plant	2.00E-08	unit	rough estimation	1	3.18	(4,5,4,3,1,5,9); Estimation, based on electronic component production site
Transport	⇨					standard values	transport systems	train	No	RER	transport, freight, rail	1.94E+00	tkm	standard distances according to Frischknecht et al. (2004)	1	2.09	(4,5,na,na,na,na,5); standard values
Transport	⇨					standard values	transport systems	road	No	RER	transport, lorry >16t, fleet average	3.23E-01	tkm	standard distances according to Frischknecht et al. (2004)	1	2.09	(4,5,na,na,na,na,5); standard values
			⇨	Waste Water to WWTP		Assumed are 50%to WWTP - 50%directly to the river …	waste management	wastewater treatment	No	CH	treatment, LCD module production effluent, to wastewater treatment, class 2	3.74E-01	m3	amount according to Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,6); data from an US-EPA LCA study
			⇨	Isopropyl alcohol		dataset "disposal, solvent mixture, to HWI" used as proxy	waste management	hazardous waste incineration	No	CH	disposal, solvents mixture, 16.5%water, to hazardous waste incineration	2.68E-03	kg	amount according to Socolof et al. (2001)	1	1.52	(1,3,2,3,4,3,6); data from an US-EPA LCA study - approximated with existing waste process
			⇨	LCD panel waste		dataset "disposal, glass, to inert landfill" used as proxy	waste management	inert material landfill	No	CH	disposal, glass, 0%water, to inert material landfill	1.27E-02	kg	amount according to Socolof et al. (2001)	1	1.52	(1,3,2,3,4,3,6); data from an US-EPA LCA study - approximated with existing waste process
			⇨	Remover, unspecified		dataset "disposal, solvent mixture, to HWI" used as proxy	waste management	hazardous waste incineration	No	CH	disposal, solvents mixture, 16.5%water, to hazardous waste incineration	8.05E-03	kg	amount according to Socolof et al. (2001)	1	1.52	(1,3,2,3,4,3,6); data from an US-EPA LCA study - approximated with existing waste process
			⇨	unspecified sludge		dataset "disposal sludge, NaCl electrolysis, to residual mat. landfill" used as proxy	waste management	residual material landfill	No	CH	disposal, sludge, NaCl electrolysis, 0%water, to residual material landfill	1.49E-02	kg	amount according to Socolof et al. (2001)	1	1.52	(1,3,2,3,4,3,6); data from an US-EPA LCA study - approximated with existing waste process
continued ▼			⇨	waste acid (containing F and detergents)		dataset "disposal, solvent mixture, to HWI" used as proxy	waste management	hazardous waste incineration	No	CH	disposal, solvents mixture, 16.5%water, to hazardous waste incineration	7.03E-02	kg	amount according to Socolof et al. (2001)	1	1.52	(1,3,2,3,4,3,6); data from an US-EPA LCA study - approximated with existing waste process

Table D.3: LCD Module Assembly at Plant (Cont.)

General Flow information							Representation in ecoinvent								Uncertainty information		
Input		Process Name		Output		Remarks	Category	Sub-category	Infra-structure	Loca-tion	Modul name in ecoinvent	Mean value	Unit	Source	Type	StDv 95%	General Comment
▼ continued		assembly, LCD module	⇨	waste acids, unspecified		dataset " disposal, solvent mixture, to HWI" used as proxy	waste management	hazardous waste incineration	No	CH	disposal, solvents mixture, 16.5%water, to hazardous waste incineration	2.73E-02	kg	amount according to Socolof et al. (2001)	1	1.52	(1,3,2,3,4,3,6); data from an US-EPA LCA study - approximated with existing waste process
			⇨	waste LCD glass		dataset " disposal, glass, to inert landfill" used as proxy	waste management	inert material landfill	No	CH	disposal, glass, 0%water, to inert material landfill	1.07E-01	kg	amount according to Socolof et al. (2001)	1	1.52	(1,3,2,3,4,3,6); data from an US-EPA LCA study - approximated with existing waste process
			⇨	waste oil			waste management	hazardous waste incineration	No	CH	disposal, used mineral oil, 10%water, to hazardous waste incineration	4.19E-03	kg	amount according to Socolof et al. (2001)	1	1.52	(1,3,2,3,4,3,6); data from an US-EPA LCA study - approximated with existing waste process
			⇨	waste plastic from LCD modules			waste management	municipal incineration	No	CH	disposal, plastic, consumer electronics, 15.3%water, to municipal incineration	2.10E-01	kg	amount according to Socolof et al. (2001)	1	1.52	(1,3,2,3,4,3,6); data from an US-EPA LCA study - approximated with existing waste process
			⇨	waste acid (mainly HF)		dataset " disposal, solvent mixture, to HWI" used as proxy	waste management	hazardous waste incineration	No	CH	disposal, solvents mixture, 16.5%water, to hazardous waste incineration	3.54E-02	kg	amount according to Socolof et al. (2001)	1	1.52	(1,3,2,3,4,3,6); data from an US-EPA LCA study - approximated with existing waste process
			⇨	unspecified sludge (hazardous w.)		dataset " disposal refinery sludge, to HWI" used as proxy	waste management	hazardous waste incineration	No	CH	disposal, refinery sludge, 89.5%water, to hazardous waste incineration	8.05E-03	kg	amount according to Socolof et al. (2001)	1	1.52	(1,3,2,3,4,3,6); data from an US-EPA LCA study - approximated with existing waste process
			⇨	thinner, unspecified		dataset " disposal, solvent mixture, to HWI" used as proxy	waste management	hazardous waste incineration	No	CH	disposal, solvents mixture, 16.5%water, to hazardous waste incineration	1.41E-01	kg	amount according to Socolof et al. (2001)	1	1.52	(1,3,2,3,4,3,6); data from an US-EPA LCA study - approximated with existing waste process
			⇨	remover, unspec. (hazardous w.)		dataset " disposal, solvent mixture, to HWI" used as proxy	waste management	hazardous waste incineration	No	CH	disposal, solvents mixture, 16.5%water, to hazardous waste incineration	7.89E-02	kg	amount according to Socolof et al. (2001)	1	1.52	(1,3,2,3,4,3,6); data from an US-EPA LCA study - approximated with existing waste process
			⇨	phosphoric acid		dataset " disposal, solvent mixture, to HWI" used as proxy	waste management	hazardous waste incineration	No	CH	disposal, solvents mixture, 16.5%water, to hazardous waste incineration	3.75E-03	kg	amount according to Socolof et al. (2001)	1	1.52	(1,3,2,3,4,3,6); data from an US-EPA LCA study - approximated with existing waste process
continued ▼			⇨	nitric acid		dataset " disposal, solvent mixture, to HWI" used as proxy	waste management	hazardous waste incineration	No	CH	disposal, solvents mixture, 16.5%water, to hazardous waste incineration	8.93E-05	kg	amount according to Socolof et al. (2001)	1	1.52	(1,3,2,3,4,3,6); data from an US-EPA LCA study - approximated with existing waste process

Table D.3: LCD Module Assembly at Plant (Cont.)

General Flow information							Representation in ecoinvent								Uncertainty information		
Input		Process Name		Output		Remarks	Category	Sub-category	Infrastructure	Location	Modul name in ecoinvent	Mean value	Unit	Source	Type	StDv 95%	General Comment
▼ continued		assembly, LCD module	⇨	isopropyl alcohol (hazardous w.)		dataset " disposal, solvent mixture, to HWI" used as proxy	waste management	hazardous waste incineration	No	CH	disposal, solvents mixture, 16.5%water, to hazardous waste incineration	4.97E-01	kg	amount according to Socolof et al. (2001)	1	1.52	(1,3,2,3,4,3,6); data from an US-EPA LCA study - approximated with existing waste process
			⇨	acetone		dataset " disposal, solvent mixture, to HWI" used as proxy	waste management	hazardous waste incineration	No	CH	disposal, solvents mixture, 16.5%water, to hazardous waste incineration	7.21E-03	kg	amount according to Socolof et al. (2001)	1	1.52	(1,3,2,3,4,3,6); data from an US-EPA LCA study - approximated with existing waste process
			⇨	acetic acid		dataset " disposal, solvent mixture, to HWI" used as proxy	waste management	hazardous waste incineration	No	CH	disposal, solvents mixture, 16.5%water, to hazardous waste incineration	1.16E-03	kg	amount according to Socolof et al. (2001)	1	1.52	(1,3,2,3,4,3,6); data from an US-EPA LCA study - approximated with existing waste process
			⇨	Waste heat			air	high population density			Heat, waste	6.74E+01	MJ	calculated from the electricity input	1	1.64	(4,3,3,3,4,5,13); Calculated from electricity input
			⇨	acetic acid to air			air	high population density			Acetic acid	3.54E-04	kg	amount according to Socolof et al. (2001)	1	2.01	(1,3,2,3,1,3,23); data from an US-EPA LCA study
			⇨	acetone to air			air	high population density			Acetone	4.84E-05	kg	amount according to Socolof et al. (2001)	1	2.01	(1,3,2,3,1,3,23); data from an US-EPA LCA study
			⇨	ammonia to air			air	high population density			Ammonia	1.62E-02	kg	amount according to Socolof et al. (2001)	1	2.01	(1,3,2,3,1,3,23); data from an US-EPA LCA study
			⇨	cyclohexane to air			air	high population density			Cyclohexane	1.26E-05	kg	amount according to Socolof et al. (2001)	1	2.01	(1,3,2,3,1,3,23); data from an US-EPA LCA study
			⇨	diethylene glycol to air			air	high population density			Diethylene glycol	2.52E-05	kg	amount according to Socolof et al. (2001)	1	2.01	(1,3,2,3,1,3,23); data from an US-EPA LCA study
			⇨	hexamethyldisilizane to air			air	high population density			Boric acid	3.57E-07	kg	amount according to Socolof et al. (2001)	1	2.01	(1,3,2,3,1,3,23); data from an US-EPA LCA study
			⇨	hydrochloric acid to air			air	high population density			Hydrogen chloride	1.58E-02	kg	amount according to Socolof et al. (2001)	1	1.51	(1,3,2,3,1,3,31); data from an US-EPA LCA study
continued ▼			⇨	hydrofluoric acid to air			air	high population density			Hydrogen fluoride	1.36E-02	kg	amount according to Socolof et al. (2001)	1	1.51	(1,3,2,3,1,3,31); data from an US-EPA LCA study

Table D.3: LCD Module Assembly at Plant (Cont.)

General Flow information							Representation in ecoinvent								Uncertainty information		
Input		Process Name		Output		Remarks	Category	Sub-category	Infra-structure	Loca-tion	Modul name in ecoinvent	Mean value	Unit	Source	Type	StDv 95%	General Comment
▼ continued		assembly, LCD module	⇨	hydrogen to air			air	high population density			Hydrogen	3.46E-05	kg	amount according to Socolof et al. (2001)	1	1.51	(1,3,2,3,1,3,31); data from an US-EPA LCA study
			⇨	isopropyl alcohol to air			air	high population density			Sodium tetrahydroborate	4.64E-03	kg	amount according to Socolof et al. (2001)	1	2.01	(1,3,2,3,1,3,23); data from an US-EPA LCA study
			⇨	N-bromoacetamide to air			air	high population density			Boron trifluoride	2.39E-03	kg	amount according to Socolof et al. (2001)	1	2.01	(1,3,2,3,1,3,23); data from an US-EPA LCA study
			⇨	nitric acid to air		as NOx to air	air	high population density			Nitrogen oxides	7.01E-05	kg	amount according to Socolof et al. (2001)	1	1.51	(1,3,2,3,1,3,31); data from an US-EPA LCA study
			⇨	nitrogen fluoride to air			air	high population density			Nitrogen fluoride	6.38E-02	kg	amount according to Socolof et al. (2001)	1	1.51	(1,3,2,3,1,3,31); data from an US-EPA LCA study
			⇨	phosphine to air			air	high population density			Phosphine	1.63E-02	kg	amount according to Socolof et al. (2001)	1	1.51	(1,3,2,3,1,3,31); data from an US-EPA LCA study
			⇨	phosphoric acid to air			air	high population density			Phosphoric acid	1.26E-05	kg	amount according to Socolof et al. (2001)	1	1.51	(1,3,2,3,1,3,31); data from an US-EPA LCA study
			⇨	sulfur hexafluoride to air			air	high population density			Sulfur hexafluoride	1.90E-03	kg	amount according to Socolof et al. (2001)	1	2.01	(1,3,2,3,1,3,23); data from an US-EPA LCA study
			⇨	tetramethyl ammonium hydroxide to air			air	high population density			Tetramethyl ammonium hydroxide	1.67E-01	kg	amount according to Socolof et al. (2001)	1	2.01	(1,3,2,3,1,3,23); data from an US-EPA LCA study
			⇨	unspecified organic emissions to air			air	high population density			NMVOC, non-methane volatile organic compounds, unspecified origin	2.78E-02	kg	amount according to Socolof et al. (2001)	1	2.01	(1,3,2,3,1,3,23); data from an US-EPA LCA study
			⇨	1,1,1-Trichloroethane to water			water	river			Ethane, 1,1,1-trichloro-, HCFC-140	5.96E-09	kg	amount according to Socolof et al. (2001)	1	3.01	(1,3,2,3,1,3,34); data from an US-EPA LCA study
			⇨	antiomony to water			water	river			Antimony	2.97E-08	kg	amount according to Socolof et al. (2001)	1	1.51	(1,3,2,3,1,3,33); data from an US-EPA LCA study
continued ▼			⇨	arsenic to water			water	river			Arsenic, ion	2.97E-08	kg	amount according to Socolof et al. (2001)	1	1.51	(1,3,2,3,1,3,33); data from an US-EPA LCA study

Table D.3: LCD Module Assembly at Plant (Cont.)

General Flow information							Representation in ecoinvent								Uncertainty information		
Input		Process Name		Output		Remarks	Category	Sub-category	Infra-struc-ture	Loca-tion	Modul name in ecoinvent	Mean value	Unit	Source	Type	StDv 95%	General Comment
▼ continued		assembly, LCD module	⇨	BOD to water			water	river			BOD5, Biological Oxygen Demand	4.53E-03	kg	amount according to Socolof et al. (2001)	1	1.51	(1,3,2,3,1,3,32); data from an US-EPA LCA study
			⇨	boron to water			water	river			Boron	1.19E-06	kg	amount according to Socolof et al. (2001)	1	1.51	(1,3,2,3,1,3,33); data from an US-EPA LCA study
			⇨	cadmium to water			water	river			Cadmium, ion	2.97E-08	kg	amount according to Socolof et al. (2001)	1	5.01	(1,3,2,3,1,3,35); data from an US-EPA LCA study
			⇨	chromium to water			water	river			Chromium, ion	2.30E-06	kg	amount according to Socolof et al. (2001)	1	5.01	(1,3,2,3,1,3,35); data from an US-EPA LCA study
			⇨	chromium (VI) to water			water	river			Chromium VI	5.96E-08	kg	amount according to Socolof et al. (2001)	1	5.01	(1,3,2,3,1,3,35); data from an US-EPA LCA study
			⇨	COD			water	river			COD, Chemical Oxygen Demand	6.98E-04	kg	amount according to Socolof et al. (2001)	1	1.51	(1,3,2,3,1,3,32); data from an US-EPA LCA study
			⇨	copper to water			water	river			Copper, ion	2.39E-07	kg	amount according to Socolof et al. (2001)	1	5.01	(1,3,2,3,1,3,35); data from an US-EPA LCA study
			⇨	cyanide(-1) to water			water	river			Cyanide	9.53E-07	kg	amount according to Socolof et al. (2001)	1	1.51	(1,3,2,3,1,3,33); data from an US-EPA LCA study
			⇨	dissolved solids		as "solids, inorganics" shown here	water	river			Solids, inorganic	1.97E-03	kg	amount according to Socolof et al. (2001)	1	1.51	(1,3,2,3,1,3,33); data from an US-EPA LCA study
			⇨	fluorides (F-) to water			water	river			Fluoride	3.33E-03	kg	amount according to Socolof et al. (2001)	1	1.51	(1,3,2,3,1,3,33); data from an US-EPA LCA study
			⇨	hexane to water			water	river			Hydrocarbons, aromatic	1.53E-04	kg	amount according to Socolof et al. (2001)	1	3.01	(1,3,2,3,1,3,34); data from an US-EPA LCA study
			⇨	iron to water			water	river			Iron, ion	6.85E-07	kg	amount according to Socolof et al. (2001)	1	5.01	(1,3,2,3,1,3,35); data from an US-EPA LCA study
continued ▼			⇨	lead to water			water	river			Lead	1.61E-06	kg	amount according to Socolof et al. (2001)	1	5.01	(1,3,2,3,1,3,35); data from an US-EPA LCA study

Table D.3: LCD Module Assembly at Plant (Cont.)

General Flow information							Representation in ecoinvent								Uncertainty information		
Input		Process Name		Output		Remarks	Category	Sub-category	Infra-structure	Loca-tion	Modul name in ecoinvent	Mean value	Unit	Source	Type	StDv 95%	General Comment
▼ continued		assembly, LCD module	⇨	manganese to water			water	river			Manganese	5.96E-08	kg	amount according to Socolof et al. (2001)	1	5.01	(1,3,2,3,1,3,35); data from an US-EPA LCA study
			⇨	mercury to water			water	river			Mercury	2.52E-08	kg	amount according to Socolof et al. (2001)	1	5.01	(1,3,2,3,1,3,35); data from an US-EPA LCA study
			⇨	nickel to water			water	river			Nickel, ion	5.96E-08	kg	amount according to Socolof et al. (2001)	1	5.01	(1,3,2,3,1,3,35); data from an US-EPA LCA study
			⇨	nitrogen to water			water	river			Nitrogen	2.07E-02	kg	amount according to Socolof et al. (2001)	1	1.51	(1,3,2,3,1,3,33); data from an US-EPA LCA study
			⇨	oil & grease to water			water	river			Oils, unspecified	5.26E-05	kg	amount according to Socolof et al. (2001)	1	3.01	(1,3,2,3,1,3,34); data from an US-EPA LCA study
			⇨	organic phosphorus, unspec., to water		proxy "phosphate, to water" used	water	river			Phosphate	5.96E-08	kg	amount according to Socolof et al. (2001)	1	1.51	(1,3,2,3,1,3,33); data from an US-EPA LCA study
			⇨	phenol to water			water	river			Phenol	5.96E-08	kg	amount according to Socolof et al. (2001)	1	3.01	(1,3,2,3,1,3,34); data from an US-EPA LCA study
			⇨	phosphorus (yellow/white) to water			water	river			Phosphorus	1.12E-03	kg	amount according to Socolof et al. (2001)	1	1.51	(1,3,2,3,1,3,33); data from an US-EPA LCA study
			⇨	assembly of LCD module			electronics	module	No	GLO	assembly, LCD module	1.00E+00	kg				

Table D.4: Panel Components at Plant

General Flow information							Representation in ecoinvent								Uncertainty information		
Input		Process Name		Output		Remarks	Category	Sub-category	Infra-structure	Loca-tion	Modul name in ecoinvent	Mean value	Unit	Source	Type	StDv 95%	General Comment
Water (unspec.)	⇨	panel components, at plant					resource	in water			Water, unspecified natural origin	2.60E+00	m3	amount according to Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,12); data from an US-EPA LCA study
acetone	⇨						chemicals	organics	No	RER	acetone, liquid, at plant	1.29E-01	kg	amount according to Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,3); data from an US-EPA LCA study
borax	⇨						chemicals	inorganics	No	RER	Borax, anhydrous, powder, at plant	1.14E-03	kg	amount according to Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,3); data from an US-EPA LCA study
carbon dioxide	⇨						chemicals	inorganics	No	RER	carbon dioxide liquid, at plant	6.03E-02	kg	amount according to Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,3); data from an US-EPA LCA study
cyclohexane	⇨						chemicals	organics	No	RER	cyclohexane, at plant	4.86E-02	kg	amount according to Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,3); data from an US-EPA LCA study
ethanol	⇨						chemicals	organics	No	RER	ethanol from ethylene, at plant	1.46E-01	kg	amount according to Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,3); data from an US-EPA LCA study
ethylacetate	⇨						chemicals	organics	No	RER	ethyl acetate from butane, at plant	1.21E-02	kg	amount according to Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,3); data from an US-EPA LCA study
exfoliation liquid, unspec.	⇨					dataset "dimethyl sulfoxide" used as proxy	chemicals	organics	No	RER	dimethyl sulfoxide, at plant	1.79E-01	kg	amount according to Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,3); data from an US-EPA LCA study
HCFC-225ca	⇨					dataset "monochloro pentafluroethane" used as proxy	chemicals	organics	No	GLO	monochloropentafluoroethane, at plant	1.71E-03	kg	amount according to Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,3); data from an US-EPA LCA study
HCFC-225cb	⇨					dataset "monochloro pentafluroethane" used as proxy	chemicals	organics	No	GLO	monochloropentafluoroethane, at plant	1.71E-03	kg	amount according to Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,3); data from an US-EPA LCA study
heptane	⇨						chemicals	organics	No	RER	heptane, at plant	1.29E-01	kg	amount according to Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,3); data from an US-EPA LCA study
hydrochloric acid	⇨						chemicals	inorganics	No	RER	hydrochloric acid, 30% in H2O, at plant	2.18E-02	kg	amount according to Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,3); data from an US-EPA LCA study
hydrogen	⇨						chemicals	inorganics	No	RER	hydrogen, liquid, at plant	3.93E-05	kg	amount according to Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,3); data from an US-EPA LCA study
methyl kethyl ethone	⇨			continued ▼			chemicals	organics	No	RER	methyl ethyl ketone, at plant	6.05E-03	kg	amount according to Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,3); data from an US-EPA LCA study

Table D.4: Panel Components at Plant (Cont.)

General Flow information							Representation in ecoinvent								Uncertainty information		
Input		Process Name		Output		Remarks	Category	Sub-category	Infra-structure	Loca-tion	Modul name in ecoinvent	Mean value	Unit	Source	Type	StDv 95%	General Comment
nitric acid second cerium ammonium	⇨	panel components, at plant		▼ continued		"nitric acid" used as proxy	chemicals	inorganics	No	RER	nitric acid, 50% in H2O, at plant	1.41E-01	kg	amount according to Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,3); data from an US-EPA LCA study
nitrogen	⇨						chemicals	inorganics	No	RER	nitrogen, liquid, at plant	1.46E+00	kg	amount according to Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,3); data from an US-EPA LCA study
orthoboric acid	⇨					dataset "boric acid" used as a proxy	chemicals	inorganics	No	RER	boric acid, anhydrous, powder, at plant	9.13E-03	kg	amount according to Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,3); data from an US-EPA LCA study
perchloric acid	⇨					dataset "hydrochloric acid" used as a proxy	chemicals	inorganics	No	RER	hydrochloric acid, 30% in H2O, at plant	4.78E-02	kg	amount according to Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,3); data from an US-EPA LCA study
photoresist, unspec.	⇨					dataset "dipropylene glycol monoethyl ether" used as proxy	chemicals	organics	No	RER	dipropylene glycol monomethyl ether, at plant	3.68E-02	kg	amount according to Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,3); data from an US-EPA LCA study
polyethylene terephtalate	⇨						plastics	polymers	No	RER	polyethylene terephthalate, granulate, amorphous, at plant	7.93E-01	kg	amount according to Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,3); data from an US-EPA LCA study
sulfuric acid	⇨						chemicals	inorganics	No	RER	sulphuric acid, liquid, at plant	1.98E-01	kg	amount according to Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,3); data from an US-EPA LCA study
tetrahydrofuran	⇨						chemicals	organics	No	RER	tetrahydrofuran, at plant	4.78E-02	kg	amount according to Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,3); data from an US-EPA LCA study
toluene	⇨						chemicals	organics	No	RER	toluene, liquid, at plant	3.44E-01	kg	amount according to Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,3); data from an US-EPA LCA study
pigment, color resistent, unsp.	⇨					dataset "dipropylene glycol monoethyl ether" used as proxy	chemicals	organics	No	RER	dipropylene glycol monomethyl ether, at plant	4.65E-01	kg	amount according to Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,3); data from an US-EPA LCA study
diluent, unsp.	⇨					dataset "solvents, organic, unspec." used as proxy	chemicals	organics	No	GLO	solvents, organic, unspecified, at plant	1.03E-01	kg	amount according to Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,3); data from an US-EPA LCA study
polyester adhesive	⇨					dataset "polyester resin, unsaturated" used as proxy	paintings	production	No	RER	polyester resin, unsaturated, at plant	7.81E-03	kg	amount according to Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,3); data from an US-EPA LCA study
various organic chemicals	⇨					3,4,5-trifluorobromo-benzene & all those chemicals not separately mentioned here (all information from Socolof et al. (2001))	chemicals	organics	No	GLO	chemicals organic, at plant	6.30E-01	kg	amount according to Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,3); data from an US-EPA LCA study
electricity	⇨			continued ▼		50% as Chinese electricity mix (used as proxy for South Korean production)	electricity	supply mix	No	CN	electricity, medium voltage, at grid	8.06E+01	kWh	total amount according to Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,2); data from an US-EPA LCA study

Table D.4: Panel Components at Plant (Cont.)

General Flow information							Representation in ecoinvent								Uncertainty information		
Input		Process Name		Output		Remarks	Category	Sub-category	Infra-structure	Loca-tion	Modul name in ecoinvent	Mean value	Unit	Source	Type	StDv 95%	General Comment
electricity	⇨	panel components, at plant		▼ continued		50%as Japanese electricity mix (used as proxy for Taiwanese production)	electricity	supply mix	No	JP	electricity, medium voltage, at grid	8.06E+01	kWh	total amount according to Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,2); data from an US-EPA LCA study
keorsene & fuel oils #2, #6	⇨						oil	heating systems	No	RER	heat, light fuel oil, at industrial furnace 1MW	1.56E+02	MJ	amount according to Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,1); data from an US-EPA LCA study
natural gas	⇨						natural gas	heating systems	No	RER	heat, natural gas, at industrial furnace >100kW	4.90E+01	MJ	amount according to Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,1); data from an US-EPA LCA study
steam	⇨					process "steam, for chemical processes" used as proxy	washing agents	auxiliary agents	No	RER	steam, for chemical processes, at plant	1.81E+00	kg	amount according to Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,1); data from an US-EPA LCA study
infrastructure	⇨					chemical plant used as proxy	chemicals	organics	Yes	RER	chemical plant, organics	4.00E-10	unit	according to Althaus et al. (2004)	1	3.18	(4,5,4,3,1,5,9); Estimation, based on chemical production site
Transport	⇨					standard values	transport systems	train	No	RER	transport, freight, rail	2.29E+00	tkm	standard values according to Frischknecht et al. (2004)	1	2.09	(4,5,na,na,na,na,5); standard values
Transport	⇨					standard values	transport systems	road	No	RER	transport, lorry >16t, fleet average	3.81E-01	tkm	standard values according to Frischknecht et al. (2004)	1	2.09	(4,5,na,na,na,na,5); standard values
			⇨	waste water to WWTP		50%of water outflow (assumption) - dataset with elementary composition of waste water according to Socolof et al. (2001)	waste management	wastewater treatment	No	CH	treatment, liquid crystal production effluent, to wastewater treatment, class 2	2.21E-03	m3	amount according to Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,6); data from an US-EPA LCA study
			⇨	spent solvent (F003 waste) to treatment		dataset "disposal, solvent mixture, to HWI" used as proxy	waste management	hazardous waste incineration	No	CH	disposal, solvents mixture, 16.5%water, to hazardous waste incineration	3.43E-03	kg	amount according to Socolof et al. (2001)	1	1.52	(1,3,2,3,4,3,6); data from an US-EPA LCA study - approximated with existing waste process
			⇨	flammable liquids (F003 waste) to treatment		dataset "disposal, solvent mixture, to HWI" used as proxy	waste management	hazardous waste incineration	No	CH	disposal, solvents mixture, 16.5%water, to hazardous waste incineration	1.14E-02	kg	amount according to Socolof et al. (2001)	1	1.52	(1,3,2,3,4,3,6); data from an US-EPA LCA study - approximated with existing waste process
			⇨	acid waste (D002 waste) to treatment		dataset "disposal, solvent mixture, to HWI" used as proxy	waste management	hazardous waste incineration	No	CH	disposal, solvents mixture, 16.5%water, to hazardous waste incineration	1.49E-02	kg	amount according to Socolof et al. (2001)	1	1.52	(1,3,2,3,4,3,6); data from an US-EPA LCA study - approximated with existing waste process
continued ▼			⇨	spend solvent (with halogenated material) to treatment		dataset "disposal, solvent mixture, to HWI" used as proxy	waste management	hazardous waste incineration	No	CH	disposal, solvents mixture, 16.5%water, to hazardous waste incineration	1.94E-01	kg	amount according to Socolof et al. (2001)	1	1.52	(1,3,2,3,4,3,6); data from an US-EPA LCA study - approximated with existing waste process

Table D.4: Panel Components at Plant (Cont.)

General Flow information							Representation in ecoinvent								Uncertainty information		
Input		Process Name		Output		Remarks	Category	Sub-category	Infra-structure	Loca-tion	Modul name in ecoinvent	Mean value	Unit	Source	Type	StDv 95%	General Comment
▼ continued		panel components, at plant	⇨	Spent solvent (non-halogenated)		dataset "disposal, solvent mixture, to HWI" used as proxy	waste management	hazardous waste incineration	No	CH	disposal, solvents mixture, 16.5%water, to hazardous waste incineration	5.83E-01	kg	amount according to Socolof et al. (2001)	1	1.52	(1,3,2,3,4,3,6); data from an US-EPA LCA study - approximated with existing waste process
			⇨	waste solvent (photoresist) to treatment		dataset "disposal, solvent mixture, to HWI" used as proxy	waste management	hazardous waste incineration	No	CH	disposal, solvents mixture, 16.5%water, to hazardous waste incineration	2.71E-01	kg	amount according to Socolof et al. (2001)	1	1.52	(1,3,2,3,4,3,6); data from an US-EPA LCA study - approximated with existing waste process
			⇨	unspecified solid waste, to treatment		dataset of municipal solid waste used as proxy	waste management	municipal incineration	No	CH	disposal, municipal solid waste, 22.9%water, to municipal incineration	1.38E-01	kg	amount according to Socolof et al. (2001)	1	1.52	(1,3,2,3,4,3,6); data from an US-EPA LCA study - approximated with existing waste process
			⇨	used silica gel, to landfilling		dataset "inert material to sanitary landfill" used as a proxy. Inert material in ecoinvent = SiO2	waste management	sanitary landfill	No	CH	disposal, inert material, 0% water, to sanitary landfill	7.78E-03	kg	amount according to Socolof et al. (2001)	1	1.52	(1,3,2,3,4,3,6); data from an US-EPA LCA study - approximated with existing waste process
			⇨	Waste heat		calculated from the electricity input	air	high population density			Heat, waste	5.80E+02	MJ	calculated as reported in Frischknecht et al. (2004)	1	1.64	(4,3,3,3,4,5,13); Calculated from electricity input
			⇨	ethylacetate to air			air	high population density			Ethyl acetate	3.05E-05	kg	amount according to Socolof et al. (2001)	1	2.01	(1,3,2,3,1,3,23); data from an US-EPA LCA study
			⇨	HCFC-225ca, to air		as "halogenated hydrocarbons, chlorinated"	air	high population density			Hydrocarbons, chlorinated	1.75E-03	kg	amount according to Socolof et al. (2001)	1	2.01	(1,3,2,3,1,3,23); data from an US-EPA LCA study
			⇨	HCFC-225cb, to air		as "halogenated hydrocarbons, chlorinated"	air	high population density			Hydrocarbons, chlorinated	1.75E-03	kg	amount according to Socolof et al. (2001)	1	2.01	(1,3,2,3,1,3,23); data from an US-EPA LCA study
			⇨	Heptane, to air			air	high population density			Heptane	9.71E-04	kg	amount according to Socolof et al. (2001)	1	2.01	(1,3,2,3,1,3,23); data from an US-EPA LCA study
			⇨	hydrochloric acid, to air			air	high population density			Hydrogen chloride	9.15E-05	kg	amount according to Socolof et al. (2001)	1	1.51	(1,3,2,3,1,3,31); data from an US-EPA LCA study
			⇨	methyl ethyl ketone, to air			air	high population density			Methyl ethyl ketone	1.69E-03	kg	amount according to Socolof et al. (2001)	1	2.01	(1,3,2,3,1,3,23); data from an US-EPA LCA study
continued ▼			⇨	NMVOC, unspec., to air			air	high population density			NMVOC, non-methane volatile organic compounds, unspecified origin	9.71E-04	kg	amount according to Socolof et al. (2001)	1	2.01	(1,3,2,3,1,3,23); data from an US-EPA LCA study

Table D.4: Panel Components at Plant (Cont.)

General Flow information							Representation in ecoinvent								Uncertainty information		
Input		Process Name		Output		Remarks	Category	Sub-category	Infra-struc-ture	Loca-tion	Modul name in ecoinvent	Mean value	Unit	Source	Type	StDv 95%	General Comment
▼ continued		panel components, at plant	⇨	Toluene, to air			air	high population density			Toluene	6.80E-04	kg	amount according to Socolof et al. (2001)	1	2.01	(1,3,2,3,1,3,23); data from an US-EPA LCA study
			⇨	BOD, to water			water	river			BOD5, Biological Oxygen Demand	1.68E-02	kg	amount according to Socolof et al. (2001)	1	1.51	(1,3,2,3,1,3,32); data from an US-EPA LCA study
			⇨	COD, to water			water	river			COD, Chemical Oxygen Demand	2.76E-02	kg	amount according to Socolof et al. (2001)	1	1.51	(1,3,2,3,1,3,32); data from an US-EPA LCA study
			⇨	Nitrogen, to water			water	river			Nitrogen	7.14E-03	kg	amount according to Socolof et al. (2001)	1	1.51	(1,3,2,3,1,3,33); data from an US-EPA LCA study
			⇨	phosphorus, to water			water	river			Phosphorus	3.10E-04	kg	amount according to Socolof et al. (2001)	1	1.51	(1,3,2,3,1,3,33); data from an US-EPA LCA study
			⇨	suspended solids, to water			water	river			Suspended solids, unspecified	8.08E-03	kg	amount according to Socolof et al. (2001)	1	1.51	(1,3,2,3,1,3,33); data from an US-EPA LCA study
			⇨	panel components			electronics	component	No	GLO	panel components, at plant	1.00E+00	kg			# NV	

Table D.5: Backlight at Plant

General Flow information							Representation in ecoinvent								Uncertainty information		
Input		Process Name		Output		Remarks	Category	Sub-category	Infra-structure	Loca-tion	Modul name in ecoinvent	Mean value	Unit	Source	Type	StDv 95%	General Comment
Water (unspec.)	⇨	backlight, LCD screen, at plant					resource	in water			Water, unspecified natural origin	1.90E-01	m3	amount according to Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,12); data from an US-EPA LCA study
LCD light guide	⇨					PMMA as basic material - here used as proxy for the complete light guide	plastics	polymers	No	RER	polymethyl methacrylate, sheet, at plant	3.70E-01	kg	amount according to Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,3); data from an US-EPA LCA study
Aluminium (elemental)	⇨						metals	extraction	No	RER	aluminium, production mix, wrought alloy, at plant	3.32E-02	kg	amount according to Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,3); data from an US-EPA LCA study
Argon	⇨						chemicals	inorganics	No	RER	argon, liquid, at plant	3.50E-05	kg	amount according to Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,3); data from an US-EPA LCA study
Backlight lamp (CCFL)	⇨					lead used as proxy for the electrodes of CCFL lamps	metals	extraction	No	GLO	lead concentrate, at beneficiation	1.92E-03	kg	amount according to Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,3); data from an US-EPA LCA study
Cables	⇨					ribbon cable used as proxy for the internal cable of the backlight unit	electronics	component	No	GLO	cable, ribbon cable, 20-pin, with plugs, at plant	3.40E-03	kg	amount according to Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,3); data from an US-EPA LCA study
Glass, unspecified	⇨					CCFL have borosilicate glass tubes	glass	construction	No	DE	glass tube, borosilicate, at plant	4.10E-02	kg	amount according to Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,3); data from an US-EPA LCA study
Mercury	⇨						metals	extraction	No	GLO	mercury, liquid, at plant	3.95E-06	kg	amount according to Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,3); data from an US-EPA LCA study
Metals, remaining unspecified	⇨					copper used as proxy for the unspecified metals	metals	extraction	No	GLO	copper, primary, at refinery	6.74E-04	kg	amount according to Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,3); data from an US-EPA LCA study
Neon	⇨					krypton used as proxy	chemicals	inorganics	No	RER	krypton, gaseous, at plant	6.25E-05	kg	amount according to Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,3); data from an US-EPA LCA study
Poly(methyl methacrylate)	⇨						plastics	polymers	No	RER	polymethyl methacrylate, sheet, at plant	3.79E-01	kg	amount according to Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,3); data from an US-EPA LCA study
Polycarbonate resin	⇨						plastics	polymers	No	RER	polycarbonate, at plant	1.13E-01	kg	amount according to Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,3); data from an US-EPA LCA study
Polyethylene terephthalate	⇨						plastics	polymers	No	RER	polyethylene terephthalate, granulate, amorphous, at plant	2.71E-02	kg	amount according to Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,3); data from an US-EPA LCA study
Rubber, unspecified	⇨			continued ▼			plastics	polymers	No	RER	synthetic rubber, at plant	5.95E-04	kg	amount according to Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,3); data from an US-EPA LCA study

Table D.5: Backlight at Plant (Cont.)

General Flow information							Representation in ecoinvent								Uncertainty information		
Input		Process Name		Output		Remarks	Category	Sub-category	Infrastructure	Location	Modul name in ecoinvent	Mean value	Unit	Source	Type	StDv 95%	General Comment
Steel	⇨	backlight, LCD screen, at plant		▼ continued		chromium steel as proxy used	metals	extraction	No	RER	chromium steel 18/8, at plant	2.50E-02	kg	amount according to Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,3); data from an US-EPA LCA study
Diethylether	⇨						chemicals	organics	No	RER	diethyl ether, at plant	9.19E-05	kg	amount according to Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,3); data from an US-EPA LCA study
Ethanol	⇨						chemicals	organics	No	RER	ethanol from ethylene, at plant	4.58E-05	kg	amount according to Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,3); data from an US-EPA LCA study
Process materials for backlight assembly	⇨					100%organic chemicals (unspec.) assumed	chemicals	organics	No	GLO	chemicals organic, at plant	6.96E-05	kg	amount according to Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,3); data from an US-EPA LCA study
unspecified ancillary material	⇨					50%organic chemicals (unspec.) and 50%inorganic chemicals (unspec.) assumed	chemicals	organics	No	GLO	chemicals organic, at plant	2.07E-04	kg	amount according to Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,3); data from an US-EPA LCA study
unspecified ancillary material	⇨					50%organic chemicals (unspec.) and 50%inorganic chemicals (unspec.) assumed	chemicals	inorganics	No	GLO	chemicals inorganic, at plant	2.07E-04	kg	amount according to Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,3); data from an US-EPA LCA study
electricity	⇨					20%are produced in China and/or South Korea (with Chinese electricity mix as proxy)	electricity	supply mix	No	CN	electricity, medium voltage, at grid	2.45E-01	kWh	total amount according to Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,2); data from an US-EPA LCA study
electricity	⇨					80%are produced in Japan and/or Taiwan (with Japanese electricity mix as proxy)	electricity	supply mix	No	JP	electricity, medium voltage, at grid	9.81E-01	kWh	total amount according to Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,2); data from an US-EPA LCA study
LNG	⇨					natural gas as proxy used	natural gas	heating systems	No	RER	heat, natural gas, at industrial furnace >100kW	1.87E-04	MJ	amount according to Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,1); data from an US-EPA LCA study
natural gas	⇨						natural gas	heating systems	No	RER	heat, natural gas, at industrial furnace >100kW	1.87E-04	MJ	amount according to Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,1); data from an US-EPA LCA study
backlight production site	⇨					printed wiring board mounting site used as proxy	electronics	module	Yes	GLO	printed wiring board mounting plant	2.08E-07	unit	rough estimation	1	3.18	(4,5,4,3,1,5,9); Estimation, based on PWB mounting plant
Transport	⇨					standard values	transport systems	train	No	RER	transport, freight, rail	5.98E-01	tkm	standard values according to Frischknecht et al. (2004)	1	2.09	(4,5,na,na,na,na,5); standard values
Transport	⇨			continued ▼		standard values	transport systems	road	No	RER	transport, lorry >16t, fleet average	9.96E-02	tkm	standard values according to Frischknecht et al. (2004)	1	2.09	(4,5,na,na,na,na,5); standard values

Table D.5: Backlight at Plant (Cont.)

General Flow information							Representation in ecoinvent								Uncertainty information		
Input		Process Name		Output		Remarks	Category	Sub-category	Infra-structure	Loca-tion	Modul name in ecoinvent	Mean value	Unit	Source	Type	StDv 95%	General Comment
▼ continued		backlight, LCD screen, at plant	⇨	waste water to treatment		50%of water outflow (assumption) - dataset with elementary composition of waste water according to Socolof et al. (2001)	waste management	wastewater treatment	No	CH	treatment, LCD backlight production effluent, to wastewater treatment, class 2	9.50E-02	m3	amount according to Socolof et al. (2001)	1	1.52	(1,3,2,3,4,3,6); data from an US-EPA LCA study - approximated with existing waste process
			⇨	hazardous waste, unsp., to treatment		proxy from ecoinvent used	waste management	hazardous waste incineration	No	CH	disposal, hazardous waste, 25%water, to hazardous waste incineration	6.73E-03	kg	amount according to Socolof et al. (2001)	1	1.52	(1,3,2,3,4,3,6); data from an US-EPA LCA study - approximated with existing waste process
			⇨	waste glass, with Hg, to landfill		proxy from ecoinvent used	waste management	underground deposit	No	DE	disposal, spent activated carbon with mercury, 0% water, to underground deposit	1.04E-10	kg	amount according to Socolof et al. (2001)	1	1.52	(1,3,2,3,4,3,6); data from an US-EPA LCA study - approximated with existing waste process
			⇨	waste CCFL, with Hg, to treatment		proxy from ecoinvent used	waste management	underground deposit	No	DE	disposal, spent activated carbon with mercury, 0% water, to underground deposit	8.09E-10	kg	amount according to Socolof et al. (2001)	1	1.52	(1,3,2,3,4,3,6); data from an US-EPA LCA study - approximated with existing waste process
			⇨	waste CCFL, with Pb, to treatment		proxy from ecoinvent used	waste management	municipal incineration	No	CH	disposal, lead in car shredder residue, 0%water, to municipal incineration	8.09E-08	kg	amount according to Socolof et al. (2001)	1	1.52	(1,3,2,3,4,3,6); data from an US-EPA LCA study - approximated with existing waste process
			⇨	Silver, to landfill		proxy from ecoinvent used	waste management	inert material landfill	No	CH	disposal, inert waste, 5% water, to inert material landfill	2.69E-09	kg	amount according to Socolof et al. (2001)	1	1.52	(1,3,2,3,4,3,6); data from an US-EPA LCA study - approximated with existing waste process
			⇨	chromium, to landfill		proxy from ecoinvent used	waste management	inert material landfill	No	CH	disposal, inert waste, 5% water, to inert material landfill	1.50E-06	kg	amount according to Socolof et al. (2001)	1	1.52	(1,3,2,3,4,3,6); data from an US-EPA LCA study - approximated with existing waste process
			⇨	broken CCFL, to landfill		proxy from ecoinvent used	waste management	underground deposit	No	DE	disposal, hazardous waste, 0%water, to underground deposit	2.66E-07	kg	amount according to Socolof et al. (2001)	1	1.52	(1,3,2,3,4,3,6); data from an US-EPA LCA study - approximated with existing waste process
continued ▼			⇨	Cardboard, to treatment		proxy from ecoinvent used	waste management	municipal incineration	No	CH	disposal, packaging cardboard, 19.6%water, to municipal incineration	1.80E-05	kg	amount according to Socolof et al. (2001)	1	1.52	(1,3,2,3,4,3,6); data from an US-EPA LCA study - approximated with existing waste process

Table D.5: Backlight at Plant (Cont.)

General Flow information							Representation in ecoinvent								Uncertainty information		
Input		Process Name		Output		Remarks	Category	Sub-category	Infra-structure	Loca-tion	Modul name in ecoinvent	Mean value	Unit	Source	Type	StDv 95%	General Comment
▼ continued		backlight, LCD screen, at plant	⇨	Polyethylene, foamed, to treatment		proxy from ecoinvent used	waste management	municipal incineration	No	CH	disposal, polyethylene, 0.4% water, to municipal incineration	9.89E-04	kg	amount according to Socolof et al. (2001)	1	1.52	(1,3,2,3,4,3,6); data from an US-EPA LCA study - approximated with existing waste process
			⇨	PE/PP waste, to treatment		proxy from ecoinvent used	waste management	municipal incineration	No	CH	disposal, polypropylene, 15.9%water, to municipal incineration	2.69E-03	kg	amount according to Socolof et al. (2001)	1	1.52	(1,3,2,3,4,3,6); data from an US-EPA LCA study - approximated with existing waste process
			⇨	wast backlight casing (PC) to landfill		proxy from ecoinvent used	waste management	municipal incineration	No	CH	disposal, plastic, industr. electronics, 15.3%water, to municipal incineration	1.45E-05	kg	amount according to Socolof et al. (2001)	1	1.52	(1,3,2,3,4,3,6); data from an US-EPA LCA study - approximated with existing waste process
			⇨	waste backlight light guide (PMMA) to landfill		proxy from ecoinvent used	waste management	municipal incineration	No	CH	disposal, plastic, industr. electronics, 15.3%water, to municipal incineration	1.50E-03	kg	amount according to Socolof et al. (2001)	1	1.52	(1,3,2,3,4,3,6); data from an US-EPA LCA study - approximated with existing waste process
			⇨	Waste heat		calculated from the electricity input	air	high population density			Heat, waste	4.42E+00	MJ	calculated as reported in Frischknecht et al. (2004)	1	1.64	(4,3,3,3,4,5,13); Calculated from electricity input
			⇨	Diethyl ether, to air		Process emission	air	high population density			Diethyl ether	9.17E-05	kg	amount according to Socolof et al. (2001)	1	2.01	(1,3,2,3,1,3,23); data from an US-EPA LCA study
			⇨	Ethanol, to air		Process emission	air	high population density			Ethanol	4.58E-05	kg	amount according to Socolof et al. (2001)	1	2.01	(1,3,2,3,1,3,23); data from an US-EPA LCA study
			⇨	Nitrogen oxides, to air		Process emission	air	high population density			Nitrogen oxides	2.89E-02	kg	amount according to Socolof et al. (2001)	1	1.51	(1,3,2,3,1,3,31); data from an US-EPA LCA study
			⇨	Backlight			electronics	component	No	GLO	backlight, LCD screen, at plant	1.00E+00	kg			#NV	

Table D.6: LCD Screen at Plant

General Flow information							Representation in ecoinvent								Uncertainty information		
Input		Process Name		Output		Remarks	Category	Sub-category	Infra-structure	Location	Modul name in ecoinvent	Mean value	Unit	Source	Type	StDv 95%	General Comment
LCD module (including backlight unit)	⇨	LCD flat screen, 17 inches, at plant					electronics	module	No	GLO	LCD module, at plant	2.30E+00	kg	calculated from dismantling data from ReLCD project	1	1.12	(1,3,1,1,1,4,3); data from European Research project (about LCD disposal) & internet survey for total weight
printed wiring boards	⇨						electronics	module	No	GLO	printed wiring board, mixed mounted, unspec., solder mix, at plant	2.23E-01	kg	calculated from dismantling data from ReLCD project	1	1.12	(1,3,1,1,1,4,3); data from European Research project (about LCD disposal) & internet survey for total weight
metal frame	⇨						metals	extraction	No	RER	aluminium, production mix, at plant	5.93E-01	kg	calculated from dismantling data from ReLCD project	1	1.12	(1,3,1,1,1,4,3); data from European Research project (about LCD disposal) & internet survey for total weight
metal processing (I)	⇨						metals	processing	No	RER	section bar extrusion, aluminium	2.97E-01	kg	calculated from dismantling data from ReLCD project	1	1.12	(1,3,1,1,1,4,3); data from European Research project (about LCD disposal) & internet survey for total weight
metal processing (II)	⇨						metals	processing	No	RER	sheet rolling, aluminium	2.97E-01	kg	calculated from dismantling data from ReLCD project	1	1.12	(1,3,1,1,1,4,3); data from European Research project (about LCD disposal) & internet survey for total weight
plastic frame	⇨						plastics	polymers	No	RER	acrylonitrile-butadiene-styrene copolymer, ABS, at plant	2.47E-01	kg	calculated from dismantling data from ReLCD project	1	1.12	(1,3,1,1,1,4,3); data from European Research project (about LCD disposal) & internet survey for total weight
plastic processing	⇨			continued ▼			plastics	processing	No	RER	injection moulding	2.47E-01	kg	calculated from dismantling data from ReLCD project	1	1.12	(1,3,1,1,1,4,3); data from European Research project (about LCD disposal) & internet survey for total weight

Table D.6: LCD Screen at Plant (Cont.)

General Flow information							Representation in ecoinvent								Uncertainty information		
Input		Process Name		Output		Remarks	Category	Sub-category	Infra-structure	Loca-tion	Modul name in ecoinvent	Mean value	Unit	Source	Type	StDv 95%	General Comment
screws, etc.	⇨	LCD flat screen, 17 inches, at plant		▼ continued			metals	extraction	No	RER	chromium steel 18/8, at plant	7.00E-03	kg	calculated from dismantling data from ReLCD project	1	1.12	(1,3,1,1,1,4,3); data from European Research project (about LCD disposal) & internet survey for total weight
rubber parts	⇨						plastics	polymers	No	RER	synthetic rubber, at plant	1.50E-02	kg	calculated from dismantling data from ReLCD project	1	1.12	(1,3,1,1,1,4,3); data from European Research project (about LCD disposal) & internet survey for total weight
Assembly efforts	⇨						electronics	module	No	GLO	assembly, LCD screen	5.10E+00	kg	calculated from dismantling data from ReLCD project	1	1.12	(1,3,1,1,1,4,3); data from European Research project (about LCD disposal) & internet survey for total weight
Packaging (EPS part)	⇨						plastics	polymers	No	RER	polystyrene, expandable, at plant	6.75E-01	kg	Total amount from internet survey - distribution EPS/carton: own assumption	1	1.24	(4,4,1,1,1,3,3); own calculation, based on internet survey from current models
Packaging (carton part)	⇨						paper & cardboard	cardboard & corrugated board	No	RER	whitelined chipboard, WLC, at plant	8.25E-01	kg	Total amount from internet survey - distribution EPS/carton: own assumption	1	1.24	(4,4,1,1,1,3,3); own calculation, based on internet survey from current models
			⇨	17 inch LCD screen			electronics	devices	No	GLO	LCD flat screen, 17 inches, at plant	1.00E+00	unit			# NV	

Table D.7: LCD Screen Assembly

General Flow information							Representation in ecoinvent								Uncertainty information		
Input		Process Name		Output		Remarks	Category	Sub-category	Infra-structure	Location	Modul name in ecoinvent	Mean value	Unit	Source	Type	StDv 95%	General Comment
Water (unspec.)	➯	assembly, LCD screen					resource	in water			Water, unspecified natural origin	7.20E-02	m3	amount according to Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,12); data from an US-EPA LCA study
acetic acid	➯						chemicals	organics	No	RER	acetic acid, 98% in H2O, at plant	4.27E-04	kg	amount according to Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,3); data from an US-EPA LCA study
acetoene	➯						chemicals	organics	No	RER	acetone, liquid, at plant	6.87E-04	kg	amount according to Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,3); data from an US-EPA LCA study
aluminium sulphate	➯						chemicals	inorganics	No	RER	aluminium sulphate, powder, at plant	7.00E-03	kg	amount according to Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,3); data from an US-EPA LCA study
ammonia & ammonium containing substances	➯					data of ammonia, ammonium bifluoride, ammonium fluoride and ammonium hydroxide	chemicals	inorganics	No	RER	ammonia, liquid, at regional storehouse	1.95E-03	kg	amount according to Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,3); data from an US-EPA LCA study
argon	➯						chemicals	inorganics	No	RER	argon, crude, liquid, at plant	5.25E-04	kg	amount according to Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,3); data from an US-EPA LCA study
calcium hydroxide	➯						construction materials	binder	No	CH	lime, hydrated, packed, at plant	9.27E-03	kg	amount according to Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,3); data from an US-EPA LCA study
carbon dioxide	➯						chemicals	inorganics	No	RER	carbon dioxide liquid, at plant	2.49E-06	kg	amount according to Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,3); data from an US-EPA LCA study
chlorine	➯						chemicals	inorganics	No	RER	chlorine, liquid, production mix, at plant	1.03E-03	kg	amount according to Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,3); data from an US-EPA LCA study
cyclohexane	➯						chemicals	organics	No	RER	cyclohexanol, at plant	1.35E-06	kg	amount according to Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,3); data from an US-EPA LCA study
dimethylsulfoxide	➯						chemicals	organics	No	RER	dimethyl sulfoxide, at plant	4.42E-03	kg	amount according to Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,3); data from an US-EPA LCA study
ethanol	➯						chemicals	organics	No	RER	ethanol from ethylene, at plant	9.00E-04	kg	amount according to Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,3); data from an US-EPA LCA study
hydrochloric acid	➯						chemicals	inorganics	No	RER	hydrochloric acid, 30% in H2O, at plant	2.87E-03	kg	amount according to Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,3); data from an US-EPA LCA study
hydrofluoric acid	➯			continued ▼			chemicals	inorganics	No	GLO	hydrogen fluoride, at plant	2.81E-04	kg	amount according to Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,3); data from an US-EPA LCA study

Table D.7: LCD Screen Assembly (Cont.)

General Flow information							Representation in ecoinvent								Uncertainty information		
Input		Process Name		Output		Remarks	Category	Sub-category	Infra-structure	Loca-tion	Modul name in ecoinvent	Mean value	Unit	Source	Type	StDv 95%	General Comment
hydrogen	⇨	assembly, LCD screen		▼ continued			chemicals	inorganics	No	RER	hydrogen, liquid, at plant	2.96E-02	kg	amount according to Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,3); data from an US-EPA LCA study
hydrogen peroxide	⇨						chemicals	inorganics	No	RER	hydrogen peroxide, 50%in H2O, at plant	9.80E-06	kg	amount according to Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,3); data from an US-EPA LCA study
isopropyl alcohol	⇨						chemicals	organics	No	RER	isopropanol, at plant	2.33E-02	kg	amount according to Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,3); data from an US-EPA LCA study
krypton	⇨						chemicals	inorganics	No	CH	krypton, gaseous, at regional storage	1.72E-06	kg	amount according to Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,3); data from an US-EPA LCA study
methyl ethyl ketone	⇨						chemicals	organics	No	RER	methyl ethyl ketone, at plant	4.90E-07	kg	amount according to Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,3); data from an US-EPA LCA study
nitric acid	⇨						chemicals	inorganics	No	RER	nitric acid, 50%in H2O, at plant	8.27E-04	kg	amount according to Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,3); data from an US-EPA LCA study
nitrogen	⇨						chemicals	inorganics	No	RER	nitrogen, liquid, at plant	3.93E-01	kg	amount according to Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,3); data from an US-EPA LCA study
oxygen	⇨						chemicals	inorganics	No	RER	oxygen, liquid, at plant	5.17E-04	kg	amount according to Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,3); data from an US-EPA LCA study
phosphoric acid	⇨						chemicals	inorganics	No	RER	phosphoric acid, industrial grade, 85%in H2O, at plant	2.63E-03	kg	amount according to Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,3); data from an US-EPA LCA study
propylene glycol	⇨						chemicals	organics	No	RER	propylene glycol, liquid, at plant	1.34E-03	kg	amount according to Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,3); data from an US-EPA LCA study
sodium hydroxide	⇨						chemicals	inorganics	No	RER	sodium hydroxide, 50%in H2O, production mix, at plant	2.39E-02	kg	amount according to Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,3); data from an US-EPA LCA study
sulfuric acid	⇨						chemicals	inorganics	No	RER	sulphuric acid, liquid, at plant	1.53E-02	kg	amount according to Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,3); data from an US-EPA LCA study
xylene (mixed)	⇨			continued ▼			chemicals	organics	No	RER	xylene, at plant	1.05E-04	kg	amount according to Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,3); data from an US-EPA LCA study

Table D.7: LCD Screen Assembly (Cont.)

General Flow information							Representation in ecoinvent								Uncertainty information		
Input		Process Name		Output		Remarks	Category	Sub-category	Infra-structure	Loca-tion	Modul name in ecoinvent	Mean value	Unit	Source	Type	StDv 95%	General Comment
various organic chemicals	⇨	assembly, LCD screen		▼ continued		all those chemicals not separately mentioned here (all information from Socolof et al. (2001))	chemicals	organics	No	GLO	chemicals organic, at plant	4.01E-02	kg	amount according to Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,3); data from an US-EPA LCA study
fuel oil # 4	⇨					light fuel oil used as proxy	oil	heating systems	No	RER	heat, light fuel oil, at industrial furnace 1MW	5.99E-01	MJ	amount according to Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,3); data from an US-EPA LCA study
kerosene	⇨					light fuel oil used as proxy	oil	heating systems	No	RER	heat, light fuel oil, at industrial furnace 1MW	8.46E-01	MJ	amount according to Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,3); data from an US-EPA LCA study
LNG	⇨					natural gas as proxy used	natural gas	heating systems	No	RER	heat, natural gas, at industrial furnace >100kW	9.75E+00	MJ	amount according to Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,3); data from an US-EPA LCA study
Liquified petroleum gas (LPG)	⇨					light fuel oil used as proxy	oil	heating systems	No	RER	heat, light fuel oil, at industrial furnace 1MW	1.66E+00	MJ	amount according to Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,3); data from an US-EPA LCA study
Natural gas	⇨						natural gas	heating systems	No	RER	heat, natural gas, at industrial furnace >100kW	2.57E+00	MJ	amount according to Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,3); data from an US-EPA LCA study
electricity	⇨					assumed is 100%assembly in China	electricity	supply mix	No	CN	electricity, medium voltage, at grid	4.80E+00	kWh	amount according to Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,3); data from an US-EPA LCA study
Infrastructure	⇨						electronics	module	Yes	GLO	printed wiring board mounting plant	2.08E-07	unit	rough estimation	1	3.18	(4,5,4,3,1,5,9); Estimation, based on PWB mounting plant
Transport	⇨					own estimation for origin & distances of various parts - auxiliaries: standard values	transport systems	train	No	RER	transport, freight, rail	3.36E-01	tkm	own estimations & standard distances according to Frischknecht et al. (2004)	1	2.09	(4,5,na,na,na,na,5); standard values
Transport	⇨					own estimation for origin & distances of various parts	transport systems	ship	No	OCE	transport, transoceanic freight ship	7.83E-01	tkm	own estimations	1	2.09	(4,5,na,na,na,na,5); rough estimation
			⇨	Waste Water to WWTP		Assumed are 50%to WWTP - 50%directly to the river ...	waste management	wastewater treatment	No	CH	treatment, LCD module production effluent, to wastewater treatment, class 2	9.57E-02	m3	amount according to Socolof et al. (2001)	1	1.10	(1,3,2,3,1,3,6); data from an US-EPA LCA study
			⇨	Isopropyl alcohol		dataset " disposal, solvent mixture, to HWI" used as proxy	waste management	hazardous waste incineration	No	CH	disposal, solvents mixture, 16.5%water, to hazardous waste incineration	6.87E-04	kg	amount according to Socolof et al. (2001)	1	1.52	(1,3,2,3,4,3,6); data from an US-EPA LCA study - approximated with existing waste process
continued ▼			⇨	Printed wiring boards		dataset for treatment of Printed Wiring Boards in Europe used as proxy	waste management	recycling	No	GLO	disposal, treatment of printed wiring boards	1.00E-03	kg	amount according to Socolof et al. (2001)	1	1.52	(1,3,2,3,4,3,6); data from an US-EPA LCA study - approximated with existing waste process

Table D.7: LCD Screen Assembly (Cont.)

General Flow information							Representation in ecoinvent								Uncertainty information		
Input		Process Name		Output		Remarks	Category	Sub-category	Infra-structure	Loca-tion	Modul name in ecoinvent	Mean value	Unit	Source	Type	StDv 95%	General Comment
▼ continued		assembly, LCD screen	⇨	Remover, unspecified		dataset "disposal, solvent mixture, to HWI" used as proxy	waste management	hazardous waste incineration	No	CH	disposal, solvents mixture, 16.5%water, to hazardous waste incineration	2.06E-03	kg	amount according to Socolof et al. (2001)	1	1.52	(1,3,2,3,4,3,6); data from an US-EPA LCA study - approximated with existing waste process
			⇨	unspecified sludge		dataset "disposal sludge, NaCl electrolysis, to residual mat. landfill" used as proxy	waste management	residual material landfill	No	CH	disposal, sludge, NaCl electrolysis, 0%water, to residual material landfill	3.82E-03	kg	amount according to Socolof et al. (2001)	1	1.52	(1,3,2,3,4,3,6); data from an US-EPA LCA study - approximated with existing waste process
			⇨	waste acid (containing F and detergents)		dataset "disposal, solvent mixture, to HWI" used as proxy	waste management	hazardous waste incineration	No	CH	disposal, solvents mixture, 16.5%water, to hazardous waste incineration	1.80E-02	kg	amount according to Socolof et al. (2001)	1	1.52	(1,3,2,3,4,3,6); data from an US-EPA LCA study - approximated with existing waste process
			⇨	waste acids, unspecified		dataset "disposal, solvent mixture, to HWI" used as proxy	waste management	hazardous waste incineration	No	CH	disposal, solvents mixture, 16.5%water, to hazardous waste incineration	7.00E-03	kg	amount according to Socolof et al. (2001)	1	1.52	(1,3,2,3,4,3,6); data from an US-EPA LCA study - approximated with existing waste process
			⇨	waste oil			waste management	hazardous waste incineration	No	CH	disposal, used mineral oil, 10%water, to hazardous waste incineration	1.07E-03	kg	amount according to Socolof et al. (2001)	1	1.52	(1,3,2,3,4,3,6); data from an US-EPA LCA study - approximated with existing waste process
			⇨	waste plastic from LCD screen			waste management	municipal incineration	No	CH	disposal, plastic, consumer electronics, 15.3%water, to municipal incineration	5.40E-03	kg	amount according to Socolof et al. (2001)	1	1.52	(1,3,2,3,4,3,6); data from an US-EPA LCA study - approximated with existing waste process
			⇨	waste acid (mainly HF)		dataset "disposal, solvent mixture, to HWI" used as proxy	waste management	hazardous waste incineration	No	CH	disposal, solvents mixture, 16.5%water, to hazardous waste incineration	9.07E-03	kg	amount according to Socolof et al. (2001)	1	1.52	(1,3,2,3,4,3,6); data from an US-EPA LCA study - approximated with existing waste process
			⇨	unspecified sludge (hazardous w.)		dataset "disposal refinery sludge, to HWI" used as proxy	waste management	hazardous waste incineration	No	CH	disposal, refinery sludge, 89.5%water, to hazardous waste incineration	2.06E-03	kg	amount according to Socolof et al. (2001)	1	1.52	(1,3,2,3,4,3,6); data from an US-EPA LCA study - approximated with existing waste process
continued ▼			⇨	thinner, unspecified		dataset "disposal, solvent mixture, to HWI" used as proxy	waste management	hazardous waste incineration	No	CH	disposal, solvents mixture, 16.5%water, to hazardous waste incineration	3.60E-02	kg	amount according to Socolof et al. (2001)	1	1.52	(1,3,2,3,4,3,6); data from an US-EPA LCA study - approximated with existing waste process

Table D.7: LCD Screen Assembly (Cont.)

General Flow information							Representation in ecoinvent								Uncertainty information		
Input		Process Name		Output		Remarks	Category	Sub-category	Infra-structure	Loca-tion	Modul name in ecoinvent	Mean value	Unit	Source	Type	StDv 95%	General Comment
▼ continued		assembly, LCD screen	⇨	remover, unspec. (hazardous w.)		dataset "disposal, solvent mixture, to HWI" used as proxy	waste management	hazardous waste incineration	No	CH	disposal, solvents mixture, 16.5%water, to hazardous waste incineration	2.02E-02	kg	amount according to Socolof et al. (2001)	1	1.52	(1,3,2,3,4,3,6); data from an US-EPA LCA study - approximated with existing waste process
			⇨	phosphoric acid		dataset "disposal, solvent mixture, to HWI" used as proxy	waste management	hazardous waste incineration	No	CH	disposal, solvents mixture, 16.5%water, to hazardous waste incineration	9.60E-04	kg	amount according to Socolof et al. (2001)	1	1.52	(1,3,2,3,4,3,6); data from an US-EPA LCA study - approximated with existing waste process
			⇨	nitric acid		dataset "disposal, solvent mixture, to HWI" used as proxy	waste management	hazardous waste incineration	No	CH	disposal, solvents mixture, 16.5%water, to hazardous waste incineration	2.29E-05	kg	amount according to Socolof et al. (2001)	1	1.52	(1,3,2,3,4,3,6); data from an US-EPA LCA study - approximated with existing waste process
			⇨	isopropyl alcohol (hazardous w.)		dataset "disposal, solvent mixture, to HWI" used as proxy	waste management	hazardous waste incineration	No	CH	disposal, solvents mixture, 16.5%water, to hazardous waste incineration	1.27E-01	kg	amount according to Socolof et al. (2001)	1	1.52	(1,3,2,3,4,3,6); data from an US-EPA LCA study - approximated with existing waste process
			⇨	acetone		dataset "disposal, solvent mixture, to HWI" used as proxy	waste management	hazardous waste incineration	No	CH	disposal, solvents mixture, 16.5%water, to hazardous waste incineration	1.85E-03	kg	amount according to Socolof et al. (2001)	1	1.52	(1,3,2,3,4,3,6); data from an US-EPA LCA study - approximated with existing waste process
			⇨	acetic acid		dataset "disposal, solvent mixture, to HWI" used as proxy	waste management	hazardous waste incineration	No	CH	disposal, solvents mixture, 16.5%water, to hazardous waste incineration	2.97E-04	kg	amount according to Socolof et al. (2001)	1	1.52	(1,3,2,3,4,3,6); data from an US-EPA LCA study - approximated with existing waste process
			⇨	Waste heat			air	high population density			Heat, waste	1.73E+01	MJ	calculated from the electricity input	1	1.64	(4,3,3,3,4,5,13); Calculated from electricity input
			⇨	acetic acid to air			air	high population density			Acetic acid	9.07E-05	kg	amount according to Socolof et al. (2001)	1	2.01	(1,3,2,3,1,3,23); data from an US-EPA LCA study
			⇨	acetone to air			air	high population density			Acetone	1.24E-05	kg	amount according to Socolof et al. (2001)	1	2.01	(1,3,2,3,1,3,23); data from an US-EPA LCA study
			⇨	ammonia to air			air	high population density			Ammonia	4.15E-03	kg	amount according to Socolof et al. (2001)	1	1.51	(1,3,2,3,1,3,31); data from an US-EPA LCA study

Table D.7: LCD Screen Assembly (Cont.)

General Flow information							Representation in ecoinvent								Uncertainty information		
Input		Process Name		Output		Remarks	Category	Sub-category	Infra-structure	Loca-tion	Modul name in ecoinvent	Mean value	Unit	Source	Type	StDv 95%	General Comment
▼ continued		assembly, LCD screen	⇨	cyclohexane to air			air	high population density			Cyclohexane	3.23E-06	kg	amount according to Socolof et al. (2001)	1	2.01	(1,3,2,3,1,3,23); data from an US-EPA LCA study
			⇨	diethylene glycol to air			air	high population density			Diethylene glycol	6.46E-06	kg	amount according to Socolof et al. (2001)	1	2.01	(1,3,2,3,1,3,23); data from an US-EPA LCA study
			⇨	hexamethyldisilizane to air			air	high population density			Boric acid	9.13E-08	kg	amount according to Socolof et al. (2001)	1	2.01	(1,3,2,3,1,3,23); data from an US-EPA LCA study
			⇨	hydrochloric acid to air			air	high population density			Hydrogen chloride	4.04E-03	kg	amount according to Socolof et al. (2001)	1	1.51	(1,3,2,3,1,3,31); data from an US-EPA LCA study
			⇨	hydrofluoric acid to air			air	high population density			Hydrogen fluoride	3.47E-03	kg	amount according to Socolof et al. (2001)	1	1.51	(1,3,2,3,1,3,31); data from an US-EPA LCA study
			⇨	hydrogen to air			air	high population density			Hydrogen	8.87E-06	kg	amount according to Socolof et al. (2001)	1	1.51	(1,3,2,3,1,3,31); data from an US-EPA LCA study
			⇨	isopropyl alcohol to air			air	high population density			Sodium tetrahydroborate	1.19E-03	kg	amount according to Socolof et al. (2001)	1	2.01	(1,3,2,3,1,3,23); data from an US-EPA LCA study
			⇨	N-bromoacetamide to air			air	high population density			Boron trifluoride	6.12E-04	kg	amount according to Socolof et al. (2001)	1	2.01	(1,3,2,3,1,3,23); data from an US-EPA LCA study
			⇨	nitric acid to air		as nitrogen oxides	air	high population density			Nitrogen oxides	1.79E-05	kg	amount according to Socolof et al. (2001)	1	1.51	(1,3,2,3,1,3,31); data from an US-EPA LCA study
			⇨	nitrogen fluoride to air			air	high population density			Nitrogen fluoride	1.63E-02	kg	amount according to Socolof et al. (2001)	1	1.51	(1,3,2,3,1,3,31); data from an US-EPA LCA study
			⇨	phosphine to air			air	high population density			Phosphine	4.17E-03	kg	amount according to Socolof et al. (2001)	1	1.51	(1,3,2,3,1,3,31); data from an US-EPA LCA study
			⇨	phosphoric acid to air			air	high population density			Phosphoric acid	3.23E-06	kg	amount according to Socolof et al. (2001)	1	1.51	(1,3,2,3,1,3,31); data from an US-EPA LCA study
			⇨	sulfur hexafluoride to air			air	high population density			Sulfur hexafluoride	4.87E-04	kg	amount according to Socolof et al. (2001)	1	2.01	(1,3,2,3,1,3,23); data from an US-EPA LCA study
continued ▼			⇨	tetramethyl ammonium hydroxide to air			air	high population density			Tetramethyl ammonium hydroxide	4.29E-02	kg	amount according to Socolof et al. (2001)	1	2.01	(1,3,2,3,1,3,23); data from an US-EPA LCA study

Table D.7: LCD Screen Assembly (Cont.)

General Flow information							Representation in ecoinvent								Uncertainty information		
Input		Process Name		Output		Remarks	Category	Sub-category	Infra-structure	Loca-tion	Modul name in ecoinvent	Mean value	Unit	Source	Type	StDv 95%	General Comment
▼ continued		assembly, LCD screen	⇨	unspecified organic emissions to air			air	high population density			NMVOC, non-methane volatile organic compounds, unspecified origin	7.12E-03	kg	amount according to Socolof et al. (2001)	1	2.01	(1,3,2,3,1,3,23); data from an US-EPA LCA study
			⇨	1,1,1-Trichloroethane to water			water	river			Ethane, 1,1,1-trichloro-, HCFC-140	1.53E-09	kg	amount according to Socolof et al. (2001)	1	3.01	(1,3,2,3,1,3,34); data from an US-EPA LCA study
			⇨	antiomony to water			water	river			Antimony	7.60E-09	kg	amount according to Socolof et al. (2001)	1	1.51	(1,3,2,3,1,3,33); data from an US-EPA LCA study
			⇨	arsenic to water			water	river			Arsenic, ion	7.60E-09	kg	amount according to Socolof et al. (2001)	1	5.01	(1,3,2,3,1,3,35); data from an US-EPA LCA study
			⇨	BOD to water			water	river			BOD5, Biological Oxygen Demand	1.16E-03	kg	amount according to Socolof et al. (2001)	1	1.51	(1,3,2,3,1,3,32); data from an US-EPA LCA study
			⇨	boron to water			water	river			Boron	3.05E-07	kg	amount according to Socolof et al. (2001)	1	1.51	(1,3,2,3,1,3,33); data from an US-EPA LCA study
			⇨	cadmium to water			water	river			Cadmium, ion	7.60E-09	kg	amount according to Socolof et al. (2001)	1	5.01	(1,3,2,3,1,3,35); data from an US-EPA LCA study
			⇨	chromium to water			water	river			Chromium, ion	5.89E-07	kg	amount according to Socolof et al. (2001)	1	5.01	(1,3,2,3,1,3,35); data from an US-EPA LCA study
			⇨	chromium (VI) to water			water	river			Chromium VI	1.53E-08	kg	amount according to Socolof et al. (2001)	1	5.01	(1,3,2,3,1,3,35); data from an US-EPA LCA study
			⇨	COD			water	river			COD, Chemical Oxygen Demand	1.79E-04	kg	amount according to Socolof et al. (2001)	1	1.51	(1,3,2,3,1,3,32); data from an US-EPA LCA study
			⇨	copper to water			water	river			Copper, ion	6.12E-08	kg	amount according to Socolof et al. (2001)	1	5.01	(1,3,2,3,1,3,35); data from an US-EPA LCA study
			⇨	cyanide(-1) to water			water	river			Cyanide	2.44E-07	kg	amount according to Socolof et al. (2001)	1	1.51	(1,3,2,3,1,3,33); data from an US-EPA LCA study
			⇨	dissolved solids		as "solids, inorganics" shown here	water	river			Solids, inorganic	5.03E-04	kg	amount according to Socolof et al. (2001)	1	1.51	(1,3,2,3,1,3,33); data from an US-EPA LCA study
continued ▼			⇨	fluorides (F-) to water			water	river			Fluoride	8.53E-04	kg	amount according to Socolof et al. (2001)	1	1.51	(1,3,2,3,1,3,33); data from an US-EPA LCA study

Table D.7: LCD Screen Assembly (Cont.)

General Flow information							Representation in ecoinvent								Uncertainty information		
Input		Process Name		Output		Remarks	Category	Sub-category	Infra-structure	Loca-tion	Modul name in ecoinvent	Mean value	Unit	Source	Type	StDv 95%	General Comment
▼ continued		assembly, LCD screen	⇨	hexane to water			water	river			Hydrocarbons, aromatic	3.92E-05	kg	amount according to Socolof et al. (2001)	1	3.01	(1,3,2,3,1,3,34); data from an US-EPA LCA study
			⇨	iron to water			water	river			Iron, ion	1.75E-07	kg	amount according to Socolof et al. (2001)	1	5.01	(1,3,2,3,1,3,35); data from an US-EPA LCA study
			⇨	lead to water			water	river			Lead	4.11E-07	kg	amount according to Socolof et al. (2001)	1	5.01	(1,3,2,3,1,3,35); data from an US-EPA LCA study
			⇨	manganese to water			water	river			Manganese	1.53E-08	kg	amount according to Socolof et al. (2001)	1	5.01	(1,3,2,3,1,3,35); data from an US-EPA LCA study
			⇨	mercury to water			water	river			Mercury	6.46E-09	kg	amount according to Socolof et al. (2001)	1	5.01	(1,3,2,3,1,3,35); data from an US-EPA LCA study
			⇨	nickel to water			water	river			Nickel, ion	1.53E-08	kg	amount according to Socolof et al. (2001)	1	5.01	(1,3,2,3,1,3,35); data from an US-EPA LCA study
			⇨	nitrogen to water			water	river			Nitrogen	5.29E-03	kg	amount according to Socolof et al. (2001)	1	1.51	(1,3,2,3,1,3,33); data from an US-EPA LCA study
			⇨	oil & grease to water			water	river			Oils, unspecified	1.35E-05	kg	amount according to Socolof et al. (2001)	1	3.01	(1,3,2,3,1,3,34); data from an US-EPA LCA study
			⇨	organic phosphorus, unspec., to water		proxy "phosphate, to water" used	water	river			Phosphate	1.53E-08	kg	amount according to Socolof et al. (2001)	1	1.51	(1,3,2,3,1,3,33); data from an US-EPA LCA study
			⇨	phenol to water			water	river			Phenol	1.53E-08	kg	amount according to Socolof et al. (2001)	1	3.01	(1,3,2,3,1,3,34); data from an US-EPA LCA study
			⇨	phosphorus (yellow/white) to water			water	river			Phosphorus	2.87E-04	kg	amount according to Socolof et al. (2001)	1	1.51	(1,3,2,3,1,3,33); data from an US-EPA LCA study
			⇨	assembly of LCD screen			electronics	module	No	GLO	assembly, LCD screen	1.00E+00	kg			#NV	

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