MIKADO: a Decision Support Tool for Pollution Reduction in Aluminium Pressure Die Casting

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I can still remember the unease before starting my research project. Several questions relating to the country in which to carry out the research and the contents of the project had to be dealt with. In that time many people were involved in keeping me on track by helping me out to apply for a post-graduate research scholarship, to document myself with appropriate literature and in deciding where to carry out my research. To all of them I express here my gratitude.

In early 2002, I started the work presented in this thesis. I arrived in February that year at the Environmental Systems Analysis Group at the University of Wageningen and realised that all the ideas I had for the work seemed possible to put into practice and made sense also to others. My promotion team were primarily responsible for me to put into practice what I was aiming to do. I express here my gratitude to my promotor – Leen Hordijk. It is certainly a challenge to be guided by the Director of the International Institute for Applied Systems Analysis (IIASA) in Austria. But even with a busy schedule, when needed he took over the daily supervision and was available to meet me regularly during my stay at IIASA (Oct-Dec. 2003). It was an excellent experience to work with Leen. His very critical comments but equally sound advice were vital many times throughout the research. I also would like to thank my co-promotor - Carlos Costa. I did not have many chances to discuss with him. Nevertheless, in our discussions his advice was always very constructive. Lastly, my daily supervisor – Carolien Kroeze. She played a primary role throughout the research period. She is one of the most efficient persons that I have ever met. From her I learnt how to plan my work efficiently, to define priorities and also I learnt the basis of working in science. She was the best daily supervisor one can wish and she definitely had an important role given the endurance of the research period.

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Chapter 1: Introduction

1.1. Background

1.1.1. Industry and the environment

Industrial activities cause a variety of environmental problems. These problems receive attention through environmental policies aimed at limiting pollution of air, water and soil and at enhancing conservation of resources and nature. For many industrial companies, environmental performance in terms of emissions, production of waste and the use of resources is an increasing concern. Assessing this performance is not a simple task, because of the complexity of industrial processes and the complexity of the environmental issues given the variety of the compounds emitted and the variety of their environmental effects.

The efforts to improve environmental performance of the industry have traditionally been driven by environmental regulations. Environmental laws, applicable to the industrial sectors, often limit the emissions of specific pollutants. Companies typically respond to these regulations by taking single actions aiming to live up to the environmental restrictions, by for instance, reducing the amount of a compound emitted. Alternatively, companies may define internal environmental policies, for instance, by implementing environmental management systems (e.g. standards as ISO 14001, 2004 or EMAS, 2001). Such pro-activeness may be implicitly driven by environmental restrictions, but requires a more integrated approach in defining ways to reduce the total environmental burden of a company.

The attempts to improve the environmental performance vary between different types of industry. Industrial sectors taking the lead in this include, for instance, the pulp and paper sector (e.g. Lee and Ding, 2000; Pineda-Henson et al., 2002; Bordado and Gomes, 2003; Lopes et al., 2003; Oral et al., 2005; Lee and Rhee, 2005; Mahmood and Elliot, 2006; Gabbrielli et al., 2006), chemical industries (e.g. Eder, 2003; Alvarez et al., 2004; Smith et al., 2004; Seyler et al., 2005; Mendivil et al., 2005; Kleizen, 2006) and the metals industries.

The metals industry is one of the most studied industrial sectors. A large number of environmental studies about the metals industry have been published (e.g. Proctor et al., 2000; Moors et al., 2005; Tan and Khoo, 2005a; Rebitzer and Buxmann, 2005; Moors, 2006; Norgate et al., 2007). These studies focus predominantly on the primary and secondary metals industry. Metals casting industry is an exception in this respect: the number of studies on the environmental performance of the metal casting is limited. Nevertheless, this industry is dominated by relatively small businesses supplying the largest share of casting products currently used worldwide. Within the metals casting industry a distinction can be made between ferrous and non-ferrous metals industries. The aluminium pressure die casting industry belongs to the second category and will be subject of our analysis.

1.1.2. Environmental management in the aluminium pressure die casting industry

Aluminium products have the largest market share among the non-ferrous industries (CAEF, 2003; US Department of Energy, 2004) and the aluminium pressure die casting has the largest share of the total aluminium market (US Department of Energy, 1998). In this study, we have therefore chosen to analyse the aluminium pressure die casting.

The aluminium pressure die casting is a widely used manufacturing process that produces two-thirds of the aluminium castings used in the automotive industry (Brown, 1999). The characteristics of these die casting products are the light weight, the accurate dimensional shape and the smooth- or textured–surfaced product. These characteristics fulfil the specifications required by the automotive industry (Kim et al., 2003). The current market share is expected to increase due to the demand for aluminium products to be used in the automotive industry. All this, added to the fact that the technologies used for the casting process are comparable within Europe and between Europe and USA (Tan and Khoo, 2005b), makes this industry an interesting industrial sector to be studied in terms of its contribution to the environmental problems.

The environmental problems caused by the aluminium pressure die casting industry are various and are related with emissions released to air, soil and water. The process emissions to air include metals from aluminium alloy, compounds released during fuel combustion, hydrogen fluoride emissions from the use of fluxing agents to remove impurities from molten alloy, and volatile organic compounds from the use of lubricants. The solid waste produced includes aluminium dross, ceramic lining from furnaces. Other types of solid waste are ceramic abrasives and steel shot from operations taking place during the metals surface finishing. Liquid effluents include losses of emulsion used to lubricate the die casting moulds. These emissions, waste and effluents contribute to environmental problems such as global warming, acidification, tropospheric ozone formation, toxicity problems (human, terrestrial and aquatic), as well as natural resource depletion and problems associated with solid waste production.

When reviewing the literature on the assessment of the environmental performance of the metals industry, we observe that many studies exist on metals industry in general, but only a few exist on aluminium die casting. Moreover, these few studies on aluminium die casting differ in many aspects, for instance with respect to the goal of the study, the environmental aspects taken into account, the part of the production process studied, or the inclusion of costs. In the following, we analyse these studies.

Tables 1.1. and 1.2. present a number of interesting studies on environmental management. The studies in Table 1.1.focus specifically on pressure die casting. The studies overviewed are mainly related to the aluminium pressure die casting. Nevertheless, interesting studies referring to the zinc pressure die casting process are also included. The two examples overviewed include relevant studies of a process that follows the aluminium pressure die casting on the most commonly technologies used. In Table 1.2. the examples refer to the metals industry in general. These studies will be discussed with respect to the study aim, intended user of the study, the environmental impact categories included, use of natural resources and emissions considered, the parts of the process considered, type of costs included and the environmental systems analysis (ESA) tools used.

Table 1.1. Overview of selected studies on environmental management in the aluminium (and zinc) pressure die casting industry (relevant studies included). The overview includes the aim of the study, the intended user of the results, the environmental impact categories included, the environmental pressure (use of natural resources and emission considered), the parts of the industrial process that are included, the type of cost included and the environmental systems analysis (ESA) tools used.

Studies	Aim	User	Environmental impact categories	Environmental Pressure	Processes considered	Costs	ESA tools
Park et al. (2002)*	Cost-effectiveness analysis of waste management	Company	Not specifically assessed.	Waste production, soluble and insoluble metals	The finishing process used to clean and polish die casting products	Capital expenditure and the annual operating costs	Technology Assessment. Cost analysis (capital and operating costs)
Kim et al. (2003)	Supporting environmental improvement of die casting	Industrial sector	Depletion of resources, global warming, photo oxidant formation, acidification, eutrophication, human and ecotoxicity	Use of natural gas, electricity, water, oils. Solid waste production, CO_2 and VOC emission.	The casting process, including application of mould release agent and extraction of components	None	Life Cycle Assessment and Multi-Criteria Analysis
EIPPCB (2005)	Description of pollution reduction options	Industrial sector	Not specifically assessed	Emissions and resource consumption by companies	Relevant sources of environmental problems	Capital expenditure for a few cases	None
Dalquist and Gutowski (2004)	Analysis of environmental impact of die casting	Industrial sector	Not specifically assessed	Qualitative assessment of substance flows in die casting	Die preparation (application of mould release agent), the melting of scrap, casting and finishing	None	None
Backhouse et al. (2004)	Life-cycle comparison of iron and aluminium alloy castings	Industrial sector	Global warming	Energy consumption, greenhouse gases emissions	The full aluminium casting process	None	Life Cycle Assessment (cradle to grave)
Tan and Khoo (2005b)*	Environmental assessment of a die casting product	Industrial sector	Climate change, acidification, respiratory inorganics, respiratory organics, ecotoxicity	Air emissions	Smelting, casting, recycling and transportation	None	Life Cycle Assessment (cradle to gate) and Multi-Criteria Analysis

*these two example studies refer to the zinc pressure die casting process.

Table 1.2. As Table 1.1., but for a selection of studies on the metals industry in general.

Studies	**Aim**	**User**	**Environmental impact categories**	**Environmental pressure**	**Processes considered**	**Costs**	**ESA tools**
Choi et al (1997)	Modelling environmental impact of manufacturing processes	Researchers	Not specifically assessed	Solid waste, energy consumption, waste water, noise	All production process in the manufacturing of a product (toy train)	None	Life Cycle Assessment
Rabah (1999)	Economic assessment of controlling emission of particulates from cast iron foundries	Industrial sector	Not specifically assessed	Air emission of total solid particulates	Furnaces used in iron foundries	Capital expenditure and the annual operating costs	Cost -effectiveness analysis
Moors et al. (2005)	Design strategies towards cleaner metals production	Industrial sector and policy makers	Not specifically assessed	Post-mining waste production and emissions of SO_2, CO_2, NOx, CO, dust, and VOC	Primary production of zinc, aluminium and steel.	None	Not specified
Tan and Khoo (2005a)	List strategies to improve the environmental life cycle of primary aluminium	Industrial sector	Global warming, acidification and human toxicity	Coal use, air emissions, waste production and other by-products	Refinery, smelter and casting in primary production of aluminium	None	Life Cycle Assessment (cradle to gate)
Rebitzer and Buxmann (2005)	Life Cycle Assessment of an aluminium automotive component	Company	Global warming	Energy consumption and greenhouse gas emissions	Full life cycle of the product: raw materials production, manufacturing, use and end of life.	None	Life Cycle Assessment
Moors (2006)	Analysis of technological changes for policy purposes	Policy makers	Not specifically assessed.	Waste production, energy consumption, air emissions	Extraction and smelting of raw materials from the primary aluminium production	None	Qualitative Technology Assessment

Table 1.1. and Table 1.2. lead to the following observations.

Firstly, it can be observed that the studies serve different purposes and users. Table 1.1 shows that some studies aim to provide the aluminium die casting sector with information on how to realise a more environmentally sound die casting process (Kim et al., 2003; EIPPCB, 2005; Dalquist and Gutowski, 2004) or on determining its environmental performance (Backhouse et al., 2004). Some of these studies also aim to help the industrial sector to comply with environmental regulations or proposed policy instruments. The intended user of the results is for most studies the industrial sector. We found only one study focusing specifically on the company level (Park et al., 2002). This study, however, focuses only on waste management and therefore does not include a complete environmental assessment.

The selected examples from the metals sector (Table 1.2) indicate that the intended users of the studies may also include researchers and policy makers. For instance, researchers are the intended users of a study aiming to develop an assessment model to determine the environmental performance of a single product (Choi et al., 1997). Alternatively, policy makers may benefit from the results of the studies by Moors et al. (2005) and Moors (2006), who propose policy instruments to help to comply with environmental regulations. The other studies are especially interesting for the industry and aim to reduce a specific pollutant such as solid particulates (Rabah, 1999) or aim at defining pollution reduction strategies by focusing on the life cycle (Tan and Khoo, 2005a; Rebitzer and Buxmann, 2005).

It will be clear from the above that most of the studies do not take the perspective of the company but rather focus on industrial sectors as a whole. In the case where the company was the intended user, the studies either focus on a specific environmental issue (Park et al., 2002) or analyse the life cycle of a specific product (Rebitzer and Buxmann, 2005).

Table 1.1. also shows that no studies exist on aluminium die casting that include all environmental impact categories simultaneously. The most complete is the analysis by Kim et al. (2003), but the authors do not consider the complete die casting process, since emissions and waste from finishing operations are not considered. From Table 1.2 it is clear that none of the examples for the metals industry in general includes a complete environmental assessment. In fact, only Tan and Khoo (2005a) and Rebitzer and Buxmann (2005) explicitly consider environmental impacts. Most other studies do not specifically assess the environmental impact categories, but rather analyse the use of resources and emissions or waste produced as indicators for the environmental pressure.

Another conclusion is that the environmental pressure (including all the resources used, pollutants emitted or liquid effluent or solid wastes produced) is not covered in the studies reviewed here (Table 1.1 and 1.2). Many studies include gaseous emissions resulting from energy use (Kim et al., 2003; EIPPCB, 2005; Backhouse et al., 2004; Tan and Khoo, 2005b; Moors et al., 2005; Tan and Khoo, 2005a; Rebitzer and Buxmann, 2005; Moors, 2006). However, other pollutants released are less systematically included. Further, not all the pollutants are quantitatively assessed in all studies. In some cases they are analysed only qualitatively (Moors et al., 2005; Moors, 2006).

Next, we evaluated which part of the production process is considered in the studies. The studies on aluminium die casting differ considerably in this respect (Table 1.1.). Most studies focus on the typical processes included in the production line, or parts of it. None of them also include auxiliary processes of a typical die casting plant, such as the wastewater treatment plant and the internal transportation of semi-products. Some studies perform a gate-to-gate analysis but include the processes taking place during the finishing of die cast parts (Park et al., 2002). Some others include only the processes taking place during the casting operation (Kim et al., 2003) or are limited to the most relevant for environmental management (EIPPCB, 2005). Some consider the full life cycle or relevant parts of it (e.g. cradle to grave by Backhouse et al. (2004); or cradle to gate by Tan and Khoo (2005b)). It can again be concluded that none of the abovementioned studies cover, on a quantitative basis, all the relevant processes on a gate-to-gate basis.

Both Table 1.1. and Table 1.2. show that economic aspects of environmental control have only been considered in a small number of studies. In these few cases the costs of environmental control are included as the capital expenses and operational costs of selected pollution reduction options (Park et al., 2002; Rabah, 1999). Only one of the studies reviewed (Rabah, 1999) includes a cost-effectiveness analysis.

Finally, environmental systems analysis tools that are used in the studies differ. A number of tools are used individually or in combination. Several studies apply partial Life Cycle Assessment, either individually (Backhouse et al., 2004; Choi et al., 1997; Tan and Khoo, 2005a; Rebitzer and Buxmann, 2005) or in combination with Multi-Criteria Analysis (Kim et al., 2003; Tan and Khoo, 2005b). Some other tools used include Technology Assessment (Park et al., 2002; Moors, 2006) and Cost-Effectiveness Analysis (Rabah, 1999). However, from Table 1.1. and Table 1.2. it cannot be concluded which analytical tools are most appropriate for analyses of alternative environmental decisions that take a company perspective.

From the above, we conclude that a decision support tool taking a company perspective and covering all relevant environmental issues as well as cost of environmental management is not available in the literature.

1.2. Objective and Research Questions

The overall objective of the study is to develop a decision support tool (DST) to analyse options to reduce the environmental impact of an industrial company. The DST will take a company perspective and is developed as a tool aiming at assisting the company management in the analyses of possible strategies to improve the company's environmental performance. The DST is model based and allows for the assessment of the potential environmental impact resulting from emissions of environmental pollutants, as well as the effectiveness of reduction options and the associated costs. The tool is developed for a case study taken from the aluminium pressure die casting sector, and is using data of a plant located in Portugal.

The study objective will be achieved by answering the following research questions (RQ):

RQ 1	What existing environmental systems analysis methods and tools can in principle be combined in a decision support tool (DST) and used to analyse the environmental performance of a plant from a company perspective?
RQ 2	Which technical pollution reduction options are available for reducing the environmental impact of an aluminium pressure die casting plant? What are their technical potentials to reduce this impact, and the associated costs for the plant?
RQ 3	How can a model be developed that can be used from a company perspective to analyse options to reduce the environmental impact of aluminium pressure die casting?
RQ 4	How do different strategies to combine pollution reduction options improve the environmental performance of an aluminium pressure die casting plant, and what are the associated costs for the plant?

1.3. Research Strategy

Environmental Systems Analysis (ESA) is often used to assist decision making in finding solutions to complex environmental problems. ESA procedures have been described by Checkland (1979), Wilson (1984), Findeisen and Quade (1997) and Pluimers (2001). Based on these studies this thesis follows a six step procedure. These steps are: 1) Problem definition, 2) Evaluation and selection of existing ESA tools; 3) Identification of pollution reduction options, 4) Model building (including sensitivity analysis), 5) Model application (includes the analysis of model performance) and 6) Evaluation of the methodological approach.

In Step 1 *(Problem definition)* the problem is formulated and the system defined. In this thesis the problem is associated with the development of a tool for modelling the industrial process and implementing pollution reduction options and the associated costs. The decision support tool (DST) to be developed aims to support the industrial managers in deciding between alternative pollution reductions strategies to be implemented in a plant. This general problem is approached via a case study. The system considered is an aluminium pressure die casting plant located in Portugal. The industrial system boundary is set at the gates of the business concerned. We thus perform a gate-to-gate analysis. In Step 1 the system is defined in terms of inputs and outputs and their relations. The data used is specific for the selected plant and has been complemented by industry specific data from the literature.

Step 2 (*Evaluation and selection of existing ESA tools*) overviews a number of existing analytical tools currently used in environmental systems analyses of industry. The tools that could be used to analyse the environmental performance of a company are reviewed. They are evaluated with respect to their usefulness, alone or in combination, in decision support tools for companies that want to reduce their environmental impact. Next, the DST to be developed is described in general terms. We first describe its characteristics and then list the potential environment systems analysis tools that are useful for our DST.

Step 3 (*Identification of pollution reduction options*) includes the construction of an inventory of reduction options, their potential to reduce emissions, and the associated costs. The reduction options to be analysed are specific for the selected plant. In this step, a general overview will be given of the pollution reduction options aiming at reducing the emissions to air, soil and water from an aluminium pressure die casting plant. The options will be investigated in terms of their potential to reduce pollution and also in terms of the costs associated with their implementation. The options to be developed for the selected plant are process specific and assumed to be implemented at the level of the plant sub-processes or sub-sub-processes. These options may include add-on techniques or be more structural, i.e., by affecting the materials consumption or changes in process operations. They focus either on the different pollutants released by the processes or on the materials/energy consumed in the processes.

Step 4 (*Model building*) aims at exploring the consequences for the environmental impact and associated costs of individual pollution reduction options or combinations thereof. The model building is followed by an analysis of the model sensitivity to changes in model parameters. In this step a model (our DST) is developed to analyse options to reduce the environmental impact of aluminium die casting. This model takes a company perspective, so that it can be used as a decision supporting tool for environmental management. The model structure and the modelling approach are based on a study by Van Langen (2002), who describes the development of a definition language for designing processes (DESIRE). This language provides a structure and a grammar to define objects, objects' properties and methods. Van Langen stated that his approach can be used in designing models for estimating the emissions from industrial processes.

Step 5 (*Model application*) uses the model to explore the implementation of individual reduction options or combinations of options in well defined reduction strategies. In this step the model is explored. Three different types of analyses are made. At first, we analyse the plant's environmental performance without implementing pollution reduction options. The analysis focuses on the relative contribution of different industrial processes levels to the environmental impact. Second, the individual pollution reduction options are analysed systematically by calculating their potential to reduce environmental problems and the cost associated with the reduction. Third, in order to analyse the situation in which a company decides to implement a number of options simultaneously, different strategies to combine reduction options are defined. These reduction strategies may, for instance, aim for reducing the largest environmental problem, or a specific activity, or a specific pollutant. Alternatively, a company may wish to combine the most cost effective options, or combining add-on techniques, or only more structural reduction options. Therefore, a range of combinations are presented, and their effects on the plant's environmental performance analysed. The associated costs resulting from the implementation of these options are also analysed.

In the final Step 6 (*Evaluation of the methodological approach*) the environmental systems analysis approach will be discussed in terms of iterations performed, sequence of steps and the comparison with other model studies. In this step, model uncertainties and the implication of the results of our study to the aluminium pressure die casting sector as well for other metals industry or the industry in general are also discussed. This may reveal the applicability of the approach for other industries or sectors.

In this study an environmental systems analysis is performed at the plant level, using a specific combination of ESA tools. This combination aims to fulfil the current gap in decision support tools that provides companies with means to analysing options to reduce their environmental impact by defining pollution reduction options and by assessing the economic and environmental benefits of these options.

1.4. Thesis outline

The thesis includes six chapters presenting the results of six steps of the environmental systems analysis procedure according to the formulated research questions. (Figure 1.1.)

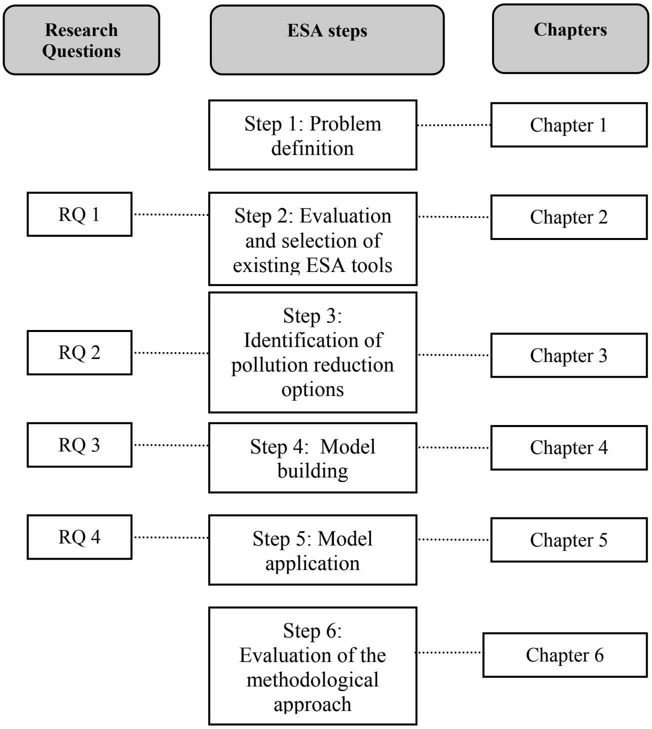

Figure 1.1. Schematic representation of research questions, environmental system analysis (ESA) steps and thesis chapters.

This first chapter (Chapter 1) provides the general introduction, and describes the objective, the research questions addressed and the research strategy.

Chapter 2 presents an overview of the different analytical tools aiming to assess the environmental performance in the industry. Thus, a selection of promising tools illustrates the need for a new DST that takes a company perspective. The literature review allows for defining the main characteristics of the decision support tool and leads to potential ESA tools useful for a DST taking a company perspective.

Chapter 3 gives a general overview of pollution reduction options aiming to reduce the emissions to air, soil and water of the aluminium pressure die casting plant. The techniques are investigated in terms of their potential to reduce pollution and also in terms of the costs associated with the implementation of these options. These options focus either on the different pollutants released or on the materials/energy used in the process. Possible actions or alternatives that appear to lead to an improvement of the current situation are identified and (partially) presented in Chapter 3. This preliminary analysis of the alternatives is further explored in Chapter 5.

Chapter 4 describes the model developed to analyse the pollution reduction options in order to reduce the environmental impact. This chapter describes the mathematical formulation of the model. The model is developed for and applied to the aluminium die casting plant supplying car manufacturers with aluminium die casting products. A first assessment of the environmental impact for the plant is made and results of a partial model sensitivity analysis are presented.

Chapter 5 explores the model in order to analyse scenarios to reduce the environmental impact of the aluminium die casting plant. These scenarios present the modelled responses to the reduction options assumed to be implemented. The model calculates the potential to reduce emissions, and the costs associated with implementation of reduction options. First, the model results are presented for a situation in which no reduction options are assumed to be implemented (so-called zero case, reflecting the current practice in the plant). Secondly, a systematic analysis of reduction options is performed. Finally, seven types of reduction strategies are analysed by assuming to implement, simultaneously, different reduction options. These strategies are analysed with respect to their potential to reduce emissions, environmental impact and costs associated with the implementation of options.

Finally, the results and methodology are discussed and conclusions drawn. Chapter 6 includes a discussion of the stepwise procedure taken and compares our decision support tool with other model studies. It discusses the model uncertainties and the implications of the results for industry. Finally, recommendations for future studies are formulated. Thus Chapter 6 not only concludes on the results for the case study, but also discusses the extent to which these results can be generalised to other industries.

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Chapter 2: Selecting Environmental Systems Analysis Tools: strengths and weaknesses for use in a decision support tool

Abstract

An overview of selected environmental systems analysis (ESA) tools currently used by industry is given, including tools to assess the environmental performance of a company. These tools may be useful for a decision support tool (DST) that takes a company perspective, while considering environmental and economic aspects on the decision-making process.

We define criteria for a first selection of ESA tools. The criteria are related to the usefulness of a tool in an analysis that: 1) takes a company perspective; 2) includes environmental and economic aspects of decision making; 3) includes a complete coverage of the potential environmental impacts and 4) allows for an assessment of the consequences of pollution reduction strategies. Based on the purpose of our DST together with the criteria we identified twelve tools. These twelve tools are reviewed with respect to their purpose, methodology, final product, strengths, weaknesses and relevance for an environmental analysis taking a company perspective.

Next, we present the characteristics of the DST to be developed. These characteristics allow for identifying the ESA tools that are a promising basis for the DST to be developed. These seven characteristics are: (i) the tool considers a gate-to-gate approach; (ii) the tool considers the processes within the company that are relevant for the assessment of the environmental impact; (iii) the tool uses company specific data easily available from the process owner; (iv) the tool considers up-to-date and company specific pollution reduction options; (v) the tool provides information on the cost-effectiveness of the reduction options; (vi) the tool can be used to express the company's environmental performance in one overall environmental indicator; and lastly (vii) the tool can be used to explore possible user-defined pollution reduction strategies.

Finally, a selection of the tools that are useful for our particular DST is made. We conclude that a combination of the following seven tools is most promising: Life Cycle Analysis, Substance Flow Analysis, Multi-Criteria Analysis, Technology Assessment, Sensitivity Analysis, Scenario Analysis and Cost-Effectiveness Analysis.

2.1. Introduction

In this chapter, different environmental systems analysis (ESA) tools assessing the environmental performance of a company will be reviewed. The tools will be discussed with respect to their usefulness, alone or in combination, in decision support tools for companies that want to analyse options to reduce their environmental impact.

We aim to answer the first research question of this thesis: "What existing environmental systems analysis methods and tools can in principle be combined in a decision support tool (DST) and used to analyse the environmental performance of a plant from a company perspective?".

In the following, we will first review ESA tools currently used by industry (section 2.2). Next, the characteristics of the DST to be developed will be described (section 2.3). And finally, we will select the tools to be combined in our DST (section 2.4).

2.2. Overview of Environmental Systems Analysis Tools currently used by industry

Several ESA tools exist that have been used by industry. For the purpose of the thesis in this overview, a selection of environmental systems analysis tools is discussed (selected from SETAC, 1997; Wrisberg et al., 2002, Sonnemann et al., 2004; Finnveden and Moberg, 2005; Moberg, 2006).

The tools included are considered useful in an integrated analysis of possibilities to improve the environmental performance of an industrial company, while considering several environmental pollutants, and while taking a company's perspective. The main criteria for the choices of tools are their usefulness in an analysis 1) that takes a company perspective; 2) that includes environmental and economic aspects of decision making; 3) that includes a complete coverage of the potential environmental impacts and 4) that allows for determination of the consequences of a set of alternative strategies for pollution reduction.

Based on these criteria, we selected twelve ESA tools. These include Environmental Management Systems, Life Cycle Assessment, Environmental Performance Evaluation, Substance Flow Analysis, Multi-Criteria Analysis, Technology Assessment, Sensitivity Analysis, Uncertainty Analysis, Total Cost Assessment, Cost Benefit Analysis, Cost-Effectiveness Analysis and Scenario Analysis. In the following, these tools[1] are discussed. A short description is presented together with a brief reference to the tools' characteristics and the extent to which they have been applied in industry.

- An Environmental Management System (EMS) specifies how an organisation can formulate an environmental policy and objectives taking legislative requirements and information about significant environmental aspects into account (UNEP/SETAC,

[1] Wrisberg et al. (2002) and Sonnemann (2004) distinguish between analytical tools, procedural tools and technical elements. Here, however, we refer to all these analytical instruments as ESA tools.

2005). This tool has been widely implemented and has a strong policy perspective, assuring that the organisation not only meets present day environmental legal and policy requirements but will continue to do so (ISO, 2004). Using EMS, industrial companies aim at keeping the environmental burden of their processes within the limits set by environmental legislation or to minimise the impacts of their processes (Neto et al., 2003; ISO, 2005).

- Life Cycle Assessment (LCA) is a tool aiming at specifying the environmental consequences of products or services over their entire lifetime (ISO, 1997; Guinée, 2002; Rebitzer et al., 2004). LCA is a tool for comparative assessments, either between different products providing similar functions or between different life cycle stages of a product in an improvement analysis (Björklund, 2000). LCA has been applied to products and functions in various sectors, predominantly in the primary and secondary sectors of industry (e.g. Berkhout and Howes, 1997; Scholl and Nisius, 1998; Frankl and Rubik, 1999; Jiménez-González et al., 2000; Lee and Ding, 2000; Zobel et al., 2002; Curran, 2004; Siegenthaler and Margni, 2005; Rebitzer and Buxmann, 2005; Tan and Khoo, 2005; Rebitzer, 2005).

- Environmental Performance Evaluation (EPE) uses indicators to transform the vast quantity of information about a firm in a comprehensive and concise manner by using indicators (Olsthoorn et al., 2001; Kolk and Mauser, 2002; Barbirolli and Raggi, 2003). At a firm level the indicators of the environmental performance are mostly used to relate absolute material and energy flows to process variables providing information about an organisation's environmental performance (ISO, 1999; Jasch, 2000). Because many firms have developed their own performance indicators, several initiatives to bring consensus on indicators have been taken (WRI, 1997; NRTEE, 1999; WBCSD, 1999; GRI, 2000). Moreover, initiatives proposing the harmonisation of environmental performance indicators are taking place (Berkhout, et al., 2001).

- Substance Flow Analysis (SFA) can be used to quantify the in- and outflows, as well as a balance of one particular substance trough the material economy (SETAC, 1997). It can highlight opportunities for environmental improvement related to the substance by identifying major inflow and outflow nodes in the system (SETAC, 1997). Substance Flow Analysis (SFA) focuses on specific substances, either within a region or through its entire life cycle. Typical examples include studies of nitrogen flows or flows of a specific metal (Kytzia and Nathani, 2004; Finnveden and Moberg, 2005).

- Multi-Criteria Analysis (MCA) is a tool to support decision making based on multiple criteria. MCA may assist in identifying trade-offs between different criteria and finding the best solutions (Wrisberg et al., 2002). The tool is developed for complex problems that include qualitative and/or quantitative aspects of the problem in the decision-making process (CIFOR, 1999). This tool can be used to evaluate the relative importance of all criteria involved and reflect their importance in the final decision making process (CIFOR, 1999). MCA has been applied to studies in which aggregation of environmental data is needed. Examples can be found in Pineda-Henson et al. (2002), Pun et al. (2003), Rahimi and Weidner (2004), Cziner et al. (2005), Hermann et al. (2006).

- The purpose of Technology Assessment (TA) is to evaluate the impact of a new technology before it is implemented at a large scale. Recently the term environmental technology assessment came into use (Björklund, 2004.). TA is a tool that assesses the impact of technology, to choose from technologies, to contribute to improved technology, to identify protective measures and to show if a technology complies with laws and regulations (UN Agenda 21, 1992; Björklund, 2004). Some examples where TA can be used are, for instance, to analyse the use of end-of-pipe techniques, the substitution of unfriendly products or trough the use of technology innovation to reduce the environmental burden of industrial production (Moors et al., 2005; Assefa et al., 2005).

- Sensitivity Analysis (SA) is a systematic inventory of the changes in model results as a consequence of changing the values of the parameters or the input variables used in a model. Another definition (ISO, 1997) is that it is a systematic procedure for estimating the effects of the choices made regarding methods and data on the outcome of a study. This tool can be used to analyse the sensitivity of the model results to values of model parameters and is used in model building and in presenting results from model studies (e.g. Sonesson et al., 2000; Pluimers, 2001).

- Uncertainty Analysis (UA) is conducted to assess the uncertainties in the results of a study. This may be done by comparing the importance of uncertain input parameters with respect to their contributions to output uncertainty. Morgan and Henrion (1990) considered elements of effective uncertainty analysis and communication of these uncertainties is essential for quantitative policy analysis (see Morgan and Henrion for a discussion of the effectiveness of uncertainty analysis). Examples of uncertainty analysis range from estimating uncertainties in emission inventories (e.g. Van Aardenne, 2002; Frey and Zao, 2004) to the estimation of uncertainties in industrial databases (e.g. Sugiyama et al., 2005) or in model results (e.g. Pluimers, 2001; Norris and Yost, 2002; Neuman, 2003; Walker et al., 2003) and in life cycle assessments (e.g. Kaplan et al., 2005; Geisler et al., 2005). Many methods to assess uncertainties exist, ranging from qualitative assessments of uncertainties to quantitative statistical approaches.

- Total Cost Assessment (TCA) describes the analysis of the full range of internal costs and savings resulting from pollution prevention projects and other environmental project undertaken by a firm (Wrisberg et al., 2002; UNEP/SETAC, 2005). The tool seeks to integrate environmental costs into a capital budgeting analysis (Beaver, 2000). Examples of studies related with developments and industrial applications of TCA are overviewed in Backman and Thun (1999).

- Cost Benefit Analysis (CBA) is an economic tool used to determine whether or not the benefits of an investment or a policy outweigh its costs (Wrisberg et al., 2002). It aims at expressing all positive and negative effects of an activity in monetary units. These effects may include economic and environmental aspects (RPA, 1998).

- Cost-Effectiveness Analysis (CEA) is a variant of cost benefit analysis (CBA) (Wrisberg et al., 2002) and can be used to estimate the costs per unit of avoided emission (Rabah, 1999; Pluimers 2001; Klimont et al., 2002). Cost-effectiveness analysis is a techno-economical tool that considers only the internals costs, i.e., the cost resulting from emission reduction technologies (Sonnemann et al., 2004). These costs are compared to the reduction of the environmental pressure as a consequence of the economic investment. Cost-effectiveness is considered to be a useful criterion for ranking alternatives (Schwarz, 1997).

- Scenario Analysis (ScenA) is a tool to explore future trends. In many studies, it results in a set of answers to "What… if" type for questions illustrating the future consequences of a range of alternative decisions (Schwarz, 1997; Pesonen et al., 2000; Pallottino et al., 2005). Scenarios do not necessarily portrait what the future will look like but instead aim to stimulate ways of thinking about alternative futures. Scenario analysis is a useful tool when complexity and uncertainty are high (Wollenberg et al., 2000). Many examples of the use of scenarios analysis are available in the literature (e.g. Pluimers, 2001; Fukushima and Hirao, 2002).

Each tool has its specific characteristics which are reviewed in Table 2.1. Obviously, the tools differ with respect to their purpose, methodology, final product, strengths, weaknesses and relevance for an analysis taking a company perspective. In the following, the tools are discussed with respect to each of these characteristics.

In Table 2.1. the tools are first compared with respect to their purpose. The comparison shows that they all provide industry with information that is helpful for environmental decision making. Nevertheless, the tools serve different purposes. Some tools are primarily used to assess the environmental impact of human activities (e.g. EMS, LCA, EPE, SFA), while others are more focusing on the evaluation or consequences of environmental management (e.g. TA, CBA). Three tools specifically address economic consequences of decisions made (TCA, CBA, CEA).

Second, the tools are compared with respect to the methodology applied. For some tools specific procedures exist (EMS, LCA, EPE, MCA and SA). For some others, the method is not as clearly defined and may depend on the objective of the study at hand (SFA, TA, UA, TCA, CBA, CEA and ScenA). Some tools are often used in combination (e.g. the use of EPE within EMS, the use of MCA based on results from LCA, the use of SA as a complementary step to LCA or the use of CEA after LCA). This illustrates that individual tools in itself are often not sufficient for dealing with complex issues.

Third, the tools differ with respect to their products. The results are in most cases quantitative. They range from the changes in the environmental performance to the costs per unit environmental performance improved. For instance, LCA results are typically in terms of the potential environmental impact for certain environmental impact categories. EPE results include a number of indicators, which in contrast to LCA, allow for identifying trends in environmental performance. Finally MCA can be used to express the environmental performance in one overall indicator.

Fourth, all tools have their specific strengths. This may help in selecting the most appropriate tool for a specific study. For instance, EMS, LCA, EPE and SFA are comparable in the sense that they all aim to quantify the environmental performance. However, EMS is probably the most widely accepted by industrial companies, LCA is the most powerful tool to assess the complete lifetime of a product, EPE may be the most interesting to use in comparative analyses of complex systems, and SFA is the most comprehensive tool to assess specific compounds. Likewise, the three tools assessing costs (CBA, CEA and TCA) have their specific strengths: TCA and CBA provide the most complete cost assessment, but TCA with the lowest uncertainties.

Fifth, some weaknesses of the tools are identified. These include the absence of a well structured method (e.g. EMS, TA) or the availability of a large number of methods (e.g. SA, UA, TCA), making the choice of tools to be used difficult. Other weaknesses include the complexity of analytical method (LCA) or the resources required (CBA), the difficulty of comparison between different organisations (EPE), the focus on only one or few substances (SFA), the subjective elements in the analytical approach (MCA, CBA). An important weakness of CEA is the fact that the benefits are only included in physical terms, while a weakness of ScenA is that it may overlook the most optimal scenario.

Finally, the relevance for the analysis taking a company perspective is identified. Table 2.1 clearly shows that the twelve tools discussed are all highly relevant for analyses of the environmental performance of a company, as well as for assessments of environmental management decisions. Pollution reduction options may be evaluated in terms of their effectiveness and with respect to the costs. Future trends can be analysed, and the uncertainties in the results assessed. Moreover, some tools may gain insight in the quality of the model. We can also conclude that none of the tools is in itself sufficient to perform a comprehensive and complete assessment of the type we envisage here. In the following section, therefore, the characteristics of our decision support tool are described. This is then used as a basis for a further selection of tools to be used for our DST.

Table 2.1. Comparison of ESA tools currently used by industry with respect to their purpose, methodology, product of the tool, strengths, weaknesses and relevance from a company perspective.

	Purpose of the tools	Methodology	Product of the tool	Strengths	Weaknesses	Relevance from a company perspective
EMS	To ensure effective implementation of environmental management	Environmental policy, planning, implementation and operation, checking and corrective action, and management review	Quantification of environmental performance of an organisation	Widely applied by organizations. No detailed LCA required	No single method available; organisation-specific and therefore determined by each organisation	Worldwide recognition by organisations. In some cases used to meet environmental standards
LCA	To assess the environmental impact throughout a product life cycle	Goal & scope definition, inventory analysis, impact assessment and interpretation	Set of environmental indicators making possible to identify problematic parts of life cycle	Avoids problem shifting; comprehensive through 'cradle-to grave" approach	The complexity, the extensive data and time requirements, not practical	The environmental scores for a number of impact categories. However, the full life cycle may not be relevant from a company perspective
EPE	To assess an organisation's environmental performance	Data collection, analyse and convert data, report and communication.	Set of environmental indicators expressing the performance of an organisation; can be used for benchmarking.	Understandable and useful indicators that allow to identify opportunities for improved management	Based on available data and therefore often incomplete; comparison within an organisation may be difficult	Environmental scores for many performance indicators; currently used by many companies
SFA	To account inflows and outflows of substances through the environment, the economy or a company	Mass balance allowing to spot hidden or unexpected flows and emissions	Quantification of mass flows and balance of particular substance	Assessment of specific compounds along the life cycle; links industrial metabolism to specific environmental issues	Focus on one substance could give misleading results. Ignorance of side-effects on other substance chains	Identification of opportunities for environmental improvement related to specific substances
MCA	To evaluate consequences of alternative decisions for multiple criteria	Establishing the decision context, identifying options, identifying criteria, scoring, weighting deriving an overall value for each option	One single environmental indicator (score)	Easily combined with other tools. Possibility to combine results with different dimensions into one indicator	The subjectivity of the valuation step	One environmental indicator reflecting the overall environmental performance of a company
TA	To assess technical, economical, political, legal, and/or environmental impact of industrial products, processes, or technologies	Depends on the objective of the research (ex: risk assessment of chemicals -for human health; quantified risk assessment of industrial plants-on the health and welfare of people)	Quantification of consequences of new or modified technologies	Covers a broad spectrum impacts	No standard methodology available	Evaluation of individual technologies with respect to their (environmental) performance and compliance with regulations

References: **EMS**: Finkbeiner et al. (1998); EMAS (2001); ISO (2004); Sonnemann et al. (2004). **LCA**: ISO (1997); Wrisberg et al. (2002). **EPE**: ISO (1999). **SFA**: SETAC (1997); Van der Voet et al. (1999); Bouman et al.(2000); Wrisberg et al. (2002); UNEP/SETAC (2005). **MCA**: Wrisberg et al. (2002); Zopounidis and Doumpos (2002). **TA**: CEFIC (1992); Björklund (2004); Assefa et al.(2005); Moors et al. (2005).

Table 2.1. (cont.). Comparison of ESA tools currently used by industry with respect to their purpose, methodology, product of the tool, strengths, weaknesses and relevance from a company perspective.

	Purpose of the tools	**Methodology**	**Product of the tool**	**Strengths**	**Weaknesses**	**Relevance from a company perspective**
SA	To analyse the sensitivity of model results to changes in model parameters or assumptions	Systematic procedure for quantifying the effects of changes in methods and data on the results of the study	Overview of model components that are relatively influential; this may help in prioritising model improvements	Provides insight in the model behaviour and may increase model credibility, in particular when combined with uncertainty analysis	A complete sensitivity analysis is time consuming. SA does not allow for conclusions on the quality of the model.	Provides the company with insight in model sensitivity, and identifies influential parameters
UA	To identify and assess uncertainties	There are many methods available to study the effect of parameter uncertainty in models (ex: a method based on error propagation; Monte Carlo analysis)	Overview of parts of the study that are relatively uncertain; this may help in prioritising future experimental studies	Assessment of uncertainties in results and limitation of the model; may be used as an indicator for the quality of the model	Diversity of existing methods and the complexity of the analysis	Allows the model builder and user company to decide on further study to improve the model quality
TCA	To analyse all internal costs of investments for a company	Various approaches to use a comprehensive cost inventory of all internal costs of a company (ex: may consider the environmental or more general investments)	Estimation of costs per process or product	Consideration of all costs, and therefore more complete than conventional cost	Complex data collection, including indirect, less tangible, probabilistic or future cost. Does not consider eco-efficiency	Comprehensive assessment of full range internal costs and savings resulting from pollution prevention
CBA	To analyse all costs and benefits of an activity in monetary units	Assessment of net (economic) benefits of a project or activity	Quantification of costs and benefits of a project or activity	Useful for comparing activities	Large uncertainties in the monetary valuation of benefits; methodologies heavily disputed	Determines whether or not the benefits of an activity outweigh its costs.
CEA	To analyse the cost-effectiveness of an activity	Estimation of costs of an activity (fixed and variable) per unit of avoided environmental impact	Set of performance indicators providing a cost per unit of environmental improvement	Useful for comparative assessments; low uncertainties	Benefits are accounted for in physical terms (not in monetary terms)	Quantitative performance indicators assessing the cost of pollution control per unit of environmental improvement.
ScenA	To explore future trends	Describing storylines, followed by a quantitative interpretation of these futures	Answers to "What if" type of questions illustrating the consequences of a range of alternative decisions	Useful for exploring different futures of high complexity and uncertainty	No identification of the most effective scenario	Provides insight in possible future trends, given different management strategies that the company may take

References: **SA**: Quade (1997); Björklund (2000); Pluimers (2001); French and Geldermann (2005). **UA**: Morgan and Henrion (1990); Van Aardenne (2002); Cacuci (2003); Walker (2003); Kaplan et al. (2005). **TCA**: Backman and Thun (1999); Wrisberg et al. (2002); UNEP/SETAC (2005). **CBA**: RPA (1998); Wrisberg et al. (2002); UNEP/SETAC (2005). **CEA**: RPA (1998); Wrisberg et al. (2002); UNEP/SETAC (2005). **ScenA**: Schwarz (1997); Pluimers (2001), EEA (2001); Wollenberg et al. (2000).

Other ESA tools

In the above, twelve ESA tools are discussed. However, other tools exist that are not extensively discussed here, because they do not seem first choice options considering our four criteria. In the following, we discuss why we excluded some well-know tools from our overview.

Some tools are excluded because they do not focus on existing industrial activities, but on large new projects. These include, for instance, Environmental Impact Assessment (EIA, which is used to analyse the environmental aspects of future projects) and Strategic Environmental Assessment (SEA, which is used in an earlier stage then EIA, and aims to integrate sustainability into planning and assessment process).

Total Material Requirement (TMR) is also not considered here, because it is most often used in regional studies. Also the Ecological Footprint (EF) is not considered. EF is typically used for communication and learning the effects of different processes or life styles providing a tangible overview of our performance with regard to sustainability, and is unique in its capacity to communicate how life style and technical competence related to such perspective (Robèrt et al., 2002). One may argue that TMR and EF may include useful elements for studies at the company level. Nevertheless, here other tools are given priority.

Our third criterion for including tools in this overview is that the tools need to be useful in an integrated environmental analysis, considering several environmental pollutants and problems. This implies that, although some of the tools may be useful for the industry, they are not considered here because the environmental impacts are strictly related to the depletion of natural resources. This is, for instance, the case in Material Intensity Per unit Service (MIPS), which may be used in the product design and aims at dematerialisation by focusing on overuse and depletion of natural resources. It also holds for Exergy Analysis (EA), which considers the inefficient use of natural resources and is used for optimisation of energy processes. Moreover, tools are excluded from this overview if they only focus on site-specific impacts of, for instance, toxic substances. This is the case for Environmental Risk Assessment (ERA), which is a tool to determine the probability of negative effects on human health or the environment as a result of exposure to one or more physical, chemical or biological agents (Wrisberg et al., 2002; Sonnemann et al., 2004).

Combining tools

In many existing studies ESA tools are used individually. However, in environmental analyses of complex systems it is better to use a combination of tools to analyse a particular problem for which a decision is needed (Wrisberg et al., 2002; Finnveden and Moberg, 2005). The combinations of tools vary largely, as shown by Hermann et al. (2006). As an example we refer to the use of Environment Management Systems (EMS) and LCA (Finkbeiner et al., 1998; Zobel et al., 2002). Finkbeiner et al. (1998) argue that the traditional use of LCA does not help in achieving the environmental goals at the company level if the focus is on single products trough an extended life cycle analysis. These authors conclude that combining these tools (EMS and LCA) might direct efforts to an improved environmental performance and economic efficiency. Zobel et al. (2002) develop a method for the identification and assessment of environmental aspects in an EMS context by using an LCA methodology. The approach taken differs from the classical use of LCA. The authors focus on a limited analysis of the production chain by applying a gate-to-gate inventory and assess the environmental impact by aggregating in one single value all the pollutants (or natural resources) that contribute to a specific environmental problem.

Combinations of tools are in itself not enough to help the company managers in deciding on environmental management. There is a lack of tools that assess both environmental and economic impacts from organisations and companies in a comprehensive way (Finnveden and Moberg, 2005). We see a need for combining a larger set of environmental system analysis tools than what is usually done in existing studies (e.g. Backman and Thun, 1999; Zobel et al., 2002; Hermann et al., 2006).

The following sections will describe our Decision Support Tool (DST) in general terms. First, we describe the tool characteristics. Next, we select the most useful for our DST out of our list of twelve tools.

2.3. Characteristics of the Decision Support Tool

The Decision Support Tool (DST) to be developed in this thesis takes a company perspective and it is developed as a tool serving the company management in the analyses of possible strategies to improve the environmental performance. The DST will be used to analyse options to reduce the environmental impact of an industrial company. The DST is model based and the model allows for the assessment of the potential environmental impact resulting from emissions of environmental pollutants, as well as the effectiveness of reduction options and the associated costs. In addition, the methodology developed is based on the combined use of important parts of analytical tools used in environmental systems analysis. The DST will be developed for a specific plant, located in Portugal, from the aluminium pressure die casting industrial sector. However, the tools selected may be useful for any DST with similar characteristics.

This study considers the industrial production system as first of all in the decision domain of business. Consequently, the DST is developed to be of primarily interest for business. The main characteristics of such a DST are:

i. The tool considers a gate-to-gate approach and excludes sources of environmental problems that can not be controlled by internal management decisions. The company perspective is thus reflected by the system boundaries in process, time and space.

ii. The tool considers the processes within the company that are relevant for the assessment of the environmental impact. The processes within the plant are analysed in terms of their contribution to the emission of pollutants or the use of natural resources. These processes do not only include the industrial production line but also include the internal transports taking place within the plant, the wastewater treatment, etc.

iii. The tool uses, as much as possible, plant specific data easily available from the process owner.

iv. The pollution reduction options considered in the tool are up-to-date techniques, plant specific and only those that can be managed by the company.

v. The tool provides information on the cost-effectiveness of the pollution reduction options.

vi. The tool can be used to express the plant's environmental performance in one indicator which is based on several partial indicators. This indicator, which measures the overall environmental performance, is a weighted sum of indicators for all relevant environmental problems to which the company contributes. The company can use the indicator in its decision making process.

vii. The tool can be used to explore possible user-defined pollution reduction strategies.

The seven characteristics are related to the criteria set for our DST (see section 2.2.). All the characteristics (characteristics *i* to *vii)* support criterion 1 (on taking the company perspective). Moreover, characteristic *v* supports criterion 2 (on including environmental and economic aspects of decision making) by including environmental and economic aspects of decision-making. In addition, characteristics *ii* and *vi* ensure complete coverage of the potential environmental impact as formulated in criterion 3 (on being complete by covering the potential environmental impact). Finally, characteristic *vii* supports criterion 4 (on allowing for determination of the consequences of a set of alternative strategies on pollution reduction). The tool results may be generally expressed in terms of the overall environmental impact reduction and the net additional costs and cost-effectiveness, resulting from the assumed implemented alternative reduction strategies (scenarios) generated by "what if …" type of questions on the combinations of reduction options.

2.4. Selection of ESA tools useful for a DST taking a company perspective

In section 2.2., we selected potential promising tools that may be useful in developing our DST (see Table 2.1.). The twelve tools include Environmental Management Systems (EMS), Life Cycle Analysis (LCA), Environmental Performance Evaluation (EPE), Substance Flow Analysis (SFA), Multi-Criteria Analysis (MCA), Technology Assessment (TA), Sensitivity Analysis (SA), Uncertainty Analysis (UA), Total Cost Assessment (TCA), Scenario Analysis (ScenA) and Cost-Effectiveness Analysis (CEA) Cost Benefit Analysis (CBA). However, we may not need all these tools.

In section 2.3., we described the characteristics of our DST. In the following, we confront the DST characteristics with the twelve tools listed in Table 2.1. to determine which tools can be combined to form our DST.

The first four characteristics (*i* to *iv*) mainly reveal the company perspective that the DST will take. Analysis of the full industrial production chain (gate-to-gate) and analysis of the flows of materials can be done by combining relevant parts of LCA and SFA. LCA may provide the impact assessment methodology. SFA allows for following the flows of materials through the industrial production process.

In addition, the fourth characteristic (*iv*) refers to the analysis of technological options aiming to reduce the environmental impact of the industrial process. Such analysis may be based on Technology Assessment. TA may be a useful way to analyse pollution reduction options in terms of their potential to reduce the environmental impacts, i.e., by assessing the consequences of a new technology or a modification of an existing technology.

Characteristic *v* points to the need to calculate the costs associated with the implementation of pollution reduction options. CEA is obviously the first choice to calculate the cost-effectiveness of pollution reduction options. This tool allows for ranking of pollution reduction options by calculating the costs per unit of environmental impact reduced. This implies that our DST will not provide total costs or benefits in monetary units.

It is important that the user of the model has confidence in the results. The reliability of a model depends on the quality of the model parameters and model structure. A typical way to assess the sensitivity of model results to changes in model parameters is to perform a sensitivity analysis. Thus, SA is a tool that will assist the model development and application. Characteristics *vi* and *vii* express the overall environmental impact in terms of one single indicator and the intention to define pollution reduction strategies to reduce the overall environmental impact. MCA, as a tool, allows for assessing the overall environmental impact in one overall indicator. This tool, however, may use several methods that take into account multiple criteria and their relative weights.

Characteristic *vii* implies analysis of pollution reduction strategies reflecting different management strategies, which can be done by scenario analysis (ScenA). The consequences of a range of alternative combinations of pollution reduction options may thus be analysed.

The abovementioned seven tools (LCA, SFA, TA, CEA, SA, MCA and ScenA) will be used as a basis for our DST. This set of tools excludes EMS, EPE, TCA, CBA and UA. Although of significant importance when assessing the environmental performance and total costs of an industrial process, these tools are not the first choice options for our DST for the following reasons. EMS lacks the structured methodology aimed for in our approach. Our aim is to develop a reproducible DST. EPE is currently used on the industrial practice to assess the environmental performance but is not our first choice. EPE typically results in indicators allowing for identifying trends in the performance by considering a retrospective analysis, based on measured data made available by the industry. Our approach is different from that. We aim to outline and assess possible future developments regarding strategies on pollution reduction. TCA is not selected because our aim was not to perform a full economic analysis but to limit ourselves to an analysis of the cost-effectiveness of pollution reduction options and the costs associated with the pollution reduction strategies. Moreover, TCA is time consuming and requires a cost inventory of all internal costs of a company regardless of the relevance of the costs for the analysis. Cost Benefit Analysis, which is also an economic tool used to express all positive and negative effects of an activity in monetary units, is not a first choice for our analysis. Even though CBA has been applied at the company level, the monetarisation of the benefits of environmental management is often too uncertain to make this tool useful for studies taking a company's perspective. Finally, we will not perform a full quantitative UA. Instead, we will compare our model results to company data, and we will perform a sensitivity analysis. This may be sufficient for ensuring confidence in the quality of our model.

As discussed earlier, in the literature several examples can be found of combinations of ESA tools (e.g. Schmidt et al., 1996; Finkbeiner et al., 1998; Tukker et al., 1998; Marano and Rogers, 1999; Backman and Thun, 1999; Wrisberg et al., 2002; Beaver, 2002; Moberg, 2006; Hermann et al., 2006). None of these studies, however, combine the seven tools selected here to develop a DST taking a company perspective. In the following chapters, we aim to providing companies with an instrument to assess the potential environmental impact of industrial processes and to analyse options to reduce this environmental impact and the associated costs.

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Chapter 3: Inventory of Pollution Reduction Options for an Aluminium Pressure Die Casting Plant

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Abstract

This study presents a general overview of options aiming to reduce emissions to air, soil and water from an aluminium die casting plant located in Portugal. We first identify pollution reduction options and then estimate their potential to reduce the pollution and the costs associated with the implementation of these options. We identify eighteen technical reduction options that are applicable to aluminium pressure die casting companies. The options include typical end-of-pipe solutions as well as alternative techniques or still modifications in process operations from the die casting plant. We distinguish between different types of options, including, for instance, fabric filters and scrubbers; alternative desoxidation agents; modifications of the combustion process; alternative mould release application techniques; new die casting moulds and alternative equipment. Finally, we calculate the implementation costs for the company of each reduction option. The calculated net additional costs include fixed and variable costs.

We conclude that there are promising opportunities to reduce the pollution from aluminium pressure die casting. Our inventory includes options with net negative costs, indicating that the company may in fact gain from implementing these options. Even though our study specifically focuses on one particular plant, the results may be interesting for the aluminium pressure die casting sector industry in general.

3.1. Introduction

Aluminium pressure die casting is a manufacturing process supplying automotive industry with engineered car components (Brown, 1999). During the industrial process the aluminium alloy is molten, shaped on die casting moulds and submitted to different types of surface finishing processes in order to accomplish the client's requirements (NADCA, 1991; USEPA, 1999; US Department of Energy, 1999; US Department of Energy, 2004). The industrial sector represented by the European Foundry Association produced about 1100 thousands tons of aluminium die castings products (APF, 2003). This production value has a share of about 33% of the European production for the non-ferrous metals alloys (CAEF, 2003). The material inputs entering the production process are aluminium ingots and/or aluminium alloy mass recycled within the plant. The production process requires several other inputs such as energy and subsidiary materials.

The aluminium pressure die casting industry contributes to a number of environmental problems caused by emissions released to air, soil and water (Kim et al., 2003). For instance, the industry is a source of metal emissions to the environment that may be toxic to humans and other organisms. Moreover, the industry emits air pollutants, such as nitrogen oxides and carbon dioxide, which cause tropospheric ozone formation, acidification, human toxicity and global warming. And finally, there are waste-related problems, potentially leading to soil pollution. This is the case for the aluminium dross produced in melting or the ceramic lining waste from the furnaces.

Existing studies of the aluminium pressure die casting industry focus on environmental management for the industrial sector in general and aim to provide the aluminium die casting sector with information on how to realise a more environmentally sound die casting process (e.g. Kim et al., 2003; EIPPCB, 2005; Dalquist and Gutowski, 2004) or on determining its environmental performance (e.g. Backhouse et al., 2004). Some other studies regarding the metals industry also aim to assist the industrial sector to comply with environmental regulations (Moors et al., 2005) or to analyse proposed policy instruments (Moors, 2006). Most of these studies have been performed at the level of the industrial sector, or in other words, the intended user of the study results is meant to be the die casting industry sector. Relatively few studies exist that are specific for the company level (e.g. Park et al., 2002). To our knowledge, a complete and comprehensive overview of pollution reduction options for aluminium pressure die casting plants does not exist.

In this study we therefore aim at answering the following questions.

- Which technical pollution reduction options are available for reducing the environmental impact of an aluminium pressure die casting plant?
- What are their technical potentials and the associated costs for the plant?

To answer these questions we identify emission reduction options for an aluminium die casting plant, based on an inventory of materials and energy used in the industrial process and the associated emissions of pollutants and production of waste. The identification of options available for reducing the environmental pressure is largely based on the literature and discussions with the industrial plant managers. The technical potentials to reduce the pollution and costs are either from the literature or estimated, based on the options' characteristics. The plant serving as case study provided feedback, as well as data on materials and energy consumption, and technical details about the production process.

In the following, we will first review the aluminium pressure die casting process, using information from the studied plant, including the input materials, energy and the environmental problems (section 3.2). Next, the pollution reduction options are identified and the characteristics of each option are described in terms of potential to pollution reduction and costs (section 3.3). Finally, section 3.4 presents conclusions of this study.

3.2. Aluminium Pressure Die Casting

3.2.1. The industrial process and system definition

Pressure die casting is a manufacturing process that produces accurately dimensioned, sharply defined and smooth- or textured –surfaced metal car components (Kim et al., 2003). This manufacturing process includes a number of subsequent production processes and uses a variety of materials and energy resources. The most important operations are the melting of aluminium alloy, shaping it into a semi-product (casting), several operating processes for surface finishing, and finally the product cleaning and degreasing and its expedition. The technologies used for the die casting process do not differ among European countries, or between Europe and the USA (Tan and Khoo, 2005).

In this study an existing aluminium pressure die casting plant is taken as an example. This plant is located in northern Portugal and provided information about its production processes and the input and output flows of materials and energy.

Since our study takes a company perspective, a gate-to-gate analysis is performed, i.e., this study only considers material flows within the gates of the plant. We assume that this reflects the span of control of the plant managers, and their primary interest in assessments of the environmental aspects of the plant. The company perspective is reflected by the choices made with respect to systems boundaries and systems elements (Figure 3.1). Within the system boundaries a number of processes are considered. These include processes that are contributing to pollution or waste streams and only processes that can be managed by the plant managers. We distinguish between five sub-processes within the aluminium die casting production plant: 1) Melting, 2) Casting, 3) Finishing, 4) Internal transports and 5) Auxiliary burners (see Figure 3.1).

The system boundaries are chosen such that they include all relevant processes that can be managed by the plant managers. We consider the following outputs of the system: die casting products, emissions of pollutants, liquid effluents and the production of waste. Thus the environmental pressures taken into account include, beside emissions of air pollutants, liquid effluents and waste. Liquid effluents are a mixture of water and oils (from the sub-sub-processes Pressure Die Casting and Tumbling) or of water and detergents (from Cleaning and Degreasing). These effluents are treated in the plant's wastewater treatment sites. The solid waste includes aluminium dross (from Melting), ceramic lining (lining from holding furnaces), steel shot (from Shot Blasting) and ceramic abrasives (from

Tumbling). In addition, wastewater treatment plants discharge sludge, oils and grease. These flows are plant and process-specific and are quantified here as a function of the plant inputs. These inputs include not only aluminium ingots and/or aluminium alloy mass recycled within the plant, but also auxiliary materials, water, natural gas or other fuels and materials used at the wastewater treatment sites (as shown in Figure 3.1). This selection excludes emissions of pollutants indirectly caused by the plant and taking place outside the gate of the plant. We also do not account for operations during emergency or maintenance situations. Even though these may contribute to the potential environmental impact of the plant, we consider them negligible when compared to the other processes taken into account in our analysis.

One of the implications of our choice for system boundaries and elements is that emissions from power plants producing electricity for the die casting plant are not accounted for. We realize that this could be a matter of discussion, since electricity accounts for about two-thirds of the total energy use by the plant. It therefore contributes substantially to the overall environmental impact of this industry. Our reasoning, however, is that the production of electricity takes place *outside* the gates of the plant. Even though the electricity market is more open now than it was before, we consider electricity production outside the span of control of the plant managers. Another, less important, reason for leaving it out of the current analysis is lack of data. The electricity in the plant is used for lighting, in holding furnaces and machinery (including the supply of compressed air), however, detailed data on electricity use at the sub-sub-processes is not available from the plant and also uncertainties in estimates of emissions associated with electricity production are relatively large.

The sub-processes indicated in Figure 3.1 have been used to assess potential environmental problems. For the analysis of potential reduction options it is necessary to identify processes at an even more detailed level. We refer to this as the level of sub-sub-processes. Furthermore, the plant uses wastewater treatment sites. These are typically implemented at the sub-sub-process level. In the plant, the existing wastewater treatment sites treat the liquid effluents produced during, Casting (sub-sub-process: Pressure Die Casting) and Finishing (from Tumbling and Cleaning and Degreasing) (not shown in Figure 3.1.).

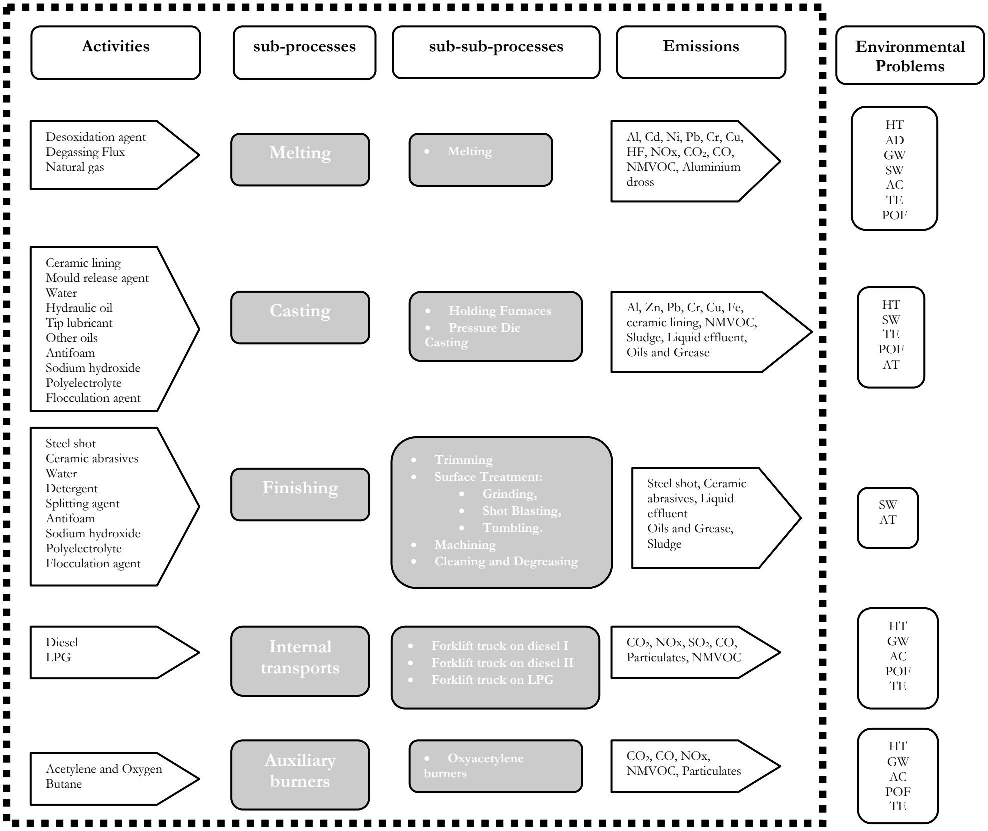

Figure 3.1. Overview of an aluminium die casting plant including activities (inputs of energy and subsidiary materials) into the (sub-)sub-processes, emissions of pollutants and the associated environmental problems. The dotted line indicates the system boundary (gate-to-gate). HT= Human Toxicity; AD= Abiotic Depletion; GW = Global Warming; SW = Solid Waste production; AC = Acidification; TE = Terrestrial Ecotoxicity ; POF = Photochemical Ozone Formation; AT = Aquatic Toxicity.

3.2.2. Environmental aspects

The environmental problems caused by the aluminium pressure die casting industry are various and are related with emissions released to air, soil and water. Air pollution is caused by emissions of metals from aluminium alloy, compounds released during fuel combustion, hydrogen fluoride (HF) emissions from the use of fluxing agents to remove impurities from molten alloy, and volatile organic compounds (VOCs) from the use of lubricants. Solid waste includes aluminium dross and ceramic lining from furnaces. Other types of solid waste are ceramic abrasives and steel shot from operations taking place during the metals surface finishing. Water pollution is caused by losses of emulsion used to lubricate the die casting moulds. These emissions, wastes and effluents cause toxicity problems (for people, as well as terrestrial and aquatic ecosystems), natural resource depletion, global warming, acidification, tropospheric ozone formation, as well as problems associated with solid waste production.

The industrial plant studied provided most of the data on inputs and outputs, such as material flows, energy use, emissions and waste production. Missing data were estimated from the literature, based on expert judgement, or based on information on the characteristics of materials used provided by the plant suppliers. We specified relevant material flows at the level of sub-sub-processes. Table 3.1 illustrates the present industrial practice of the aluminium die casting facility and presents the different industrial processes involving the material and energy flows (so-called activity) as well as the pollutants released.

Melting is a relatively energy intensive sub-process. The use of natural gas for melting is a potential source of air pollutants (Table 3.1). Moreover, during Melting heavy metals are emitted to the atmosphere and a relatively large amount of solid waste is produced (i.e. aluminium dross). Casting is also a relatively large source of heavy metals (Table 3.1). In addition, Casting is an important source of non-methane volatile organic compounds (NMVOCs), solid waste and liquid effluents. During Finishing solid wastes and liquid effluents are produced. Finally, Internal Transports and Auxiliary Burners are sources of air pollutants resulting largely from the use of diesel and LPG (Table 3.1). However, Melting and Casting seem to be the largest sources of pollutants and waste. Their contribution to the overall environmental impact of this plant may be considerably larger than that of the other sub-processes. Therefore, Melting and Casting deserve special attention in a study focusing on the reduction of environmental pollution.

Table 3.1. Activities (α) and emissions of pollutants (x) per sub-sub-process (p_{ij}) for the current industrial process operations in the aluminium die casting plant studied, assuming that no pollution reduction options are implemented. The activities refer to the use of materials and energy at the plant.

Process (p)	sub-process (p_i)	sub-sub-process (p_{ij})		Activities (α)	Amount used	Pollutants (x)	Amount released
Die Casting company	Melting (i=1)	Melting		Desox. agent Degassing flux Natural gas	6.4 ton/yr [a] 851 kg/yr [a] 802000 m^3/yr [a]	Aluminium [c] Cadmium [c] Nickel [c] Lead [c] Chromium [c] Copper [c] Hyd. Fluoride [d] NOx [e] CO_2 [e] CO [e] NMVOC [e] Al. dross [f]	2444 kg/yr 1 kg/yr 1 kg/yr 6 kg/yr 1 kg/yr 10 kg/yr 1479 kg/yr 5955 kg/yr 2084 ton/yr 961 kg/yr 67 kg/yr 118 ton/yr
	Casting (i=2)	Holding Furnaces		Ceramic Lining	1456 kg/yr [b]	Aluminium [c] Zinc [c] Lead [c] Chromium [c] Copper [c] Iron [c] Cer. Lining [b]	30 kg/yr 47 kg/yr 4 kg/yr 3 kg/yr 23 kg/yr 227 kg/yr 1456 kg/yr
		Pressure Die Casting		Mould R. Ag. Water Hydraulic Oil Tip Lubricant Other oils Antifoam Sod.hydroxide Polyelectrolyte Floccul.agent	65 m^3/yr [a] 6300 m^3/yr [a] 53 m^3/yr [a] 7.4 m^3/yr [a] 17 m^3/yr [a] 0.23 m^3/yr [h] 0.15 m^3/yr [h] 0.12 m^3/yr [h] 1.54 m^3/yr [h]	NMVOC [c] Sludge [f] Liquid effluent [g] Oils and Grease [f]	576 kg/yr 40 ton/yr 4624 ton/yr 31 ton/yr
	Finishing (i=3)	Surface Treatment	Shot Blasting	Steel Shot	7.5 ton/yr [a]	Steel shot [f]	2044 kg/yr
			Tumbling	Water Ceramic Abrasives Splitting agent	0.50 m^3/yr [i] 12 ton/yr [a] 576 kg/yr [a]	Cer. abrasives [f] Liquid effluent [g] Sludge [f]	5034 kg/yr 0.1 m^3/yr 0.1 ton/yr
		Cleaning and Degreasing		Water Detergent Antifoam Sod.hydroxide Polyelectrolyte Floccul. agent	22 m^3/yr [i] 0.16 m^3/yr [a] 0.001m^3/yr [h] 0.0007 m^3/yr [h] 0.0006 m^3/yr [h] 0.007 m^3/yr [h]	Liquid effluent [g] Oils and Grease [f] Sludge [f]	22 m^3/yr 0.2 ton/yr 0.2 ton/yr
	Internal Transports (i=4)	Forklift Truck on Diesel I Forklift Truck on Diesel II Forklift truck on LPG		Diesel LPG	29 ton/yr [a] 18 m^3/yr [a]	CO_2 [j] NOx [j] SO_2 [j] CO [j] Particulates [j] NMVOC [j]	170 ton/yr 2235 kg/yr 155 kg/yr 157kg/yr 18 kg/yr 77 kg/yr
	Auxiliary Burners (i=5)	Oxyacetylene burners Butane burners		Acetylene Oxygen Butane	119 kg/yr [a] 366 kg/yr [a] 968 kg/yr [a]	CO_2 [l), k] CO [l] NOx [l] NMVOC [l] Particulates [l]	4 ton/yr 0.5 kg/yr 3 kg/yr 0.1 kg/yr 0.1 kg/yr

a) Yearly consumption of materials and energy at the industrial plant. Pedro (2005). Personal communication.
b) Waste is assumed equal to use. Estimated from emission factor. EIPPCB (2005).
c) Emissions to air. Emission estimated from annual average pollutant concentrations (mg/m^3) measured at the industrial plant. Pedro (2005). Personal communication.
d) Emission to air. Emission estimated from fluorides contents of desoxidation agent and degassing flux. Pedro (2005). Personal communication.
e) Emission to air. Emission estimated from average value for emission factor for natural gas and the facility yearly natural gas consumption. EMEP/CORINAIR (2004).
f) Yearly reported emission at the industrial plant. Pedro (2005). Personal communication.
g) Liquid effluent. Emission estimated based on the yearly water consumption and losses at the industrial plant. Pedro (2005). Personal communication.
h) Calculated based on the annual consumption of materials by processes taking place in the wastewater treatment plants and the amount of liquid effluent produced by each sub-sub-process.
i) Water use. Estimated based on the mass balance for the annual water use.
j) Emissions to air. Emission estimated from emissions factor made available from Salvador Caetano, S.A. and the yearly forklift trucks working hours. Monteiro (2004). Personal communication.
k) Emission to air. Estimated from emission factor of butane and annual butane use. Pedro (2005). Personal communication.
l) Emission to air. Emission estimated from emission factor of acetylene and facility yearly acetylene use. Pedro (2005). Personal communication.

3.3. Pollution reduction options

3.3.1. Criteria for choosing the pollution reduction options

The reduction options considered include abatement techniques that consist of end-of-pipe solutions for environmental problems, as well as structural options such as alternative input materials and production process modifications and new process technologies. Reduction options are included in the analysis if they meet the following criteria:

- The options aim to reduce the pollutants released during the operations taking place within the plant gates.
- The options reduce the emissions of pollutants, liquid effluents or solid waste production.
- The options are up-to-date and currently available commercial technologies.
- The options do not affect the safety performance of the company and do not reduce the production rate or the final product quality.
- The reduction options aim at reducing the pollutants emitted by the current industrial process.

Application of these criteria will lead to the selection of a set of relevant emission reduction options for small unit processes within the plant. These processes (at the sub-sub-process level) cause the pressures on the environment (as seen in Table 3.1).

3.3.2. Types of pollution reduction options

In this section we will describe reductions options as characterised in the preceding section. In total we have classified 11 different types of reduction options (see Table 3.2). Some options of the same type are mutually exclusive. For instance, we identified three different filters for the sub-process Melting: the reverse-air type, the pulse-jet type and the mechanical shaker type. Simultaneous application of these filters is technically not desirable. The choice for a single type of fabric filter will be based on its reduction potential and costs. In the following section (3.3.3.) we briefly describe the reduction options.

Table 3.2. Overview of options aiming at reducing the environmental problems caused by an aluminium pressure die casting plant. The individual options are described in Table 3.3.

sub-processes	Types of options	Options	Description
Melting	Filters and scrubbers	Fabric filters	This add-on technique reduces the emissions of particulate matter and air pollutants when present in particulate form (as metals) by retaining them on filter bags.
		Wet scrubbers	This add-on technique reduces the amount of particulate matter, inorganic gases and NMVOC emitted by collecting them on a liquid stream. This technique leads to the production of sludge.
	Alternative desoxidation agent	Granular desoxidation agent	This agent is used to clean the molten bath from impurities. The previous powder desoxidation agent is here replaced by a less pollutant one.
	Alternative degassing technique	Impeller station using N_2	This agent is used to clean the molten bath from gaseous impurities (as hydrogen). The previous technique using a solid agent is replaced by this new technique that uses a gaseous degassing agent.
	Alternative metal loading in furnaces	Compact metal loading in furnaces	The alloy materials rejected internally (including runners and products recycled internally) may be reduced in size and feed back in the melting furnaces. This new alternative allows the reduction in the size of alloy materials that feed the melting furnaces, affecting positively the furnace thermal efficiency.
	Combustion process modification	Air enrichment with oxygen (30%O_2) Oxyfuel firing (100%O_2)	Introduces oxygen in the melting process.
Casting	Scrubbers	Wet scrubbers	*See above (sub-process Melting) for description.*
	Alternative to mould release agent application	New mould release agent	The former mould lubricant agent is replaced by a low concentrated one. The specific use of the mould agent is reduced.
		Powder agent	The former spraying technique is replaced by electrostatic deposition that uses a powder mould release agent.
	New die casting moulds	Reduce runners [a),*)] mass	Total replacement of the die casting moulds used by alternative ones. In these new moulds the channels (runners) that allow the molten metal to enter the mould cavity are reduced in mass. This ultimately leads to an increase of metal yield (mass ratio: final products/molten alloy).
	Reduce scrap rate	Reduce scrap rate [*)]	Reduction of scrap generated. This ultimately leads to an increase of metal yield (mass ratio: final products/molten alloy).
Finishing	Reduce scrap rate	Reduce scrap rate [*)]	*See above for description.*
Internal Transport	Electrical equipment	Use electric forklift trucks	Uses electric forklift trucks instead of diesel or LPG fuelled ones.

a) A runner is the alloy in the channels through which the molten aluminium is transported to the die casting moulds. After casting, the raw products are separated from the biscuits and runners and the alloy in these biscuit and runners is recycled back into the Melting sub-process. The mass in the biscuits and runners is of about the same order of magnitude as the mass of the products

*) All these options lead to an increase of Metal Yield (MY). The MY is defined as the ratio of production to molten alloy. These options either reduce the mass of runners in the die casting moulds or reduce the scrap rate in the sub-processes Casting and Finishing. Increasing metal yield reduces the mass of aluminium alloy that feeds the melting furnaces and hence the energy needed to melt the aluminium alloy. Thus, these options not only reduce the amount of aluminium that is recycled internally, but also decrease the use of subsidiary materials that are directly dependent on the amount of molten alloy. Therefore as a result, many emissions will be reduced.

3.3.3. Description of individual reduction options

In the following, eighteen reduction options are described for the following sub-processes considered: Melting, Casting, Finishing, Internal transport and Auxiliary Burners. For each option a description is made of (1) what it does and how it does it, followed by (2) an estimate of the reduction factors and the associated costs, and (3) identification side-effects of options on materials or energy used or produced. Table 3.2 and Table 3.3 overview the pollution reduction options. Table 3.2 describes the types of options considered. Table 3.3 overviews each individual option and indicates the compounds reduced by them. These options include add-on techniques (fabric filters or wet scrubbers) or more structural reduction options that may change a material or technique used. We use a so-called *reduction factor* (RF) to express the percentage reduction in emissions possible by some of the options (Table 3.4). The effect of options on the activity rates are presented in Table 3.5. Some of the reduction options may have unintended side-effects leading, for instance, to extra consumption of materials or energy or to extra production of materials (see also Table 3.5 for the so-called extra activities). The prices of activities and extra activities used to calculate the costs associated to each option are also presented in Table 3.5.

Finally, we estimated the costs of implementing these options (Table 3.6). The costs included are regarded as additional costs for the plant (in line with Geldermann and Rentz, 2004). In Table 3.6, we present the cost parameters used to calculate the net additional costs (Cna). These are the sum of the annualised capital costs (CI), the fixed costs (CO) and the variable costs (CV) (as presented in Table 3.6). For each reduction option (τ) the annualised capital costs are calculated as a function of the investment (I), the interest rate (r) and the equipment lifetime (lt). The fixed costs are calculated as a fraction (o) of the investment. In addition, there are variable costs (CV) including the cost of the consumption of materials and energy associated with the reduction options (in line with Klimont et al., 2002). In the following, we provide details on the net additional costs for each reduction option. The reduction potential and the associated costs, for each option, may together form the basis for deciding on the opportunities for pollution reduction by the industrial sector.

Table 3.3. Overview of pollution reduction options for the aluminium pressure die casting plant.

sub-process (p_i)	sub-sub-process (p_{ij})	Types of Options	Reduction Options (τ)	Abbreviation	Compounds reduced
Melting (i=1)	Melting	Filters and scrubbers	Fabric Filter. Reverse-air type [a)]	Melting_FF_RA	Heavy metals such as Cd, Ni, Pb, Cr
			Fabric Filter. Pulse-Jet type [b)]	Melting_FF_PJ	Heavy metals such as Cd, Ni, Pb, Cr
			Fabric Filter. Mechanical Shaker type [c)]	Melting_FF_MS	Heavy metals such as Cd, Ni, Pb, Cr
			Wet Scrubber. Impingement-Plate type [d)]	Melting_WS_IP	Heavy metals (Cd, Ni, Pb, Cr), Cu and HF
			Wet scrubber. Spray-chamber type [e)]	Melting_WS_SC	Heavy metals (Cd, Ni, Pb, Cr), Cu and HF and NMVOC.
		Alternative desoxidation agent	Granular desoxidation agent [f)]	Melting_GA	HF, Aluminium dross.
		Alternative degassing technique	Impeller station using N_2[f), k)]	Melting_IS	HF, Aluminium dross.
		Alternative metal loading in furnaces	Compact metal loading in furnaces [g)]	Melting_CM	CO_2, CO, NOx, and NMVOC (Natural gas combustion related emissions).
		Combustion process modification	Air enrichment with oxygen (30%O_2) [g)]	Melting_AE	CO_2, CO, NOx, and NMVOC (Natural gas combustion related emissions).
			Oxyfuel firing (100%O_2)[g)]	Melting_OF	CO_2, CO, NOx, and NMVOC (Natural gas combustion related emissions).
Casting (i=2)	Pressure die casting	Scrubbers	Wet Scrubber. Packed-Bed type [h)]	Casting_WS_PB	Heavy metals (Pb, Cr), Cu, Zn, NMVOC
			Wet scrubber. Spray-chamber type [e)]	Casting_WS_SC	Heavy metals (Pb, Cr), Cu, Zn, NMVOC.
		Alternative to mould release agent application	New mould release agent [g)]	Casting_nMA	NMVOC, liquid effluent, oils, grease and sludge.
			Powder agent [i), k)]	Casting_PA	NMVOC, liquid effluent, oils, grease and sludge.
		New die casting moulds	Reduce runners mass [j), *)]	Casting_rRR	Heavy metals (Cd, Ni, Pb, Cr), Cu, Zn, HF, CO_2, CO, NOx, and NMVOC, aluminium dross, oils, grease and sludge.
		Reduce scrap rate	Reduce scrap rate [k), *)]	Casting_rSR	Heavy metals (Cd, Ni, Pb, Cr), Cu, Zn, HF, CO_2, CO, NOx, and NMVOC, aluminium dross, oils, grease and sludge.
Finishing (i=3)	Trimming	Reduce scrap rate	Reduce scrap rate [k), *)]	Finishing_rSR	Heavy metals (Cd, Ni, Pb, Cr), Cu, Zn, HF, CO_2, CO, NOx, and NMVOC, aluminium dross, oils, grease and sludge.
Internal Transport (i=4)	Forklift Truck on Diesel (I,II) and LPG	Electrical equipment	Use electric forklift trucks [g)]	IT_eFL	CO_2, CO, NOx, and NMVOC, SO_2 and Particulates.

a) EPA-CICA Fact Sheet. EPA-452/F-03-026. USEPA (2002); b) EPA-452/F-03-025. USEPA (2002); c) EPA-452/F-03-024. USEPA (2002); d) EPA-452/F-03-012. USEPA (2002); e) EPA-452/F-03-016. USEPA (2002).
f) Brown (1999)
g) Pedro (2005). Personal communication.
h) EPA-CICA Fact Sheet.. EPA-452/F-03-015. USEPA (2002).
i) Klüber (2005)
j) INETI (2000).
k) EIPPCB (2005).
*) These reduction options may change the value of the metal yield. See footnote in Table 3.2. for a definition of metal yield.

Melting

In the sub-process Melting five types of reduction options are identified (Table 3.3). These include i) filters and scrubbers, ii) alternative desoxidation agent, iii) alternative degassing technique, iv) alternative metal loading in furnaces and v) combustion process modifications.

The options included in *filters and scrubbers*, aim at reducing emissions of heavy metals (cadmium, nickel, lead and chromium), copper, hydrogen fluoride and non-methane volatile organic compounds (Table 3.3). Fabric filters reduce the emitted heavy metals while wet scrubbers also reduce copper, hydrogen fluoride and non-methane volatile organic compounds. The potential reduction of these compounds is presented in Table 3.4. For instance, all three fabric filters considered (abbreviated in Table 3.3 as Melting_FF_RA, Melting_FF_PJ and Melting_FF_MS) could reduce emission of cadmium, nickel, lead and chromium by 99% relative to the unabated present case (Table 3.4). The wet scrubbers (abbreviated as Melting_WS_IP and Melting_WS_SC) could reduce hydrogen fluoride and copper emissions by 99% relative to the unabated present case (Table 3.4). One of the wet scrubbers analysed (Melting_WS_SC) has also a large potential to reduce non-methane volatile organic compounds (95% relative to the unabated present case) (Table 3.4). A side-effect of these scrubbers and filters is extra waste to be disposed. This is estimated at 2.5 ton of additional waste per year for fabric filters and 4 tons for wet scrubbers (both estimates refer to the plant that served as a case study here) (Table 3.5). The amount of additional waste produced is estimated based on the efficiency of the filters and scrubbers in collecting dust plus, in case of wet scrubbers, an estimated 60% of water in the sludge. It should be noted that emission factors for the abated case and for the die casting process are not available from the literature. Nevertheless, our estimates for dust collection are in line with emission factors available from the literature for the aluminium industry (EIPPCB, 2001).The net additional costs for fabric filters vary from 26 to 84 k€/y and for wet scrubbers from 8 to 13 k€/y (Table 3.6).

Another possibility to reduce the environmental impact is to change the *desoxidation agent* used. This could be done by using a granular agent (Melting_GA as abbreviated in Table 3.3) as opposed to the conventional agents. Desoxidation agents are used to remove impurities from the molten bath. We assume that the amount of granular agent used is the same as the amount of the conventional agent used now i.e., 6400 kg/year (included as extra activity in Table 3.5) (Foseco, 2002). The granular agent has a lower content of fluorides and therefore gives rise to lower emissions of hydrogen fluoride emissions (Brown, 1999). The potential of this option to reduce hydrogen fluoride emissions is 62% relative to the reference case. This option also reduces the amount of aluminium dross formed. This is caused by an estimated reduction of 5% in the aluminium alloy in the aluminium dross (Foseco, 2002). The net additional cost of this option is -0.2 k€/y (Table 3.6).

Changing the *degassing technique* is a next option. It involves a new degassing technique using an impeller station using N_2 (Melting_IS as of Table 3.3). This technique is also used to remove gas impurities from the molten bath. This is done by promoting an agitation of the molten bath and the subsequent release of the gas entrapped (EIPPCB, 2005). Using an impeller station does not require the use of a solid agent containing fluoride compounds, but instead uses nitrogen that, being injected into the molten bath, promotes gas impurities to escape. This option thus reduces hydrogen fluorides emissions and aluminium dross formed relative to the unabated present case. This amount of gas N_2 used is estimated to be 403 m^3/year (Brown, 1999; EIPPCB, 2005) (included as extra activity in Table 3.5) and the net cost is 58 k€/y (Table 3.6).

Changing the *metal loading in furnaces* may reduce the use of natural gas, and as a result all associated emissions of pollutants. This option makes use of equipment that breaks the runners (see footnote in Table 3.2 for a description of runner), to small pieces that are again melted. This option (Melting_CM as abbreviated in Table 3.3), allows loading the melting furnaces with a more compact aluminium alloy load. This contributes to smaller the voids existing between the different parts of metal load and results in an increase in the thermal efficiency of the process. Although this process is not well documented in the available literature, it clearly explores the furnace thermal efficiency. We assume that this option will increase the furnace efficiency to the average thermal efficiency (47.5%) indicated for the shaft furnaces used to melt aluminium alloy to the pressure die casting process (EIPPCB, 2005). Therefore, the option leads to a large increase on the thermal efficiency relative to the unabated present case and subsequently reduces the activity (natural gas consumption). The potential 58% reduction in natural gas use (as indicated in Table 3.5) was calculated from the heat needed to melt the same amount of aluminium alloy. Consequently, the emissions resulting from the natural gas combustion (as CO_2, CO, NOx and NMVOC) are reduced likewise. The net additional cost is, however, comparatively low (-128 k€/y, see Table 3.6) indicating that the company gains from implementing this option.

Finally, the *combustion process modification* makes use of oxygen in the melting process. This includes two options that use either a small percentage of air enrichment with oxygen (Melting_AE as abbreviated in Table 3.3) or use only oxygen. This last case is also referred to as oxyfuel firing (Melting_OF as abbreviated in Table 3.3). These combustion modifications exploit the latent heat present in the exhaust gases. As the specific heat from the exhaust gases decreases with the increase of the amount of oxygen, a decrease in the specific consumption of natural gas is expected. As result, this option leads to an increase in the efficiency of heat production and savings in the natural gas used. The option Melting_AE is calculated to reduce natural gas consumption of 2%, relative to the present case, while the reduction on the consumption of natural gas is for the option Melting_OF of 4%, relative to the current case (Table 3.5). The emissions resulting from natural gas combustion (as CO_2, CO, NOx and NMVOC) are reduced likewise. The amount of oxygen used is estimated at 4.8E+05 m^3/year, (Table 3.5 for Melting_AE) and the net cost associated with this option is 59 k€/y (Table 3.6). For the option that uses oxyfuel firing 1.6E+06 m^3 of oxygen is needed annually (Table 3.5 for Melting_OF) while the net cost is relatively high and estimated to be 224k€/y (Table 3.6).

Casting

In sub-process Casting four types of reduction options are analysed (Table 3.3). These include i) scrubbers, ii) mould release agent application, iii) new die casting moulds and iv) reducing scrap rate.

- *Sub-sub-process Pressure Die Casting*

The *scrubbers* aim to reduce emission of metals (such as lead, chromium, copper and zinc) and non-methane volatile organic compounds (NMVOCs) (Table 3.3). They include two wet scrubbers (Casting_WS_PB and Casting_WS_SC as abbreviated in Table 3.3), which are very effective in reducing emissions. The wet scrubber of the type packed bed (Casting_WS_PB) reduces lead, chromium, copper and zinc by 95% relative to the unabated present case, and NMVOCs by 99% (Table 3.4). The wet scrubber of the type spray chamber (Casting_WS_SC) reduces metals emissions (lead, chromium, copper and zinc) by 99% relative to the unabated case, and NMVOC by 95% (see Table 3.4). These two scrubbers can estimate 0.5 ton/year of waste to be disposed (Table 3.5). This estimate is based on the efficiency of the scrubbers to collect dust plus an estimated 60% of water in the sludge. The amount of dust estimated is in line with literature values for the aluminium industry (EIPPCB, 2001). The net additional cost of scrubbers are 195 k€/y (Casting_WS_PB) and 22 k€/y (Casting_WS_SC) (Table 3.6).

The *mould release agent application* includes two options. One option replaces the mould release agent by an alternative one (Casting_nMA in Table 3.3). The other uses a new technique where a powder agent is applied by electrostatic deposition into the die casting mould (Casting_PA in Table 3.3). These two options aim firstly to reduce the amount of NMVOC emitted. In addition, a reduction in the specific consumption of mould agent leads to a reduction in the waste generated by the wastewater treatment plants (oils and grease and sludge).

Using a new mould release agent (Casting_nMA) reduces the amount of agent needed compared to the current practice. This in turn leads to a reduction in water use of 30% (see Table 3.5), in the emissions of NMVOCs, as well as liquid effluent, oils, grease and sludge produced. On the other hand, the new mould release agent used annually is estimated to be 28m^3 (as indicated an extra activity in Table 3.5). The net cost associated to this reduction option is -58 k€/y, indicating that the company gains from implementing this option (Table 3.6).

The option using a powder agent (Casting_PA), replaces the old spraying technique by a new one where a lubricant (powder agent) is applied into the die casting mould, by electrostatic deposition, before each die casting operation. The powder agent used reduces the emissions of NMVOC, eliminates the production of liquid effluent and consequently of oils, grease and sludge (Klüber, 2005). When a powder agent is used, the water needed in the sub-sub-process is reduced to zero (as seen in Table 3.5). However, the use of powder agent (as an extra activity) amounts to 4020 kg/y (extra activity in Table 3.5). The net cost is 146 k€/y (as shown in Table 3.6). The reduction factor for emissions of non-methane volatile organic compounds (NMVOC) is not available from literature, but we tentatively assume a 100% potential to reduce NMVOC emissions, when using powder agent. Likewise, the production of liquid effluent, oils, grease and sludge are zero when powder agents are used.

The *new die casting moulds* aim to reduce the mass of runners (option abbreviated to Casting_rRR in Table 3.3). This is possible by replacing the moulds with smaller cavities to runners. Reducing the runners mass (or in other words, reduce the amount of alloy in the runners to the die casting mould by using new moulds) will reduce most of the pollutants released by the plant process (Table 3.3). This occurs due to the fact that the plant recycles internally the excess of aluminium alloy mass, i.e., the alloy mass that is not part of the final product is sent back to the furnaces to be molten again. The materials recycled internally include the excess of alloy in the die castings (runners) and the scrap (die castings products that do not fulfil the final product requirements). Thus, if the amount of alloy in die castings is reduced, the alloy recycled internally also decreases and the materials and energy used in the process are affected. An estimated value for the reduction of the runners' mass is not easily available from the literature. Some studies (INETI, 2000) estimate, for alternative moulds, a value that may vary up to 30% reduction in the runners' mass, when compared to the conventional die casting moulds. However, this value depends on the type of the product produced. The option (Casting_rRR) is estimated to reduce the runners' mass by 25% relative to the plant's current practice. The use of new die casting moulds is then estimated to reduce the amount of aluminium alloy that is recycled internally to the melting furnaces by 16%, when compared to the present situation. This is because the percentage reduction in the runners only contributes to a part of the aluminium alloy (including runners and scraps from Casting and Finishing), that feeds the melting furnaces. Several materials and energy used in the sub-processes Melting and Casting are reduced likewise relative to the unabated case (as seen in Table 3.5). The net cost of using new moulds in the die casting machines is 119 k€/y (Table 3.6).

Reducing the scrap rate (Casting_rSR in Table 3.3) aims to reduce the amount of scrap (rejected die casting products not fulfilling the final product requirements). As mentioned above, this option reduces the aluminium alloy mass recycled internally and therefore reduces a large number of pollutants released by the plant process. The potential to reduce the scrap rate per sub-process is not available from the literature. Rather, the available literature values refer to the conventional overall reduction of the average scrap rate for die casting companies. About 5% of the scrap is typical of an aluminium pressure die casting company (US Department of Energy, 1999; EIPPCB, 2005). This would imply a 50% reduction in the scrap rate for the sub-sub-process pressure die casting of the plant. This option is then estimated to reduce the amount of alloy that is recycled internally to the melting by 5%. Subsequently, the different materials and energy used in the sub-processes Melting and Casting, as well as emissions of pollutants are reduced by the same amount (5%), compared to the unabated case (Table 3.5). The company may gain 30 k€/y from implementing this option (Table 3.6).

Finishing

- *Sub-sub-process Trimming*

Reduction of the scrap rate (Finishing_rSR in Table 3.3) is also possible in the sub-process Finishing. For the reasons mentioned above, this option affects a large number of pollutants released by the plant. The option (Finishing_rSR) is estimated to reduce the scrap rate by 60% compared to the plant's current scrap rate for the sub-sub-process trimming. The amount of alloy that is recycled internally to Melting is also assumed to be 5% lower, as well as the use of different materials and energy in Melting, Casting and Finishing (Table 3.5) and the pollutants emitted. Moreover, net cost indicates that the company may gain 36 k€/y from implementing this option (Table 3.6).

Internal transport

- *Sub-sub-process Forklift truck on Diesel (I and II) and LPG*

Currently, three forklift trucks are used in the plant, fuelled with diesel and LPG. It is possible to replace these by electric forklift trucks (*electrical equipment*; IT_eFL in Table 3.3). This would reduce the use of diesel and LPG to zero, and as a result the release of combustion products (Table 3.5). Instead of diesel and LPG, electricity is needed. We did not estimate the amount of electricity needed, nor the emissions associated with electricity production. Assuming that these are taking place outside the gate of the plant, and therefore beyond our system boundaries. The net additional cost is -39 k€/y indicating that the company gains from implementing this option (see Table 3.6).

Auxiliary burners

- *Sub-sub-process Oxyacetylene and Butane Burners*

The plant uses oxyacetylene and butane burners. These are of environmental concern because of emissions of combustion compounds (e.g. CO_2, CO and NOx). However, they are not used regularly in the current practice at the plant. Alternatives that are more environmentally sound include, for instance, the use of electrical equipment to replace oxyacetylene burners. However, we consider their impact on the overall environmental performance small and therefore this option is not included in the current analysis.

Table 3.4. Reduction factors (RF) for options applicable to the aluminium pressure die casting plant. The reduction factors express the theoretical potential to reduce emissions by the add-on techniques considered. The units express the percentage of reduction for each pollutant (x) for each reduction option (τ). released at each sub-sub-process and relative to the unabated situation. See section 3.3.3 for a description of the pollution reduction options.

			Reduction Factors (RF) for each pollutant (x)									
sub-processes	**sub-sub-processes**	**Reduction Option (τ)**	**x=Al**	**x=Cd**	**x=Ni**	**x=Pb**	**x=Cr**	**x=Cu**	**x=HF**	**x=NMVOC**	**x=Zn**	**x=Fe**
Melting	Melting	Melting_FF_RA [a)]	99.9%	99%	99%	99%	99%	n.e.	n.e.	n.e.	n.e.	n.e.
		Melting_FF_PJ [b)]	99.9%	99%	99%	99%	99%	n.e.	n.e.	n.e.	n.e.	n.e.
		Melting_FF_MS [c)]	99.9%	99%	99%	99%	99%	n.e.	n.e.	n.e.	n.e.	n.e.
		Melting_WS_IP [d)]	99%	99%	99%	99%	99%	99%	99%	n.e.	n.e.	n.e.
		Melting_WS_SC [e)]	99%	99%	99%	99%	99%	99%	99%	95%	n.e.	n.e.
Casting	Pressure Die Casting	Casting_WS_PB [f)]	95%	n.e.	n.e.	95%	95%	95%	n.e.	99%	95%	95%
		Casting_WS_SC [e)]	99%	n.e.	n.e.	99%	99%	99%	n.e.	95%	99%	99%

n.e. = no effect

a) USEPA Air pollution control technology fact sheet. EPA-CICA Fact Sheet. EPA-452/F-03-026. USEPA (2002).
b) USEPA Air pollution control technology fact sheet. EPA-CICA Fact Sheet. EPA-452/F-03-025. USEPA (2002).
c) USEPA Air pollution control technology fact sheet. EPA-CICA Fact Sheet. EPA-452/F-03-024. USEPA (2002).
d) USEPA Air pollution control technology fact sheet. EPA-CICA Fact Sheet. EPA-452/F-03-012. USEPA (2002).
e) USEPA Air pollution control technology fact sheet. EPA-CICA Fact Sheet. EPA-452/F-03-016. USEPA (2002).
f) USEPA Air pollution control technology fact sheet. EPA-CICA Fact Sheet. EPA-452/F-03-015. USEPA (2002)

Table 3.5. Effect of each reduction option on the activity rates (Act) and Extra Activities ($X\alpha$) for the aluminium pressure die casting plant. The values refer to the use of a certain material or energy (α). The values in percentage express the reduction on each activity rate (Act_α) for each reduction option (τ) and for each sub-sub-process, relative to the unabated present situation. The units presented for the extra activities reflect the extra amount of materials (X_α), required by the use of a reduction option and related to the unabated current situation. See section 3.3.3. for a description of the pollution reduction options.

	Reduction in activity rates (Act_α)												
Reduction Option (τ)	**desoxidation agent**	**degassing flux**	**Natural gas**	**Mould Release Agent**	**Water**	**Hydraulic Oil**	**Tip Lubricant**	**Other oils**	**Steel Shot**	**Ceramic Abrasives**	**Detergent**	**Diesel**	**LPG**
Melting_FF_RA	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.
Melting_FF_PJ	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.
Melting_FF_MS	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.
Melting_WS_IP	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.
Melting_WS_SC	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.
Melting_GA	100% b)	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.
Melting_IS	n.e.	100% b)	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.
Melting_CM	n.e.	n.e.	58% e)	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.
Melting_AE	n.e.	n.e.	2% f)	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.
Melting_OF	n.e.	n.e.	4% f)	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.
Casting_WS_PB	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.
Casting_WS_SC	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.
Casting_nMA	n.e.	n.e.	n.e.	100% b)	30% h)	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.
Casting_PA	n.e.	n.e.	n.e.	100% b)	100% b)	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.
Casting_rRR	16% j)	16% j)	16% j)	16% j)	16% j)	16% j)	16% j)	16% j)	n.e.	n.e.	n.e.	n.e.	n.e.
Casting_rSR	5% k)	5% k)	5% k)	5% k)	5% k)	5% k)	5% k)	5% k)	n.e.	n.e.	n.e.	n.e.	n.e.
Finishing_rSR	5% l)	5% l)	5% l)	5% l)	5% l)	5% l)	5% l)	5% l)	5% l)	5% l)	5% l)	n.e.	n.e.
IT_eFL	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	100% b)	100% b)
unit price	1.32 €/kg m)	2.8 €/kg m)	0.33 €/m³ m)	1.53 €/liter m)	1.5€/m³ m)	1.05 €/liter m)	1.37€/liter m)	0.74 €/liter m)	0.59 €/kg m)	1.02€/kg m)	1.86€/liter m)	0.91 €/liter n)	1.23 €/kg n)

* values referring to electricity or extra water use were not estimated. n.e. = no effect. n.s. = not specified.
a) Estimated based on the amount of avoided air emissions.
b) Assuming a full replacement of the agents currently used. Melting_GA: use of a granular agent replacing the currently used. Melting_IS: use of gas N_2, replacing the solid agent. Casting_nMA: use of alternative mould release agent. Casting_PA: replace the liquid agent and water by a solid powder mould release agent. IT_eFL: use of electric forklift trucks replacing the fuelled (Diesel and LPG) currently used.
c) Estimated from Foseco (2002). Personal communication.
d) Estimated from Brown (1999) and EIPPCB (2005).
e) Estimated based on the average furnace thermal efficiency for the type of furnace used in the plant. EIPPCB (2005).
f) "Estimated" based on the latent heat present in the exhaust gases.
g) "Estimated" based on the reduction of natural gas use reported to the plant unabated situation.
h) "Estimated" based on the reduction of mould release agent use reported to the plant unabated situation.
i) "Estimated" based on use reported to the number of die casting shots produced annually by the company and the indication from product use from Klüber (2005).
j) "Estimated" based on the reduction of the aluminium alloy that is recycled internally. This option affects the materials and energy used on the sub-processes Melting and Casting.
k) "Estimated" based on the reduction of the aluminium alloy that is recycled internally. This option affects the materials and energy used on the sub-processes Melting and Casting.
l) "Estimated" based on the reduction of the aluminium alloy that is recycled internally. This option affects the materials and energy used on the sub-processes Melting, Casting and Finishing.
m) Pedro (2005), Personal communication. n) GALP energy (2004), Personal communication. o) Foseco (2005), Personal communication. p) Praxair (2005), Personnal communication. q) Klüber (2005).

Table 3.5. (cont.).

	Extra Activity (Xα)							
Reduction Option (τ)	**Electricity**	**Water**	**Waste to disposal**	**Granular agent**	**Gas N_2**	**Oxygen**	**New mould release agent**	**Powder Agent**
Melting_FF_RA	*	n.e.	2.5 ton/yr [a)]	n.e.	n.e.	n.e.	n.e.	n.e.
Melting_FF_PJ	*	n.e.	2.5 ton/yr [a)]	n.e.	n.e.	n.e.	n.e.	n.e.
Melting_FF_MS	*	n.e.	2.5 ton/yr [a)]	n.e.	n.e.	n.e.	n.e.	n.e.
Melting_WS_IP	*	*	4 ton/yr [a)]	n.e.	n.e.	n.e.	n.e.	n.e.
Melting_WS_SC	*	*	4 ton/yr [a)]	n.e.	n.e.	n.e.	n.e.	n.e.
Melting_GA	n.e.	n.e.	n.e.	6400 kg/yr [c)]	n.e.	n.e.	n.e.	n.e.
Melting_IS	*	n.e.	n.e.	n.e.	403 m^3/yr [d)]	n.e.	n.e.	n.e.
Melting_CM	*	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.
Melting_AE	n.e.	n.e.	n.e.	n.e.	n.e.	4.8E+05 m^3/yr [g)]	n.e.	n.e.
Melting_OF	*	n.e.	n.e.	n.e.	n.e.	1.6E+06 m^3/yr [g)]	n.e.	n.e.
Casting_WS_PB	*	*	0.5 ton/yr [a)]	n.e.	n.e.	n.e.	n.e.	n.e.
Casting_WS_SC	*	*	0.5 ton/yr [a)]	n.e.	n.e.	n.e.	n.e.	n.e.
Casting_nMA	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	28 m^3/yr [h)]	n.e.
Casting_PA	*	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	4020 kg/yr [i)]
Casting_rRR	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.
Casting_rSR	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.
Finishing_rSR	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.
IT_eFL	*	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.
unit price	n.s.	1.5€/m^3 [m)]	200€/ton (dust) [m)] 220 €/ton sludge [m)] 37 €/ton (dross) [m)] 51 €/ton (oils and grease) [m)]	1.3€/kg [o)]	127 €/m^3 [p)]	0.13 €/m^3 [p)]	1.7 €/liter [m)]	55 €/kg [q)]

Table 3.6. Cost parameters for the reduction options applicable to the aluminium pressure die casting plant. The costs parameters include investment cost (I), the equipment life time (lt) and a fraction of the investments (o). These cost parameters allow for the calculation of the overall annual fixed costs (CI+CO) applicable to the die casting plant. The net additional costs (Cna) are the sum of the annualised capital cost (CI), the fixed cost (CO) and the variable cost (CV). See section 3.3.3. for a description of the pollution reduction options.

sub-processes (p_i)	sub-sub-processes (p_{ij})	Reduction Options (τ)	Investment (I) in (k€)	Lifetime (lt) in (years)	Fraction of investments (o) [m)] in (fraction/yr)	Annualised capital costs (CI) [n)] in (k€/yr)	Fixed cost (CO) [o)] in (k€/yr)	Variable costs [p)] (CV) in (k€/yr)	Net additional costs [q)] (Cna) in (k€/yr)
Melting	Melting	Melting_FF_RA	675 [a)]	20 [a)]	0.03	64	20	0	84
		Melting_FF_PJ	206 [b)]	20 [b)]	0.03	19	6	0	26
		Melting_FF_MS	574 [c)]	20 [c)]	0.03	54	17	0	72
		Melting_WS_IP	86 [d)]	15 [d)]	0.03	9	3	1	13
		Melting_WS_SC	49 [e)]	15 [e)]	0.03	5	1	1	8
		Melting_GA	0	0	0	0	0	-0.2	-0.2
		Melting_IS	55 [f)]	10 [l)]	0.03	8	2	49	58
		Melting_CM	140 [g)]	10 [l)]	0.04	20	6	-153	-128
		Melting_AE	0 [h)]	0	0	0	0	59	59
		Melting_OF	170 [h)]	10 [l)]	0.03	24	5	195	224
Casting	Pressure Die Casting	Casting_WS_PB	1396 [i)]	15 [i)]	0.03	153	42	0	195
		Casting_WS_SC	155 [e)]	15 [e)]	0.03	17	5	0	22
		Casting_nMA	0	0	0	0	0	-58	-58
		Casting_PA	220 [e),j)]	10 [l)]	0.04	31	9	106	146
		Casting_rRR	1140 [k)]	10 [l)]	0.04	162	46	-89	119
		Casting_rSR	0	0	0	0	0	-30	-30
Finishing	Trimming	Finishing_rSR	0	0	0	0	0	-36	-36
Internal transport	Forklift Truck on Diesel (I and II) and LPG	IT_eFL	57 [g)]	10 [l)]	0.02	8	1	-48	-39

a) to e) and i) from USEPA (2002): a) EPA-452/F-03-026; b) EPA-452/F-03-025; c) EPA-452/F-03-024; d) EPA-452/F-03-012; e) EPA-452/F-03-016: i) EPA-452/F-03-015.
f) EIPPCB (2005); g) Pedro (2005). Personal communication; h) Praxair (2005). Personal communication; i) *see above* for USEPA Fact sheet;
j) Klüber (2005); k) INETI (2000); l) Assumed to be 10 years; m) USEPA (2002) and Klimont et al. (2002).
n) Calculated by $CI = I * r * \frac{(1+r)^{lt}}{(1+r)^{lt}-1}$ (Neto et al., submitted (Chapter 4)).

Where:
CI= annualised capital cost due to the reduction option τ in (k€/year);
I= investment due to option τ in (k€);
r= interest rate in (fraction/year) (r=0.07) (USEPA, 2002);
lt= lifetime of reduction option τ in (years).
o) Calculated by $CO = I * o$ (Neto et al. submitted (Chapter 4)).
Where: CO = fixed costs for reduction option τ in (k€/year).
p) Calculated by

$$CV = AL_p * P_{ing} + \sum_i \left[\left(\sum_j \sum_\alpha \left(Act_{\alpha_{ij}} * P_{\alpha_{ij}} \right) \right) + \left(\sum_j \sum_{X\alpha} \left(Act_{X\alpha_{ij}} * P_{X\alpha_{ij}} \right) \right) - 5315 \right]$$

(Neto et al., submitted (Chapter 4)).

Where:
CV = variable costs of all implemented pollution reduction options τ *in* (k€/year)
The other parameters refer to: aluminium ingot (AL) and its unit price (P_{ing}), activities rates (Actα) and its unit prices (Pα) or extra activities rates (ActXα) and the price of it (PXα).
q) The net additional costs (Cna) is the sum of CI+CO+CV, when subtracted the costs for the unabated situation (k€/year).

3.4. Discussion and Conclusions

We identified eighteen technical options to reduce the environmental impact of an aluminium pressure die casting plant. The options aim at reducing the different pollutants emitted by specific sub-sub-processes within a plant. The emissions of pollutants include air emissions, liquid effluents and waste streams. The options identified are categorised in eleven types that include mutually exclusive options. For each type the options considered may include end-of-pipe solutions as well as process operations changes in the die casting process. They include, for instance, fabric filters and scrubbers; the use of alternative agents or techniques; modification of the combustion process; the use of new die casting moulds; reduce the scrap rate and the use of electrical equipment. Some of the techniques/options are indicated as the best currently available for the industrial sector of the aluminium pressure die casting.

We conclude that there is ample opportunity to reduce the pollution of the die casting plant studied. The most promising reduction options are found for the sub-processes Melting and Casting. The technical potentials to reduce the environmental impact vary for the different types of options. The results indicate that is technically possible to reduce metal emissions, hydrogen fluoride and non-methane volatile organic compounds, from Melting and Casting, to very low levels (see Table 3.4). For instance, fabric filters and wet scrubbers have a large potential (up to 99.9%) to reduce metal emissions, relative to the unabated situation. It is also technically possible to change the inputs or mass flows through the system. This would reduce the so-called activity rates, which are considered the sources of pollution. Some activity rates may be reduced by more than 30% by the options considered here (Table 3.5). For instance, the option to compact the metal load reduces the amount of natural gas use by 58%. Some other options have relatively low reduction potentials (< 16% reduction relative to the unabated case) but may affect a larger number of activity levels simultaneously. This is, for instance, the case for the options that use new die casting moulds and the options reducing the scrap rate.

Some options may have intended or unintended side-effects and induce the use of new activities (Table 3.5). These may include the use of additional materials or energy or the production of additional pollutants. For instance, wet scrubbers may, as a side-effect, increase the production of sludge by 0.5 ton annually (Table 3.5). The net effect of changes in different activity levels and specific emissions on the environment could be determined trough multi-criteria analysis in which different pollutants are valued as criteria. This, however, is outside the scope of this chapter.

We calculate the net additional costs of implementing the reduction options, including variable and fixed costs. The net additional cost ranges from -128 k€/year to 224 k€/year (Table 3.6). We identify six options with net negative costs. These include the option to use a granular agent, to compact the metal load, the use of new mould release agent, the options that reduce scrap rate and the option that uses electric forklift trucks. This means that the company may earn money while implementing these options. Other options have relatively high costs (net costs >100 k€/year). Obviously, the most interesting options are among the relatively cheap options. For instance, increasing the furnace thermal efficiency may decrease the natural gas use by 58% at negative net costs (Table 3.5 and 3.6 for option Melting_CM).

There may be other possibilities to reduce pollution that were not considered here. First, for some processes we assumed that the current techniques are up-to-date and that further improvement of the environmental performance will be difficult. For instance, our number of options analysed for the Finishing sub-process is limited. We consider the technologies used by the plant for surface treatment (including grinding, shot blasting and tumbling) difficult to replace because they are up-to-date technologies (EIPPCB, 2005). This also holds for the sub-sub-processes Cleaning and Degreasing. Second, we did not account for polluting activities outside the plant's direct span of control. For instance, machining takes place outside the gates of the plant and therefore the pollution caused by this operation was not included in our analysis. We argue that companies do not have full control over operations outside the facility gates.

We did not assess the uncertainties in our estimates in a systematic way. However, the estimates of reduction factors and cost parameters are to our knowledge the best currently available. In a related study, we use our estimates in a model to analyse the effect of combinations of options for the environmental performance of an aluminium die casting plant. This study also includes a sensitivity analysis, to analyse the sensitivity of model results to ranges and uncertainties in model parameters (Neto et al., submitted (Chapter 4)).

Our study differs from many others in its completeness, and its focus on the industrial process at the plant level. In fact, we take a company perspective. This is reflected by the analysis of the materials and energy use trough the company's production process. Other studies typically cover less environmental problems (e.g. Kim et al., 2003; Backhouse et al., 2004 EIPPCB, 2005) or do not to take into account the costs associated to pollution prevention (Kim et al., 2003; Backhouse et al., 2004). The pollution reduction options identified in this study are specific for aluminium pressure die casting but even though, we used a specific plant as a basis for our analysis, the inventory of options may be generally applicable to other aluminium pressure die casting plant worldwide. In fact, it may even contain interesting elements for metals industry in general.

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Chapter 4: Modelling the Environmental Impact of an Aluminium Pressure Die Casting Plant and Options for Control

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This chapter has been submitted to Environmental Modelling and Software

Abstract

This study describes a model (MIKADO) to analyse options to reduce the environmental impact of aluminium die casting. This model takes a company perspective, so that it can be used as a decision support tool for the environmental management of a plant. MIKADO can be used to perform scenario analyses to analyse the impact on the environment of different strategies, while taking into account both economical and ecological consequences of decision-making. The MIKADO approach is based on relevant parts of a number of analytical tools, including Life Cycle Assessment and Multi-Criteria Analysis. One of the strengths of MIKADO is the integrated approach that it takes in analysing, simultaneously, all the relevant environmental problems caused by the aluminium die casting plant. The model is developed for and applied to a specific aluminium die casting plant supplying car manufacturers with aluminium die casting products. We present model results for a reference case, indicating that most of the environmental impact of the plant is associated with releases of compounds during the melting and casting of alloy, as well as with the use of natural gas. Finally, we present results of a partial sensitivity analysis, indicating the sensitivity of the model to changes in parameter values.

4.1. Introduction

Aluminium is a widely used metal, in particular in the automotive industry. The need to reduce vehicle fuel consumption by reducing the weight of the car, has increased the interest in aluminium. For instance, the total mass of aluminium in a European car roughly doubled between 1990 and 2000 (EIPPCB, 2005). The expected growth of the use of aluminium to achieve lighter cars has an effect on the aluminium die casting industry. Aluminium pressure die casting is a manufacturing process in the non-ferrous industries, producing engineered aluminium alloy products, such as car components. Aluminium castings dominate the non-ferrous sector, comprising roughly 80 percent of the light alloy castings on the European aluminium market (CAEF, 2003). Pressure die casting is a widely used casting process for aluminium alloys and about two-thirds of all aluminium castings are used in automotive industry (Brown, 1999).

The aluminium pressure die casting industry contributes to a number of environmental problems (Kim et al., 2003). For instance, it is a source of metal emissions to the environment that may be toxic to humans and other organisms. Moreover, this industry contributes to air pollution problems through emissions of gases that contribute to tropospheric ozone formation, acidification, human toxicity and global warming. And finally, there are waste-related problems, potentially leading to soil pollution.

Today, the industrial sector has to meet environmental goals, aiming to reduce the environmental impact of the industrial activities (Finkbeiner et al., 1998; Silvo et al., 2002). In many countries environmental laws exist that, for instance, regulate the emissions of a number of pollutants, or include restrictions of the use of toxic compounds or waste handling. The aluminium die casting industry shows the worldwide trends of implementing environmental management systems to quantify their environmental performance (Neto et al., 2003; Hillary, 2004; Zobel and Burman, 2004).

Despite existing regulations, it is not easy to answer the question of how the environmental impact of an individual company can be reduced most effectively. There are too many pollutants involved, and too many reduction options available, to easily get a good overview of the situation. A complicating factor is that many industrial processes result in more than one pollutant. In addition, reduction options typically, not only reduce the pollutant that they are aiming to reduce, but may have positive and negative side effects on other pollutants. And finally, industrial companies are not only interested in the most effective way to reduce emissions, but also in the most efficient way, in order to limit the costs of environmental control (Geldermann and Rentz, 2004).

Existing environmental systems analysis tools may assist in getting insight into this complexity. For instance, Life Cycle Assessment (LCA) is a tool aiming to specifying the environmental consequences of products or services over its entire lifetime (Guinée, 2002; Rebitzer et al., 2004). Substance Flow Analysis (SFA) focuses on specific substances, either within a region or through its entire life cycle; typical examples include studies of nitrogen flows or flows of a specific metal (Kytzia and Nathani, 2004; Finnveden and Moberg, 2005). Multi-Criteria Analysis (MCA) is a tool to support the selection of the best combination of outcomes that have different dimensions, and it can assist in identifying trade-offs between different criteria and finding the best solutions (Wrisberg et al., 2002). Scenario analysis typically results in a set of answers to "*What… if*" questions illustrating the consequences of a range of alternative decisions (Schwarz, 1997; Pluimers, 2001). Technology assessments are used to analyse technological options to reduce the environmental impact. Some authors defend that many possibilities to reduce the environmental burden of industrial production are present, such as, optimisation of the environmental performance through good housekeeping, end-of pipe techniques, substitution of unfriendly products or by technology innovation (Moors et al., 2005). Cost-effectiveness analysis (CEA) reveals the costs per unit of avoided emission (Rabah, 1999; Pluimers 2001; Klimont et al., 2002).

Because of the complexity of most environmental issues, the above briefly described analytical tools are seldom appropriate as a stand-alone tool for analysing environmental issues. In environmental analyses, therefore, often a combination of tools is used to analyse a particular problem. Integrated Assessment (IA) Models typically combine a number of tools. However, these IA Models seldom take a company perspective, but are rather developed to assist policy makers (Alcamo et al., 1990; Carmichael et al., 2004; Ball et al., 2005).

Industrial companies may use the systems analysis tools to analyse how to keep the environmental impact of their processes within the limits, set by environmental legislation or how to minimise the impacts in an economically feasible way. This is not a simple task, the tools mentioned above are not, by themselves, appropriate to analyse an environmental problem at the company scale. For instance, LCA is typically developed for the analysis of a product, but not of a company. Industrial companies use EPIs, but the result is a long list of emission estimates that do not give an answer to the question of what the *overall* environmental performance is, or what the best way is to reduce these emissions. MCA is a useful tool to assess the overall environmental performance, but in itself not easily applied at the company level when the set of emission estimates is not consistent with the structure of the MCA. Scenario analysis is usually applied to investigate trends at the sector or national level, but not often at the company level, due to the site-specific information that would be needed for that.

From the above it may be clear that there is a need for decision support systems, to help industrial management to decide on environmental control options for their particular plant. The purpose of this study is therefore to develop a model to analyse options to reduce the environmental impact of aluminium die casting. This model will take a company perspective, so that it can be used as a decision support tool for the environmental management. It will allow the plant management to decide on the environmental strategy to follow.

We refer to our model as MIKADO: Model of the environmental Impact of an Aluminium Die casting plant and Options to reduce this impact. In the next sections, we will first describe the MIKADO approach, the model parameters and activities of an aluminium die casting plant. The later section will present the result of a sensitivity analysis, showing the sensitivity of the model results to uncertainties in selected parts of the model.

4.2. Model Description

4.2.1. Model Design and Structure

The MIKADO structure and the modelling approach are based on the work of Van Langen who has developed object-oriented software for designing processes (DESIRE) (Van Langen, 2002). This software, and the language used in it, provides a structure and a grammar to define objects, objects' properties and methods at multiple layers. The language has been developed to allow to model processes. Van Langen shows that his approach can be used in designing models for estimating the emissions from industrial processes. One of Van Langen's case studies deals with an emissions inventory model developed as a prototype system for an environmental inventory of brick and tile fabrication in the Netherlands (Van Langen, 2002). The model described in this chapter (Chapter 4) is an application of this approach and uses as an interface to model user a software tool called EstimatER developed by the European Topic Centre on Air and Climate Change to analyse and assess alternative pollution reduction options (ETC/ACC, 2001).

The basic "object" in MIKADO is a process. The object covers the full process and has information and material exchange with the environment. The material exchanges of the process with its environment consist of: a) the raw material, energy and any other subsidiary materials needed for the process and, b) the output in terms of the products and any environmental pressures that might be caused by the process. The information exchange of the process with its environment concerns the activity rate. Whether this information about the activity rate is an input or an output is a matter of perspective: if we are interested in managing the process, the activity rate could be seen as an input to the object. If, on the other hand, the object is to describe a process with an endogenous mechanism to run it, it can be regarded as an output. The latter will mainly occur in dynamic models of processes that contain positive or negative feedback loops. In our approach we aim for a model that is to be used by the plant's management. Therefore, we subdivide the object process into several sub-processes or even, sub-sub-processes. Typically, a process in a plant can be decomposed into a series of consecutive and possibly parallel sub-processes or even sub-sub-processes that form the production line. This nested approach is useful in further specifying the process and process characteristics.

In this study we are aiming for a steady-state model that describes the environmental pressures caused by a process. We therefore will regard the information about the process activity rate as an input to the object. This rate can be expressed in different ways: it could be related to one of the inputs in the system or the required outputs. The choice will depend on the type of process modelled. In this study, the process is the production of die cast aluminium car parts. To this end an existing small/medium size enterprise located in the northern part of Portugal served as a case study. Since we are building this model to be used from a company's management's perspective, the model considers a production rate of approximately 3000 tons of aluminium die casting products as the model driver. In the model, the production rate of the process is used to calculate all necessary inputs, all outputs and all environmental pressures. Obviously, the exact functions describing the dependence of the inputs, outputs and pressures from the production are determined by the characteristics of the process. The model allows for manipulation of such process characteristics to implement possible reduction options influencing the environmental problems. By manipulating the process characteristics all functions might change. The DESIRE approach, as implemented in the user interface tool, provides the functionality for these manipulations.

The objects within our model structure are nested. This nested structure allows for describing the process characteristics for different sub-process (or sub-sub-processes). This is schematically presented in Figure 4.1 for the case plant on aluminium die casting. The production line of the die casting process consists of the following sub-processes: 1) Melting, 2) Casting, 3) Finishing. The system also includes as sub-processes: 4) Internal Transport and 5) Auxiliary Burners. These are considered sub-processes that are independent of the annual production rate. In addition, the company owns two wastewater treatment plants that are part of the die casting production line. These plants treat liquid effluents from Casting and Finishing.

The sub-processes of the production line (Melting, Casting and Finishing) are connected in series since the output from one sub-process is used as an input for the next one. The alloy entering the process includes ingots and alloy recycled internally. The molten alloy, output from the Melting, feeds the Casting sub-process, yielding the raw products. The raw products, in turn, are finished and leave the system as final products. A small part of the aluminium leaves the system as emissions, either to air, to water or as solid waste.

Obviously aluminium is not the only resource flowing through the system. Energy is needed to melt the alloy, a range of subsidiary materials is needed for many different purposes and investments, and operation costs need to be paid. In the model, all of these are derived from the production rate.

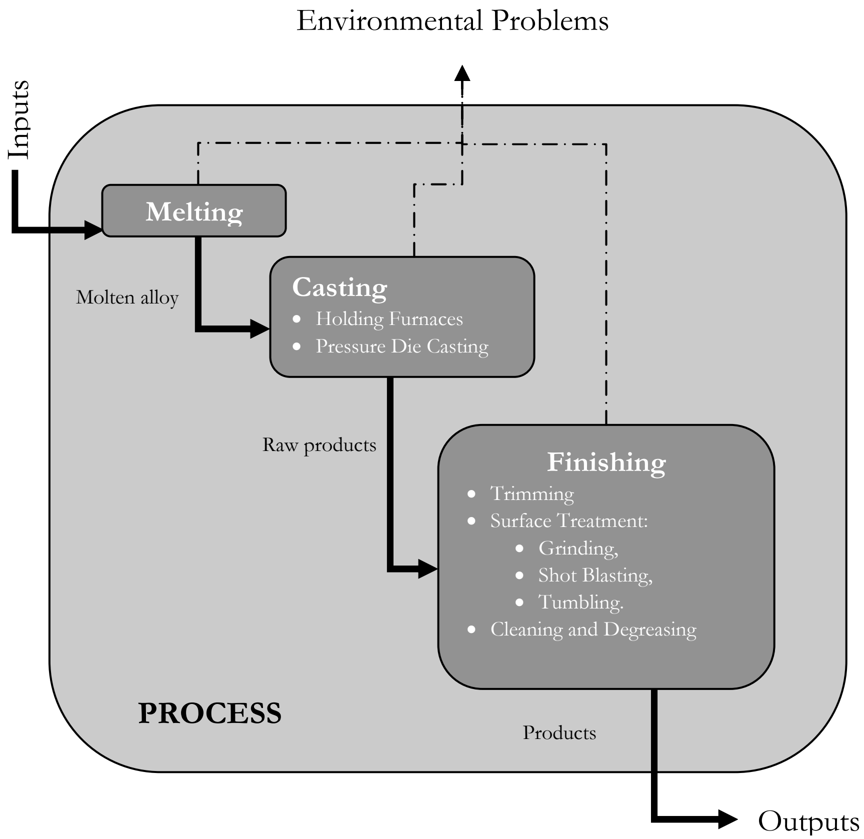

Figure 4.1. The aluminium pressure die casting plant's production line. The figure includes the sub-processes and sub-sub-processes that we included in our model (see also Table 4.1). The scheme includes the alloy mass flow throughout the production line. Part of the alloy mass flows exiting Casting and Finishing are recycled internally. For simplification, these flows of recycled alloy are excluded from the figure.

MIKADO has been structured so that each sub-process receives all inputs from the earlier sub-processes it needs to deliver the (semi)products. Wherever needed, a further detail in the model is defined by decomposition of a sub-process into sub-sub-processes. The overall structure in terms of sub-sub-process of the die casting plant is described in detail in the next sections.

In summary, the model structure is based on the mass flows through the successive steps in the production line giving rise to environmental problems. The inputs to MIKADO at the level of the aluminium die casting production line include, beside the subsidiary materials and energy, the alloy mass flows as raw products use (ingots) and/or alloy mass recycled within the production line.

In addition, some of the costs of process operation and investments are considered. The outputs of MIKADO include products, semi-products, emissions of pollutants, waste and liquid effluents, alloy mass to be recycled within the process and the costs of emission control. Moreover, the environmental performance of the plant is assessed in terms of one overall indicator.

4.2.2. Model Formulation

The MIKADO's core is formed by conservation of aluminium alloy mass throughout the production line. The alloy mass flow presented in the model is determined by the production rate. The production rate and the mass of alloy leaving the system at each sub-process level are readily available from the company managers. But, within the MIKADO structure, the activity data used refer essentially to the alloy mass flow entering each sub-process, so the raw data supplied was converted in order to refer to the tonnage of aluminium alloy mass inputs per year into each sub-process. So, the model calculates the alloy input needs at each sub-sub-process level, for the production rate, by using the values of alloy mass emissions leaving the sub-sub-process and also the amount of alloy mass recycled internally. In the manufacturing process the losses of aluminium alloy during the process are emitted to the air or leave the system as solid wastes or liquid effluents. These average values are company specific and were made available by the company managers. The alloy losses occur in all the sub-processes from the production line. The losses in the sub-process Melting are due to air emissions (0.04% of the mass of alloy inputs) and aluminium dross (0.72 % of the mass of alloy inputs). In the sub-process Casting a small amount is lost as air emissions (0.0005% of the alloy entering the Casting sub-process). In addition, in the Casting process the runners and biscuits (40% of the alloy entering Casting) and scrap that is internally recycled (6% of the alloy entering Casting) are produced. Finally, the sub-process Finishing produces aluminium burrs (4% of the alloy entering Finishing) and scrap to be internally recycled (7.5% of the alloy entering Finishing). All these losses are obviously compensated by the approximately 6% higher input of ingots as compared with finished products. The alloy mass losses in the liquid effluents are neglected in this study because aluminium losses value less than 0.001% of the mass of input alloy.

The aluminium mass flow diagram is presented in Figure 4.2 for the annual production rate (approximately 3000 tons of aluminium die casting products). The figure moreover, includes the alloy mass leaving the system for the sub-processes: 1) Melting, 2) Casting and 3) Finishing. From the figure, it is also clear that the molten alloy entering sub-process Melting is at least twice the production rate, this is due to the fact that the alloy mass includes the alloy recycled internally and the ingots of aluminium alloy. Thus, the shot weight (the shot is the semi-product from Casting that includes the final products plus the excess of materials (runners and biscuits) needed to allow the molten metal to fulfil the die casting moulds) consists, for the specific company, of a mixture of approximately 50% ingot and 50% internal recycled aluminium alloy.

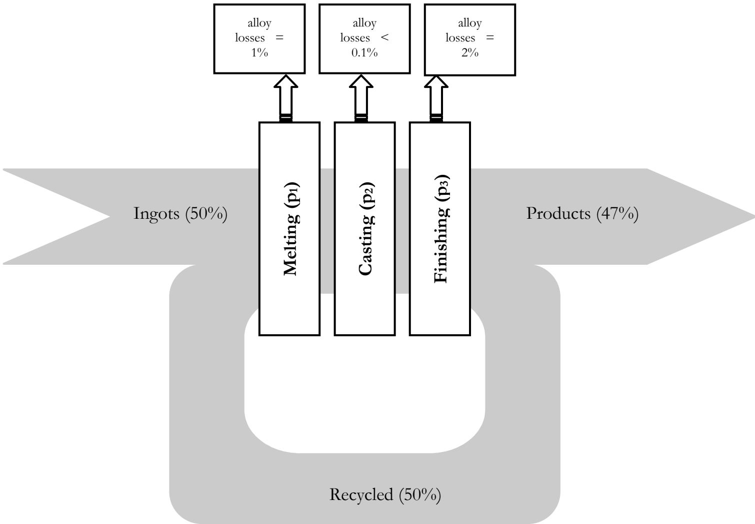

Figure 4.2. Alloy mass flow on the existing aluminium pressure die casting plant.

Table 4.1 shows the alloy mass input in each sub-sub-process and the related activities (materials or energy usage) at the sub-sub-process level for the industrial plant. The materials and energy inputs are identified for each sub-sub-process level and refer to the alloy mass flow entering each sub-process. For instance, the amount of natural gas used in the sub-process Melting is directly dependent of the amount of alloy input to the same sub-process. These activities are summed up at the firm level.

Table 4.1. Alloy mass in-flow (AL) and type of activities (α) by sub-sub-process (p_{ij}). Based on an existing aluminium pressure die casting plant and assuming no reduction options implemented on the plant.

Process (p)	sub-process (p_i)	sub-sub-process (p_{ij})		Activities: AL	Activities: α
Die Casting company	Melting (i=1)	Melting		Annual mass of alloy input to Melting	Desoxidation agent Degassing Flux Natural gas
	Casting (i=2)	Holding Furnaces		Annual mass of alloy input to Holding Furnaces	Ceramic lining
		Pressure Die Casting a)		Annual mass of alloy input to Pressure Die Casting	Mould release agent Water Hydraulic oil Tip Lubricant Other Oils Antifoam Sodium hydroxide Polyelectrolyte Flocculation agent
	Finishing (i=3)	Trimming		Annual mass of alloy input to Trimming	---
		Surface Treatment	Grinding	Annual mass of alloy input to Grinding	---
			Shot Blasting	Annual mass of alloy input to Shot Blasting	Steel shot
			Tumbling b)	Annual mass of alloy input to Tumbling	Water Ceramic abrasives Splitting agent
		Cleaning and Degreasing a)		Annual mass of alloy input to Cleaning and Degreasing	Water Detergent Antifoam Sodium hydroxide Polyelectrolyte Flocculation agent
	Internal Transports c) (i=4)	Forklift Trucks on Diesel (I and II)		---	Diesel
		Forklift Truck on LPG			LPG
	Auxiliary Burners c) (i=5)	Oxyacetylene burners		---	Acetylene and Oxygen
		Butane burners			Butane

a) Both liquid effluents leaving the sub-sub-processes Pressure Die Casting and Cleaning and Degreasing are treated in the same wastewater treatment plant. Thus, some of the agents (activities, such as: antifoam, polyelectrolyte, etc.) used in the treatment plant are allocated to these sub-sub-processes.
b) The liquid effluent leaving this process is treated in a specific wastewater treatment plant. The agent needed (splitting agent) is allocated to this sub-sub-process.
c) The activities from sub-processes Internal transports and Auxiliary burners are considered to be independent of the annual production rate.

Emissions and waste production are calculated by the model as a function of the activity rate (Act), within sub-sub-process (p_{ij}). The activity rate measures the use of materials or energy in each sub-sub-process. The emissions are calculated assuming a linear relation between the activity rate and a specific emission of a pollutant (x). The proportionality constant is called the emission factor (EF). The total emission (E_x) is calculated by summing all emissions of pollutant (x) resulting from the use of all activities (α) in all sub-sub-processes (p_{ij}).

Equations 1 to 14 are used to calculate the emissions, the activity rates, the environmental impact and the costs. Box 4.1 presents all the equations and describes all the parameters and variables.

Box 4.1. Mathematical Formulation of the model (Equations 1 to 14).

$E_{x,p_i} = \sum_j \sum_\alpha \left(Act_{\alpha_{ij}} * EF_{ij,\alpha_{ij},x} \right)$	(Equation 1)
$Act_{\alpha_{ij}} = AL_{ij} * AF_{\alpha_{ij}}$	(Equation 2a)
$Act_{\alpha_{ij}} = AL_{ij}$	(Equation 2b)
$Act_{\alpha_{ij}} = Act_{\alpha_{ij}}$	(Equation 2c)
$E_x = \sum_{p_i} \left(E_{x,p_i} \right)$	(Equation 3)
$M_{p_i} = \sum_z \left(\frac{\sum_x \left(E_{x,p_i} * CF_{z,x} \right)}{NF_z} * WF_z \right)$	(Equation 4)
$M = \sum_{p_i} \left(M_{p_i} \right)$	(Equation 5)
$E_{x,p_i} = \sum_j \sum_\alpha \sum_\tau \left(Act_{\alpha_{ij},\tau} * EF_{ij,\alpha_{ij},x,\tau} * \left(\frac{100 - RF_{x,\tau}}{100} \right) \right)$	(Equation 6)
$E_{x,p_i} = \sum_j \sum_{X\alpha} \sum_\tau \left(Act_{X\alpha_{ij},\tau} * EF_{ij,X\alpha_{ij},x,\tau} \right)$	(Equation 7)
$Act_{X\alpha_{ij},\tau} = AL_{ij} * AF_{X\alpha_{ij}}$	(Equation 8a)
$Act_{X\alpha_{ij},\tau} = AL_{ij}$	(Equation 8b)
$CI_\tau = I_\tau * r * \frac{(1+r)^{lt_\tau}}{((1+r)^{lt_\tau} - 1)}$	(Equation 9)
$CO_\tau = I_\tau * o_\tau$	(Equation 10)
$CV_{zerocase} = AL_{p,zerocase} * P_{ing} + \sum_i \sum_j \left(Act_{\alpha_{ij},zerocase} * P_{\alpha_{ij}} \right)$	(Equation 11)
$CV = AL_p * P_{ing} + \sum_i \left[\left(\sum_j \sum_\alpha \left(Act_{\alpha_{ij}} * P_{\alpha_{ij}} \right) \right) + \left(\sum_j \sum_{X\alpha} \left(Act_{X\alpha_{ij}} * P_{X\alpha_{ij}} \right) \right) \right]$	(Equation 12)
$C = \sum_\tau \left(CI_\tau + CO_\tau \right) + CV$	(Equation 13)
$C_{na} = C - C_{zerocase}$	(Equation 14)

Box 4.1 (cont.) Description of parameters and variables present on equations 1 to 14.

E_{x,p_i}	=	emission of pollutant x within the sub-process p_i *in* (kg of pollutant x /year) or (m^3 of pollutant x /year).
x	=	index for type of pollutant emitted such as: metals (Al, Cd, Ni, Pb, Cr, Cu, Zn, ….), CO_2, NOx, CO, NMVOC, etc.
p	=	index for process p (Table 4.1).
i	=	index for sub-process from process p (Table 4.1).
j	=	index for sub-sub-process within sub-process i from process p (Table 4.1).
α	=	index for type of activity, referring to energy or materials such as: use of natural gas, mould release agent, water, desoxidation agent, etc. (Table 4.1).
Act_α	=	activity rate (Act) expressing the use of a certain material or energy (α) *in* (unit activity/year) (Table 4.3).
AL	=	aluminium alloy mass inflow *in* (ton alloy /year).
AF_α	=	activity factor (AF) expressing the unit of activity (α) used by the amount of aluminium alloy mass flow *in* (unit activity/ton alloy) (Table 4.3).
$EF_{\alpha,x}$	=	emission factor (EF) for pollutant x, related to a certain type of activity (α) *in* (kg/ unit activity) or (m^3/ unit activity) (Table 4.4).
E_x	=	total emission of pollutant x *in* (kg of pollutant x /year) or (m^3 of pollutant x /year).
M_{p_i}	=	environmental impact from sub-process p_i (unitless).
z	=	index for type of environmental impact category: Human toxicity, terrestrial ecotoxicity, global warming, acidification, photochemical ozone formation, abiotic depletion, aquatic toxicity and solid waste production.
$CF_{z,x}$	=	characterisation factor (CF) for environmental impact category z due to emission of pollutant x (Table 4.8).
NF_z	=	normalisation factor (NF) for environmental impact category z (Table 4.9).
WF_z	=	weighting factor (WF) for environmental impact category z (unitless) (Table 4.10).
M	=	overall environmental impact (unitless).
M_{z,p_i}	=	environmental impact for a specific environmental impact category (z) resulting from sub-process p_i (unitless).
$RF_{x,\tau}$	=	reduction factor for pollutant x due to the reduction option τ *in* (%) (Table 4.5).
τ	=	index for reduction option (Table 4.2).
$Act_{\alpha,\tau}$	=	activity rate (Act) related with a certain type of activity (α) that may change by the reduction option τ *in* (unit activity/year) (Table 4.5).
$EF_{\alpha,x,\tau}$	=	emission factor (EF) for pollutant x, related to a certain type of activity (α), that may change by the reduction option τ *in* (kg/ unit activity) or (m^3/ unit activity).
$X\alpha$	=	index for type of extra activity (Xα), induced by the reduction option τ and referring to energy or materials such as: use of gas N_2, oxygen, powder agent or waste to be disposed (Table 4.5).
$Act_{X\alpha,\tau}$	=	activity rate (Act) expressing the use of an extra material or energy (Xα), induced by the reduction option τ *in* (unit activity/year) (Table 4.5).
$EF_{X\alpha,x,\tau}$	=	emission factor (EF) for pollutant x, related to a certain type of an extra activity (Xα) induced by the reduction option τ *in* (kg/unit activity) or (m^3/ unit activity).
$AF_{X\alpha}$	=	activity factor (AF) expressing the unit of an extra activity (Xα) used by the amount of aluminium alloy mass flow *in* (unit activity/ton alloy).
CI_τ	=	annualised capital cost due to the option τ in (k€/year) (Table 4.6).
I_τ	=	investment due to option τ *in* (k€) (Table 4.6).
r	=	interest rate *in* (fraction/year) (r=0.07) (USEPA, 2002).
lt_τ	=	lifetime of reduction option τ *in* (years) (Table 4.6).
CO_τ	=	fixed costs for reduction option τ *in* (k€/year) (Table 4.6).
o_τ	=	fraction of investment indicating the fixed costs for reduction option τ *in* (fraction/year) (Table 4.6).

Box 4.1 (cont.) Description of parameters and variables present on equations 1 to 14.

$CV_{zerocase}$	=	variable costs for the situation zero case (i.e. no application of pollution reduction options) *in* (k€/year).
$AL_{p,zerocase}$	=	aluminium ingot mass entering process (p), for zero case (i.e. no application of pollution reduction options) *in* (ton/year).
P_{ing}	=	price of aluminium ingot *in* (k€/kg) (Table 4.7).
$Act_{\alpha,zerocase}$	=	activity rate (Act) expressing the use of an activity (α) for zero case *in* (unit activity/year) (Table 4.3).
$P_{\alpha_{ij}}$	=	price of activity α *in* (€/ unit activity) (Table 4.7).
CV	=	variable costs of all implemented pollution reduction options τ *in* (k€/year) (in Table 4.6 the variable costs for each individual reduction option are present).
$P_{X\alpha_{ij}}$	=	price of extra activity Xα *in* (€/ unit activity) (Table 4.7).
C	=	total annual costs *in* (k€/year).
C_{na}	=	net additional costs, expressing the difference in the costs for the implementation of one or more reduction options when subtracted the costs for zero case *in* (k€/year).

Equation 1 is generic and calculates the emission of a pollutant at each sub-process level (p_i). The equation is used for all the different types of emissions (air, liquid effluent and solid waste).

Emissions of the pollutants may result directly from the use of an activity (α) (such as natural gas), the alloy mass, or considered to be independent of the alloy mass flows (in the case of fuel use in internal transports).

Thus, the activity rate in each case is determined by: a) the use of an activity that is directly dependent of alloy mass (Equation 2a); b) the annual alloy mass consumption (Equation 2b) or c) the annual use of a certain activity considered independent of alloy mass (Equation 2c).

In Equation 2a the activity rate is the use of a certain activity function of the alloy mass flow. This equation allows for the calculations of emissions to air, non related alloy solid wastes and liquid effluents with exception to: a) to air emissions of metals and alloy related solid wastes (such as aluminium dross) and, b) emissions resulting from Internal Transports and Auxiliary burners.

Equation 2b calculates the amount of metal pollutants or metal related solid wastes (x) emitted from sub-process (p_i). The metal emissions are originated on alloy inputs in each sub-sub-process. Therefore, the emissions of, for instance, aluminium, in sub-process Melting, refers to the amount of alloy entering this sub-process.

In Equation 2c the activity rate refers to the use of an activity (fuel use), that is used in the sub-processes 4) Internal Transport and 5) Auxiliary Burners. These are, as described above, independent of the production rate. The equation allows for the calculation of emissions of combustion.

In this case the same pollutant is released in different sub-processes and the total amount is summed up within different sub-processes. The overall emission from the process p is calculated by equation 3, where the emission of pollutant (x) is calculated as a result of the sum of all emissions in all sub-processes.

The impact assessment methodology used follows three steps, in line with current approaches in Life Cycle Assessment and Multi-Criteria Analysis (Pennington et al., 2004): 1) Characterisation (Guinée, 2002) 2) Normalisation (Huibregts et al., 2003) and 3) Weighting (or Valuation) (Kortman et al., 1994, Goedkoop, 1995 and Kamp, 2005).

The potential environmental impacts are assessed for the depletion of natural resources, emissions, solid waste and liquid effluents resulting from the industrial plant. The potential environmental impact categories (z) are: the human toxicity, terrestrial ecotoxicity, global warming, acidification, photochemical ozone formation, abiotic depletion, aquatic toxicity and solid waste production.

Equation 4 calculates the overall potential environmental impact of sub-process (p_i) using Characterisation Factors (CF), Normalisation Factors (NF) and Weighting Factors (WF).

Equation 5 presents the calculation of the overall potential environmental impact (M). It results in the sum of potential environmental impacts for each sub-process (p_i).

The calculation of the impact (Mz) related with the environmental impact category (z) for the sub-process (p_i) is derived from equation 4.

The model formulated in equations 1 to 5 reflects the zero case, describing the current industrial process operation, assuming that no pollution reduction options are implemented. Nevertheless, MIKADO is designed in such a way that pollution reduction options can be added to analyse the reduction in the amount of pollutants released. The model user interface allows for selecting or de-selecting options. In Table 4.2 an overview of the reduction options by sub-sub-processes is given. Reduction options can either be an add-on technique added to the process, a different technique or a change in process operation. Within the types of options the individual reduction options are considered mutually exclusive. The pollution reduction options aims for pollution reduction at the specific sub-sub-process (p_{ij}) where they are located, but it may have an effect on the emissions reduction at another sub-process level.

Table 4.2. Overview of pollution reduction options for an aluminium pressure die casting plant. See Chapter 3 (section 3.3.3.) for a detailed description of the reduction options.

sub-process (p_i)	sub-sub-process (p_{ij})	Types of Options	Reduction Options (τ)	Abbreviation	Compounds reduced
Melting (i=1)	Melting	Filters and scrubbers	Fabric Filter. Reverse-air type [a)]	Melting_FF_RA	Heavy metals such as Cd, Ni, Pb, Cr
			Fabric Filter. Pulse-Jet type [b)]	Melting_FF_PJ	Heavy metals such as Cd, Ni, Pb, Cr
			Fabric Filter. Mechanical Shaker type [c)]	Melting_FF_MS	Heavy metals such as Cd, Ni, Pb, Cr
			Wet Scrubber. Impingement-Plate type [d)]	Melting_WS_IP	Heavy metals (Cd, Ni, Pb, Cr), Cu and HF
			Wet scrubber. Spray-chamber type [e)]	Melting_WS_SC	Heavy metals (Cd, Ni, Pb, Cr), Cu and HF and NMVOC.
		Alternative desoxidation agent	Granular desoxidation agent [f)]	Melting_GA	HF, Aluminium dross.
		Alternative degassing technique	Impeller station using N_2[f), k)]	Melting_IS	HF, Aluminium dross.
		Alternative metal loading in furnaces	Compact metal loading in furnaces [g)]	Melting_CM	CO_2, CO, NOx, and NMVOC (Natural gas combustion related emissions).
		Combustion process modification	Air enrichment with oxygen (30%O_2) [g)]	Melting_AE	CO_2, CO, NOx, and NMVOC (Natural gas combustion related emissions).
			Oxyfuel firing (100%O_2)[g)]	Melting_OF	CO_2, CO, NOx, and NMVOC (Natural gas combustion related emissions).
Casting (i=2)	Pressure die casting	Scrubbers	Wet Scrubber. Packed-Bed type [h)]	Casting_WS_PB	Heavy metals (Pb, Cr), Cu, Zn, NMVOC
			Wet scrubber. Spray-chamber type [e)]	Casting_WS_SC	Heavy metals (Pb, Cr), Cu, Zn, NMVOC.
		Alternative to mould release agent application	New mould release agent [g)]	Casting_nMA	NMVOC, liquid effluent, oils, grease and sludge.
			Powder agent [i), k)]	Casting_PA	NMVOC, liquid effluent, oils, grease and sludge.
		New die casting moulds	Reduce runners mass [j), *)]	Casting_rRR	Heavy metals (Cd, Ni, Pb, Cr), Cu, Zn, HF, CO_2, CO, NOx, and NMVOC, aluminium dross, oils, grease and sludge.
		Reduce scrap rate	Reduce scrap rate [k), *)]	Casting_rSR	Heavy metals (Cd, Ni, Pb, Cr), Cu, Zn, HF, CO_2, CO, NOx, and NMVOC, aluminium dross, oils, grease and sludge.
Finishing (i=3)	Trimming	Reduce scrap rate	Reduce scrap rate [k), *)]	Finishing_rSR	Heavy metals (Cd, Ni, Pb, Cr), Cu, Zn, HF, CO_2, CO, NOx, and NMVOC, aluminium dross, oils, grease and sludge.
Internal Transport (i=4)	Forklift Truck on Diesel (I and II) and LPG	Electrical equipment	Use electric forklift trucks [g)]	IT_eFL	CO_2, CO, NOx, and NMVOC, SO_2 and Particulates.

a) to e) and h) USEPA Air pollution control technology fact sheet. EPA-CICA Fact Sheet. USEPA (2002). a) EPA-452/F-03-026; b) EPA-452/F-03-025; c) EPA-452/F-03-024; d) EPA-452/F-03-012; e) EPA-452/F-03-016;. f) Brown (1999); g) Pedro (2005). Personal communication; h) EPA-452/F-03-015; i) Klüber (2005); j) INETI (2000); k) EIPPCB (2005).

*) These reduction options may change the value of the metal yield. Metal yield is defined as the ratio of production to molten alloy. These options either reduce the mass of runners in the die casting moulds or reduce the scrap rate in the sub-processes Casting and Finishing.

Equation 6 presents how the emissions of pollutants are calculated for each sub-process when an individual reduction option (τ) is implemented. Again equations 2a, 2b and 2c are used to calculate the specific emissions in terms of their dependency of the production rate or the alloy mass. The equation is also valid when two or more reduction options are implemented. Within the same sub-process the emission of pollutant (x) may change due to changes in the reduction factor, or activity rate, or emissions factor, or a combination of these three.

In some cases a reduction option introduces an extra activity ($X\alpha$). For instance, the option Impeller station (Melting_IS) induces the use of the gas N_2. Equation 7 is generally used to calculate the pollutants emitted but the extra activity may be calculated differently. On the one hand, the extra activity may be induced by the use of a new activity that depends on the production rate (then equation 8a is used) or for the case when the extra activity is mainly due to the alloy mass flow, as in the case where an add-on technique is implemented (this leads to the production of an extra activity like for instance, the dust collected from bag houses or the sludge formed when wet scrubbers are implemented). Equation 8b calculates the extra activity rate for that case.

The implementation of each individual reduction has an associated cost. The costs are calculated including fixed costs (equipment investments and the fixed operational costs) and the variable costs as (the costs of equipment operation). The costs are calculated in equations 9 to 14.

The costs are regarded as additional costs for emission abatement options (in line with Geldermann and Rentz, 2004). The fixed costs of individual reduction options are calculated using equations 9 and 10. Equation 9 calculates the total annual investment cost, taking into account the interest rate (r) and equipment lifetime (lt). Equation 10 calculates the fixed operational costs as a fraction (o_τ) of investment. The parameters in these equations are provided for all reduction options.

Operational costs for the die casting production line are directly dependent on the aluminium alloy mass inputs, with the exception of the internal transports and auxiliary burners, for which the operational costs depend on the activity – fuel use. Nevertheless, in both situations the operational costs are calculated using the activity level (α), a potential use of an extra activity ($X\alpha$) and the activity's unit price (P). That makes the cost calculation analogous to the materials and energy uses and also similar to emission calculations.

A distinction is made for the zero case and the situation for which one or more reduction options are used. Equation 11 presents how the operational costs are calculated for the zero case. The quantification of total operational costs, as stated before, is not aimed at. Only the costs of aluminium ingot, materials and energy uses that may change by a reduction option are calculated. For sub-processes Internal Transports and Auxiliary Burners, the operational costs for the zero case are a function of the activity rate (fuels used) and the fuel unit price.

Equation 12 is used when one or more reduction options are implemented. Simultaneously, the operational costs for combined options result from the sum of activities and extra activities multiplied by the respective unit price. Equation 13 shows how the total costs are calculated for the implementation of one or more reduction options at the firm level. Equation 14 calculates the net additional costs (C_{na}) resulting from the implementation of one or more reduction options. Total costs of relevant inputs for the situation zero case equals the operational costs in the zero case $(C_{zerocase} = CV_{zerocase})$.

4.3. Model parameters and activities of the aluminium die casting plant

The model described above contains a number of parameters that need to be quantified. The Portuguese industrial plant provided information about the production process and specific annual data of process inputs and outputs, such as materials, energy, emissions, liquid effluents, and waste production. Also other information used in the model, such as alloy mass flows and recycling was readily available from this company. Missing data were either estimated from the literature based on expert judgement, or based on information provided by industrial suppliers.

This section presents the values used in the description of the die casting process, as used in the model. These values include the activity rates, emission factors, reduction factors and extra activity rates, investments and variable costs and the factors (characterisation, normalisation and weighting factors) used on the environmental impact assessment. During MIKADO runs, the user might change these parameters to values that better describe the processes in another company.

4.3.1. Activity data

Since the model is driven by the production rate, the core of the model is formed by the aluminium alloy mass flow throughout the production line. A closer look into the connections of the sub-sub-processes within the die casting production line (Figure 4.1), reveals a number of additional aluminium flows between the different sub-processes. The Casting sub-process leads to raw products that are still connected to the biscuits and runners. These are the channels through which the molten aluminium is transported into the die casting moulds. After casting, the raw products are separated from the biscuits and runners and the alloy in these biscuit and runners is recycled back into the Melting sub-process. The mass in the biscuits and runners is of the same order of magnitude as the mass in the raw products. In addition, a small part of the products resulting from the sub-processes Casting and Finishing are discarded because of non-compliance with client or internal specifications. These are also fed back into the Melting sub-process. The activity data related with the alloy mass flow is previously referred above in section 4.2.2. .

The remaining activity data concerning the use of subsidiary materials and energy are derived from the plant's raw data. The activity rates (Act_{α}) are presented by sub-sub-process level (p_{ij}). For the aluminium production line, the activities are calculated in terms of alloy mass inflow for each sub-process on an annual basis (Table 4.3 and Box 4.1). In the other cases where the activity rates (Act_{α}) are considered to be independent from the production rate, such as in the sub-processes Internal Transports, Auxiliary Burners (Table 4.3 and Box 4.1), they refer to the annual fuel consumption.

Table 4.3 summarises the annual activity characteristics of each sub-process for MIKADO. The activity factors are easily converted from the company raw data after knowing the aluminium alloy losses at the sub-process level. These activity factors (AF_α) are expressed in terms of the tonnage of aluminium alloy mass inputs per year into each sub-process. The activity rates (Act_α) are reported by the facility or derived by the activity factors, by knowing the alloy entering each sub-process.

Table 4.3. Activity Factors (AF) and Activity rates (Act) for each type of activity (α) by sub-sub-process (p_{ij}) for the calculation of emissions from an aluminium die casting plant. The activity factors refer to the tonnage of molten alloy used in each sub-sub-process.

sub-process (p_i)	sub-sub-process (p_{ij})	α	$AF_{\alpha_{ij}}$	$Act_{\alpha_{ij}}$	unit
Melting	Melting	Desoxidation Agent	1.033	---	kg/ton alloy
		Degassing Flux	0.138	---	kg/ton alloy
		Natural gas	5.170 [a)]	---	GJ/ton alloy
Casting	Holding Furnaces	Ceramic lining	0.249	---	kg/ton alloy
	Pressure Die Casting	Mould release agent	10.50	---	liters/ton alloy
		Water	1.03 [b)]	---	m^3/ton alloy
		Hydraulic oil	8.56	---	liters/ton alloy
		Tip lubricant	1.20	---	liters/ton alloy
		Other Oils	2.77	---	liters/ton alloy
		Antifoam	0.037 [c)]	---	liters/ton alloy
		Sodium hydroxide	0.025 [c)]	---	liters/ton alloy
		Polyelectrolyte	0.020 [c)]	---	liters/ton alloy
		Flocculation agent	0.25 [c)]	---	liters/ton alloy
Finishing	Surface Treatment – Shot Blasting	Steel Shot	4.95	---	kg/ton alloy
	Surface Treatment – Tumbling	Water	0.000322 [b)]	---	m^3/ton alloy
		Ceramic abrasives	7.68	---	kg/ton alloy
		Splitting agent	0.38 [c)]	---	kg/ton alloy
	Cleaning and Degreasing	Water	0.0075	---	m^3/ton alloy
		Detergent	0.053 [d)]	---	liters/ton alloy
		Antifoam	0.000342 [c)]	---	liters/ton alloy
		Sodium hydroxide	0.000243 [c)]	---	liters/ton alloy
		Polyelectrolyte	0.000197 [c)]	---	liters/ton alloy
		Flocculation agent	0.003 [c)]	---	liters/ton alloy
Internal Transport	Fork lift trucks on Diesel (I and II)	Diesel I	---	18304	kg/year
		Diesel II	---	10610	kg/year
	Fork lift trucks on LPG	LPG	---	17680	liters/year
Auxiliary Burners	Oxyacetylene burners	Acetylene	---	119	kg/year
		Oxygen	---	366	kg/year
	Butane burners	Butane	---	968	kg/year

a) Implied activity factor; in the model the gas consumption is calculated based on heat needed to melt the alloy and the furnace thermal efficiency. (Heat of combustion=39.96 MJ/m^3, from Transgás (2005). Personal communication).
b) Implied activity factor; the model includes a mass balance for water.
c) Implied activity factor; in the model the emissions are calculated as a fraction of liquid effluent, which in turn is a fraction of ton alloy.
d) Implied activity factor; in the model the detergent consumption is calculated as a fraction of water use, which in turn is a fraction of ton alloy.

4.3.2. Emission factors

The emission factor describes the relation between the activity rate and the emission for a specific pollutant. Emission factors are calculated from annual activity rates for each sub-process. There are different ways to quantify emissions. These include direct measurements, mass balance calculations, process based modelling and the emission factor approach (Frey and Small, 2003). The emission factor approach is the simplest one and typically used in environmental studies of economic sectors (e.g. Pluimers, 2001; Winiwarter and Schimak, 2005) or by country (e.g. IPCC Guidelines, 1997; Zárate et al., 2000). The emission factor calculation performed here differs in scope in terms of process and location from the literature investigated. The emission factors presented in this chapter are process specific and are mainly derived from average emission measurements carried out at the facility in combination with the known alloy flows, energy consumption and the use of subsidiary materials. When no measures were available, emission factors were then estimated based on mass balance calculations, specific literature data or provided by suppliers. The company's suppliers made materials characteristics available. The emission factors for each sub-sub-process are presented in Table 4.4.

Table 4.4. Emission Factors (EF) by sub-process (p_{ij}) referred to the tonnage of molten alloy used in each sub-sub-process. For sub-processes Internal Transport and Auxiliary Burners, EF is referred to the annual fuel use. Assuming no reduction options implemented.

sub-process (p_i)	**sub-sub-process** (p_{ij})	**Pollutant** (x)	$EF_{ij,\alpha_{ij},x}$	**Emission Factor Units**
Melting	Melting	✓ Aluminium	0.3945 [a]	kg / ton molten alloy
		✓ Cadmium	0.000196 [a]	kg / ton molten alloy
		✓ Nickel	0.000151 [a]	kg / ton molten alloy
		✓ Lead	0.000947 [a]	kg / ton molten alloy
		✓ Chromium	0.000124 [a]	kg / ton molten alloy
		✓ Copper	0.00168 [a]	kg / ton molten alloy
		✓ Hydrogen Fluoride	0.0534 [b]	kg / kg degassing flux
		✓ Hydrogen Fluoride	0.224 [b]	kg/kg desoxidation agent
		✓ Aluminium dross	0.949 [c]	kg / kg degassing flux
		✓ Aluminium dross	0.788 [c]	kg/kg desoxidation agent
		✓ CO	30.03 [d]	g/GJ
		✓ CO_2	65.11 [d]	kg/GJ
		✓ NO_x	186 [d]	g/GJ
		✓ NMVOC	2.1 [d]	g/GJ
Casting	Holding Furnaces	✓ Aluminium	0.00489 [a]	kg/ton casted alloy
		✓ Zinc	0.00763 [a]	kg/ton casted alloy
		✓ Lead	0.000611 [a]	kg/ton casted alloy
		✓ Chromium	0.000458 [a]	kg/ton casted alloy
		✓ Copper	0.00366 [a]	kg/ton casted alloy
		✓ Iron	0.0370 [a]	kg/ton casted alloy
		✓ Ceramic lining wasted	0.237 [e]	kg/ton casted alloy
	Pressure Die Casting	✓ NMVOC	0.00892 [a]	kg/l mould release agent
		✓ Liquid effluent	0.76 [f]	m³ / ton alloy
		✓ Sludge	7	kg/ton casted alloy
		✓ Oils and grease	5	kg/ton casted alloy
Finishing	Surface Treatment – Shot Blasting	✓ Steel Shot	0.27 [e]	kg/kg steel shot
	Surface Treatment – Tumbling	✓ Ceramic abrasives	0.43 [e]	kg/kg ceramic abrasives
		✓ Liquid effluent	0.000064 [f]	m³ / ton alloy
		✓ Sludge	0.07	kg/ton alloy
	Cleaning and Degreasing	✓ Liquid effluent	0.0074 [f]	m³ / ton alloy
		✓ Sludge	0.07	kg/ton alloy
		✓ Oils and grease	0.05	kg/ton alloy
Internal Transport	Fork lift trucks on Diesel (I)	✓ CO_2	76.92 [g]	kg/GJ
		✓ NO_x	0.54 [g]	kg/GJ
		✓ CO	0.08 [g]	kg/GJ
		✓ Particulates	0.01 [g]	kg/GJ
		✓ SO_2	0.11 [g]	kg/GJ
		✓ NMVOC	0.03 [g]	kg/GJ
	Fork lift trucks on Diesel (II)	✓ CO_2	95.69 [g]	kg/GJ
		✓ NO_x	0.64 [g]	kg/GJ
		✓ CO	0.15 [g]	kg/GJ
		✓ Particulates	0.02 [g]	kg/GJ
		✓ SO_2	0.13 [g]	kg/GJ
		✓ NMVOC	0.07 [g]	kg/GJ
	Fork lift trucks on LPG	✓ CO_2	67.48 [g]	kg/GJ
		✓ NO_x	1.67 [g]	kg/GJ
		✓ CO	0.02 [g]	kg/GJ
		✓ NMVOC	0.02 [g]	kg/GJ
Auxiliary Burners	Oxyacetylene burners	✓ CO_2	67.80 [h]	kg/GJ
	Butane burners	✓ CO_2	65.41 [i]	kg/GJ
		✓ NO_x	0.0688 [i]	kg/GJ
		✓ CO	0.0096 [i]	kg/GJ
		✓ NMVOC	0.0027 [i]	kg/GJ
		✓ Particulates	0.0027 [i]	kg/GJ

a) Emissions to air. Emission factor derived from annual average pollutant concentrations (mg/m³) measured at the industrial plant. Pedro (2005). Personal communication.
b) Emission to air. Emission factor derived from fluorine contents of desoxidation agent and degassing flux. Pedro (2005). Personal communication
c) Solid waste. Emission factor derived from the composition of desoxidation agent and degassing flux used. Pedro (2005). Personal communication
d) Emission to air. Average value for emission factor related with natural gas use, derived from range present. EMEP/CORINAIR (2004).
e) Solid waste. Emission factor from EIPPCB (2005).
f) Liquid effluent. Implied emission factor; the model includes a mass balance for water. The emission factor is derived from annual water consumption and losses at the industrial plant. Pedro (2005). Personal communication.
g) Emissions to air. Emission factor made available from Salvador Caetano, S.A and the annual forklift workinh hours. Monteiro (2004). Personal communication.
h) Emission to air. Emission factor derived from annual acetylene consumption. Pedro (2005). Personal communication.
i) Emission to air. Emission factor related with butane use. Pedro (2005). Personal communication.

4.3.3. Reduction Factors and Extra Activities

The implementation of reduction options leads to a decrease in the pollution. Several reduction options were defined for the die casting plant; they are process specific and were proposed by industrial facility managers or found in specialised literature. Table 4.2 (section 4.2.2.) gives an overview of the 18 pollution prevention options included in our model. These reduction options are either add-on technologies, the replacement of an existing technique or a change in process operation. These reduction options reduce the original emission factors, change the activity rates (such as: energy consumption) or in the case of add-on technologies, might add a reduction factor responsible for the pollution abatement.

When add-on technologies are used, the reduction factors of one or more pollutants are well known and available in literature. Table 4.5 includes the values of reduction factors (RF) per reduction option using an add-on technology. In addition, the reduction options may also influence the activity rate itself either by altering the amount of materials or energy used or by introducing an extra activity in the industrial process or through a combination of both situations. Table 4.5 also includes the changes in the activity rates (Act_{α}) and extra activity rates ($Act_{X\alpha}$) relative to the zero case when an individual reduction option (τ) is implemented. The table only presents the activities and extra activities affected by each individual reduction option.

Table 4.5. Reduction factors ($RF_{x,\tau}$), reduction in activity rates (Act_{α}) and extra activity rates ($Act_{X\alpha}$) caused by reduction options. See Chapter 3 (section 3.3.3.) for a detailed description of the reduction options.

	Reduction factor ($RF_{x,\tau}$)										**Reduction in activity rates (Act_{α})**				
Reduction Options (τ)	x = Al	x=Cd	x=Ni	x=Pb	x=Cr	x =Cu	x=HF	x =NMVOC	x=Zn	x=Fe	α=desoxidation agent	α=degassing flux	α=natural gas	α=mould release agent	α=water
Melting_FF_RA a)	99.9%	99%	99%	99%	99%	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.
Melting_FF_PJ b)	99.9%	99%	99%	99%	99%	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.
Melting_FF_MS c)	99.9%	99%	99%	99%	99%	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.
Melting_WS_IP d)	99%	99%	99%	99%	99%	99%	99%	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.
Melting_WS_SC e)	99%	99%	99%	99%	99%	99%	99%	95%	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.
Melting_GA	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	100% h)	n.e.	n.e.	n.e.	n.e.
Melting_IS	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	100% h)	n.e.	n.e.	n.e.
Melting_CM	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	58% k)	n.e.	n.e.
Melting_AE	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	2% l)	n.e.	n.e.
Melting_OF	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	4% l)	n.e.	n.e.
Casting_WS_PB f)	95%	n.e.	n.e.	95%	95%	95%	n.e.	99%	95%	95%	n.e.	n.e.	n.e.	n.e.	n.e.
Casting_WS_SC e)	99%	n.e.	n.e.	99%	99%	99%	n.e.	95%	99%	99%	n.e.	n.e.	n.e.	n.e.	n.e.
Casting_nMA	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	100% h)	n.e.
Casting_PA	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	100% h)	100% h)
Casting_rRR	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	16% p)	16% p)	16% p)	16% p)	16% p)
Casting_rSR	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	5% p)	5% p)	5% p)	5% p)	5% p)
Finishing_rSR	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	5% q)	5% q)	5% q)	5% q)	5% q)
IT_eFL	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.

n.e. = no effect.

a) to f) from USEPA (2002): a) EPA-452/F-03-026. b) EPA-452/F-03-025. c) EPA-452/F-03-024. d) EPA-452/F-03-012. e) EPA-452/F-03-016. f) EPA-452/F-03-015.

g) Estimated based on the amount of avoided air emissions.

h) Assuming a full replacement of the agents currently used. Melting_GA: use of a granular agent replacing the currently used. Melting_IS: use of gas N2, replacing the solid agent. Casting_nMA: use of alternative mould release agent. Casting_PA: replace the liquid agent and water by a solid powder mould release agent. IT_eFL: use of electric forklift trucks replacing the fuelled (Diesel and LPG) currently used.

i) Estimated from Foseco (2002). Personal communication.

j) Estimated from Brown (1999) and EIPPCB (2005).

k) "Estimated" based on the average furnace thermal efficiency for the type of furnace used in the plant. From EIPPCB (2005).

l) "Estimated" based on the latent heat present in the exhaust gases.

n) "Estimated" based on the reduction of natural gas use reported to the plant unabated situation.

o) "Estimated" based on the reduction of mould release agent use reported to the plant unabated situation.

p) "Estimated" based on use reported to the number of die casting shots produced annually by the company and the indication from product use from Klüber (2005).

q) "Estimated" based on the reduction of the aluminium alloy that is recycled internally. This option affects the materials and energy used on the sub-processes Melting and Casting.

r) "Estimated" based on the reduction of the aluminium alloy that is recycled internally. This option affects the materials and energy used on the sub-processes Melting, Casting and Finishing.

Table 4.5. (cont.)

Reduction Options (τ)	Reduction in activity rates (Act_α)						Extra activity rates ($Act_{X\alpha}$) caused by reduction options					
	α= hydraulic oil, tip lubricant and other oils	α=steel shot	α=ceramic abrasives	α=detegent	α= diesel	α= LPG	Xα= waste to disposal	Xα=granular agnet	Xα= gas N_2	Xα=oxygen	Xα= new mould release agent	Xα= powder agent
Melting_FF_RA [a]	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	2.5 ton/yr [g]	n.e.	n.e.	n.e.	n.e.	n.e.
Melting_FF_PJ [b]	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	2.5 ton/yr [g]	n.e.	n.e.	n.e.	n.e.	n.e.
Melting_FF_MS [c]	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	2.5 ton/yr [g]	n.e.	n.e.	n.e.	n.e.	n.e.
Melting_WS_IP [d]	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	4 ton/yr [g]	n.e.	n.e.	n.e.	n.e.	n.e.
Melting_WS_SC [e]	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	4 ton/yr [g]	n.e.	n.e.	n.e.	n.e.	n.e.
Melting_GA	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	6400 kg/yr [i]	n.e.	n.e.	n.e.	n.e.
Melting_IS	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	403 m^3/yr [j]	n.e.	n.e.	n.e.
Melting_CM	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.
Melting_AE	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	4.8E+05 m^3/yr [m]	n.e.	n.e.
Melting_OF	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	1.6E+06 m^3/yr [m]	n.e.	n.e.
Casting_WS_PB [f]	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	0.5 ton/yr [g]	n.e.	n.e.	n.e.	n.e.	n.e.
Casting_WS_SC [e]	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	0.5 ton/yr [g]	n.e.	n.e.	n.e.	n.e.	n.e.
Casting_nMA	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	28 m^3/yr [n]	n.e.
Casting_PA	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	4020 kg/yr [o]
Casting_rRR	16% [p]	16% [p]	16% [p]	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.
Casting_rSR	5% [p]	5% [p]	5% [p]	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.
Finishing_rSR	5% [q]	5% [q]	5% [q]	5% [q]	5% [q]	5% [q]	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.
IT_eFL	n.e.	n.e.	n.e.	n.e.	100% [h]	100% [h]	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.

n.e. = no effect.
a) to f) from USEPA (2002): a) EPA-452/F-03-026. b) EPA-452/F-03-025. c) EPA-452/F-03-024. d) EPA-452/F-03-012. e) EPA-452/F-03-016. f) EPA-452/F-03-015.
g) Estimated based on the amount of avoided air emissions.
h) Assuming a full replacement of the agents currently used. Melting_GA: use of a granular agent replacing the currently used. Melting_IS: use of gas N2, replacing the solid agent. Casting_nMA: use of alternative mould release agent. Casting_PA: replace the liquid agent and water by a solid powder mould release agent. IT_eFL: use of electric forklift trucks replacing the fuelled (Diesel and LPG) currently used.
i) Estimated from Foseco (2002). Personal communication.
j) Estimated from Brown (1999) and EIPPCB (2005).
k) "Estimated" based on the average furnace thermal efficiency for the type of furnace used in the plant. From EIPPCB (2005).
l) "Estimated" based on the latent heat present in the exhaust gases.
n) "Estimated" based on the reduction of natural gas use reported to the plant unabated situation.
o) "Estimated" based on the reduction of mould release agent use reported to the plant unabated situation.
p) "Estimated" based on use reported to the number of die casting shots produced annually by the company and the indication from product use from Klüber (2005).
q) "Estimated" based on the reduction of the aluminium alloy that is recycled internally. This option affects the materials and energy used on the sub-processes Melting and Casting.
r) "Estimated" based on the reduction of the aluminium alloy that is recycled internally. This option affects the materials and energy used on the sub-processes Melting, Casting and Finishing.

4.3.4. Investments and Variable Costs

The total annual costs (C) (Equation 13 of Box 4.1) are calculated based on fixed and variable costs. When a reduction option is used, investments are needed. The total annual fixed costs are calculated by two components: the investment costs and the fixed operational costs. Variable costs are related to materials and energy uses and to the production rate. Table 4.6 shows an overview of cost-related parameters per reduction option. Table 4.7 summarises the unit prices for the activity data.

Table 4.6. Cost parameters (I, l_t, o_j) used for the calculation of the overall annual fixed costs (CI+CO). Model results for the variable costs (CV). These fixed and variable costs of reduction options are applicable to the die casting facility. The variable cost for zero case ($CV_{zerocase}$) is 5315 k€/year. See Chapter 3 (section 3.3.3.) for a detailed description of the reduction options.

Reduction Options (τ)	**Investment (I) in (k€)**	**Lifetime (lt) in (years)**	**Annualised Capital Cost (CI) [m] in (k€/year)**	**Fraction of investments (o_τ) [n] in (fraction/year)**	**Fixed cost (CO) [o] in (k€/year)**	**Variable cost (CV) [p] in (k€/year)**
Fabric Filter. Reverse-air type	675 [a]	20 [a]	64	0.03	20	5315
Fabric Filter. Pulse-Jet type	206 [b]	20 [b]	19	0.03	6	5315
Fabric Filter. Mechanical Shaker type	574 [c]	20 [c]	54	0.03	17	5315
Wet Scrubber. Impingement-Plate type	86 [d]	15 [d]	9	0.03	3	5316
Wet scrubber. Spray-chamber type	49 [e]	15 [e]	5	0.03	1	5316
Granular desoxidation agent	0	0	0	0	0	5315
Impeller station using N_2	55 [f]	10 [l]	8	0.03	2	5364
Compact metal loading in furnaces	140 [g]	10 [l]	20	0.04	6	5162
Air enrichment with oxygen (30%O_2)	0	0	0	0	0	5374
Oxyfuel firing (100%O_2)	170 [h]	10 [l]	24	0.03	5	5510
Wet Scrubber. Packed-Bed type	1396 [i]	15 [i]	153	0.03	42	5315
Wet scrubber. Spray-chamber type	155 [e]	15 [e]	17	0.03	5	5315
New mould release agent	0	0	0	0	0	5257
Powder agent	220 [j]	10 [l]	31	0.04	9	5421
Reduce runners' mass	1140 [k]	10 [l]	162	0.04	46	5226
Reduce scrap rate	0	0	0	0	0	5285
Reduce scrap rate	0	0	0	0	0	5279
Use electric forklift trucks	57 [g]	10 [l]	8	0.02	1	5267

a) to e) and i) USEPA Air pollution control technology fact sheet - EPA-CICA Fact Sheet. a) EPA-452/F-03-026; b) EPA-452/F-03-025; c) EPA-452/F-03-024; d) EPA-452/F-03-012; e) EPA-452/F-03-016; i) EPA-452/F-03-015.
f) EIPPCB (2005).
g) Pedro (2005). Personal communication.
h) Praxair (2005). Personal communication.
j) Klüber (2005); k) INETI (2000); l) Assumed to be 10 years; m) The annualised capital costs (CI) is calculated by Equation 9 (see Box 4.1).
n) USEPA (2002) and Klimont et al. (2002).
o) The fixed cost (CO) is calculated by equation 10 (see Box 4.1).
p) The variable costs (CV) is calculated by equation 12 (see Box 4.1), and include costs of all relevant inputs (5315 k€/year in the zero case).

Table 4.7. Price of aluminium ingot, activities (P_{α}) and extra-activites ($P_{X\alpha}$). The aluminium die casting plant provided the prices presented for the zero case. The prices for material use on the reduction options were in some cases provided by the case plant but mostly provided by the die casting industry suppliers.

Parameter	**Price**	**unit**	**References**
Aluminium ingot	1.54	€/kg	Pedro (2005). Personal communication.
Antifoam	2.1	€/liter	Pedro (2005). Personal communication.
Ceramic abrasives	1.02	€/kg	Pedro (2005). Personal communication.
Degassing Flux	2.8	€/kg	Pedro (2005). Personal communication.
Desoxidation Agent	1.32	€/kg	Pedro (2005). Personal communication.
Detergent	1.86	€/liter	Pedro (2005). Personal communication.
Diesel	0.91	€/liter	GALP (2004). Personal communication.
Flocculation agent	0.25	€/liter	Pedro (2005). Personal communication.
Gas N_2	127	€/m^3	Praxair (2005). Personal communication.
Granular agent	1.3	€/kg	Foseco (2005). Personal communication
Hydraulic oil	1.05	€/liter	Pedro (2005). Personal communication.
LPG	1.23	€/kg	GALP, 2004. Personal communication.
Mould release agent	1.53	€/liter	Pedro (2005). Personal communication.
Natural gas	0.33	€/m^3	Pedro (2005). Personal communication.
New mould release agent	1.7	€/liter	Pedro (2005). Personal communication.
Other Oils	0.74	€/liter	Pedro (2005). Personal communication. Average value of three different oils used in the die casting machines.
Oxygen	0.13	€/m^3	Praxair (2005). Personal communication.
Polyelectrolyte	2.84	€/liter	Pedro (2005). Personal communication.
Powder agent	55	€/kg	Klüber (2005). Personal communication.
Sodium hydroxide	0.17	€/liter	Pedro (2005). Personal communication.
Splitting agent	3.37	€/kg	Pedro (2005). Personal communication.
Steel Shot	0.59	€/kg	Pedro (2005). Personal communication.
Tip lubricant	1.37	€/liter	Pedro (2005). Personal communication.
Waste to disposal (dust)	200	€/ton	Pedro (2005). Personal communication.
Waste to disposal (aluminium dross)	37	€/ton	Pedro (2005). Personal communication.
Waste to disposal (oils ands grease)	51	€/ton	Pedro (2005). Personal communication.
Waste to disposal (sludge)	220	€/ton	Pedro (2005). Personal communication.
Water	1.5	€/m^3	Pedro (2005). Personal communication.

4.3.5. Environmental impact assessment

Potential environmental impacts are assessed for depletion of natural resources, air emissions, solid wastes and liquid effluents resulting from the industrial plant. The potential environmental impact categories or environmental problems (z) resulting from the operation of the industrial process, include:

- Human toxicity
- Terrestrial ecotoxicity
- Global warming
- Acidification
- Photochemical ozone formation
- Abiotic depletion
- Aquatic toxicity
- Solid waste production.

For the environmental problem Abiotic depletion the consumption of natural gas is used as an indicator for the use of non-renewable resources. The impact category aquatic toxicity indicates the amount of liquid effluent produced by the company and solid waste is an indicator of the amount produced.

Following the current practice in Life Cycle Assessment and Multi-Criteria Analysis, the environmental impact assessment in MIKADO includes three steps (Pennington et al., 2004): 1) Characterisation, 2) Normalisation and 3) Weighting.

All emissions contributing to a specific environmental problem were aggregated in one single value by multiplication by a characterisation factor (CF). For the Characterisation step the methodology of Guinée (Guinée et al., 2002) was used. CF expresses the relative contribution of each pollutant to a specific environmental problem. Table 4.8 shows the CF used in the characterisation step. The emissions are quantified in kilograms 1.4 dichlorobenzene (DCB) for human toxicity and ecotoxicity, in kilograms of antimony for natural resources depletion, in kilograms CO_2 for global warming, in kilograms of SO_2 for acidification, in kilograms of ethylene for ozone precursors.

In the Normalisation step we divide the potential impact for each environmental problem (value from Characterisation) by the impact score for a reference situation. This way, the relative contribution of the process is related to a reference situation (region, country or the whole world). The normalisation factors (NF) applied here (see Equation 4 on Box 4.1) use the Western Europe 1995 as a reference situation (Huijbregts et al., 2003) (Table 4.9). Exceptions are the NF for ATP and SW; these values are developed from emissions from Western European territory in the period 1990-1994 (Blonk, 1997). For the NF for solid waste we choose the maximum value of the range by Blonk (1997).

Four different methods for the weighting were used: a) considering all environmental problems equally important, b) Panel method I (Kamp, 2005) c) Panel method II (Kortman et al., 1994) and d) Distance to target method (Goedkoop, 1995). In addition, the model user may define the set of valuation factors for each environmental problem. Table 4.10 lists the weighting factors used.

Table 4.8. Characterisation Factors (CF) per pollutant (x) for each environmental impact category (z).

Environmental impact category (z)	Pollutant (x)	CF a)	CF Units
Human Toxicity Potential (HTP inf) b)	NOx	1.20E+00	kg 1.4-DCB eq. / kg
	Particulates	8.20E-01	
	Cd	1.50E+05	
	Ni	3.50E+04	
	Pb	4.70E+02	
	Cr	3.40E+06	
	Cu	4.30E+03	
	Zn	1.00E+02	
	HF	2.90E+03	
	NMVOC	1.40E+04	
	SO_2	9.60E-02	
Abiotic Depletion Potential (ADP) Ultimate reserves and extraction rates	Natural gas	1.87E-02	kg antimony eq. / m^3
Global Warming Potential (GWP 100) c)	CO_2	1.00E+00	kg CO_2 eq. / kg
Acidification Potential Average Europe (AP Huijbregts, 1999; average Europe total, A&B)	NOx	5.00E-01	kg SO_2 eq. / kg
	SO_2	1.20E+00	
	HF	1.60E+00	
Ecotoxicity Potential terrestrial (ECP inf) d)	Cd	8.10E+01	kg 1.4-DCB eq. / kg
	Ni	1.20E+02	
	Pb	1.60E+01	
	Cr	3.00E+03	
	Cu	7.00E+00	
	Zn	1.20E+01	
	HF	2.90E-03	
	NMVOC	2.50E-03	
Photochemical ozone formation potential (POCP Jenkin & Hayman, 1999 and Derwent et al. 1998; high NOx)	CO	2.70E-02	kg ethylene eq. / kg
	NOx	2.80E-02	
	NMVOC	3.73E-01	
	SO_2	4.80E-02	
Aquatic toxicity (ATP)	*Not available*		
Solid waste (SW)	*Not available*		

a) See CML (2002).
b) HTP inf. (Time horizon infinite)
c) GWP100 (Time horizon = 100 years)
d) ECP inf. (Time horizon infinite)

Table 4.9. Normalisation Factors (NF) for Western Europe per environmental impact category (z). The reference situation is assumed to be Western Europe in 1995 (Huijbregts et al., 2003).

Environmental impact category (z)	**NFz**	**unit**
Human Toxicity Potential (HTP)	7.6E+12	1.4-DCB eq./yr
Abiotic Depletion Potential (ADP)	1.5E+10	kg antimony eq./yr
Global Warming Potential (GWP)	4.8E+12	kg CO_2 eq./yr
Solid waste (SW) [a)]	54E+10	kg/yr
Acidification Potential (AP)	2.0E+10	kg SO_2 eq./yr
Ecotoxicity Potential (ECP)	4.7E+10	1.4-DCB eq./yr
Photochemical Ozone Formation Potential (POCP)	8.2E+09	kg ethylene eq. /yr
Aquatic toxicity (ATP) [b)]	4.4E+14	m^3 aquatic ecotoxicity /yr

[a), b)] These values are developed for the reference situation : Western European territory in the period 1990-1994 (Blonk, 1997).

[a)] The NF for solid waste was assumed to be the maximum value in the range (9.7– $54*10^{10}$) (Blonk, 1997).

Table 4.10. Weighting Factors (WF) used in Impact Assessment.

Valuation method used in Impact Assessment	
• **All problems equally important**	
Environmental impact category (z)	WFz
Human Toxicity Potential (HTP)	0.125
Ecotoxicity Potential (ECP)	0.125
Global Warming Potential (GWP)	0.125
Acidification Potential (AP)	0.125
Photochemical ozone formation potential (POCP)	0.125
Abiotic Depletion Potential (ADP)	0.125
Aquatic toxicity (ATP)	0.125
Solid waste to be dumped (SW)	0.125
• **Panel method I (Kamp, 2005)**	
Environmental impact category (z)	WFz
Human Toxicity Potential (HTP)	0.119 [a)]
Ecotoxicity Potential (ECP)	0.119
Global Warming Potential (GWP)	0.154
Acidification Potential (AP)	0.130
Photochemical ozone formation potential (POCP)	0.097
Abiotic Depletion Potential (ADP)	0.143
Aquatic toxicity (ATP)	0.121
Solid waste to be dumped (SW)	0.119 [a)]
a) Assumed to be equal to ECP	
• **Panel method II (Kortman et al., 1994)**	
Environmental impact category (z)	WFz
Human Toxicity Potential (HTP)	0.117
Ecotoxicity Potential (ECP)	0.135
Global Warming Potential (GWP)	0.164
Acidification Potential (AP)	0.120
Photochemical ozone formation potential (POCP)	0.042 [a)]
Abiotic Depletion Potential (ADP)	0.152 [b)]
Aquatic toxicity (ATP)	0.135 [c)]
Solid waste to be dumped (SW)	0.135 [c)]
a) Derived from Seppälä (Seppälä et al., 2002). Express the relation between the values of POCP and GWP in both valuation methods. b) Derived from Panel Method I (Kamp, 2005). Express the relation between the values of ADP and GWP in both valuation methods. c) Assumed to be equal to ECP	
• **Distance to target method (Goedkoop, 1995)**	
Environmental impact category (z)	WFz
Human Toxicity Potential (HTP)	0.118
Ecotoxicity Potential (ECP)	0.118
Global Warming Potential (GWP)	0.059
Acidification Potential (AP)	0.235
Photochemical Ozone Formation Potential (POCP)	0.118
Abiotic Depletion Potential (ADP)	0.118 [a)]
Aquatic toxicity (ATP)	0.118 [b)]
Solid waste to be dumped (SW)	0.118 [b)]
a) Assumed equal to most environmental problems b) Assumed to be equal to ECP	

4.4. Model Results and Sensitivity Analysis

In this section, we will present some model results to explore the model system. In the following chapter (Chapter 5) we will present more detailed analyses of strategies to reduce the environmental impact of aluminium die casting.

First, we analysed MIKADO results using the values of parameters as described in the previous sections. Figure 4.3 and Figure 4.4 present results for this *zero case*, assuming not only the use of previously defined values for parameters but also that no reduction options are implemented. Figure 4.3 shows the calculated environmental impacts for four different MCA approaches used, those differing in the valuation of the different environmental problems, while Figure 4.4 only shows results for the valuation method that assumed all environmental problems equally important.

The results indicate that the sub-process Melting is responsible for 51-54% of the overall environmental impact, and Casting for 39-42% (Figure 4.3). Thus these two processes alone contribute by over 90% to the environmental impact of the plant. The environmental impact of Melting and Casting is mostly associated with human toxicity problems caused by metal emissions and emissions of ozone precursors and the abiotic depletion of natural gas (Figure 4.4). We also conclude that the relative contributions of sub-processes (p_i) to the overall environmental impact (M) are similar for the four MCA approaches, indicating that the model for this case is not sensitive to the type of valuation method used.

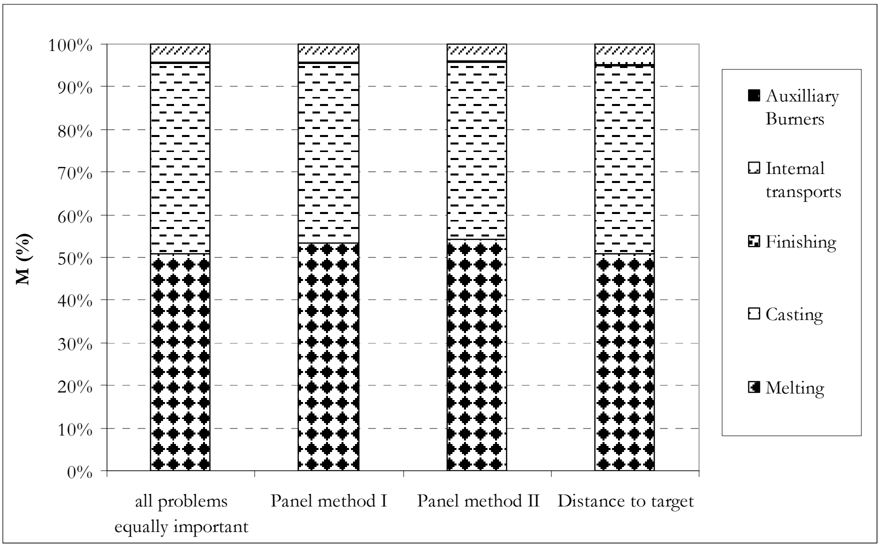

Figure 4.3. The contribution (%) of each sub-process of an aluminium die casting plant to the overall environmental impact (M) for four Multi-Criteria Analysis (MCA) approaches taking different valuation methods: All problems equally important, Panel Method I (Kamp, 2005), Panel Method II (Kortman et al., 1994), Distance to target (Goedkoop, 1995). (unit: % relative to the M).

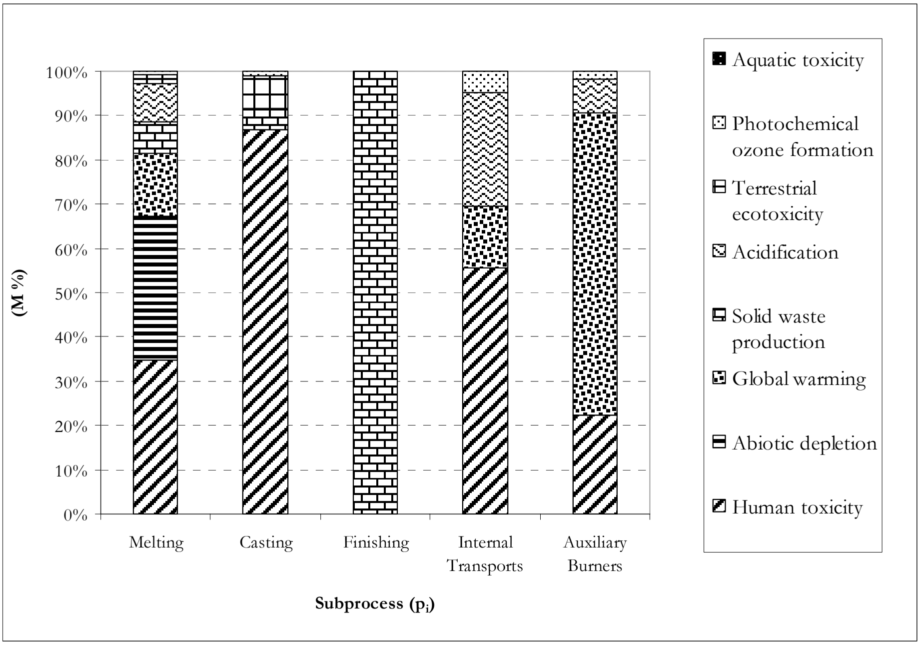

Figure 4.4. The relative contribution of sub-process (p_i) to different environmental problems (using the valuation method that considers all problems equally important), and assuming no implementation of reduction options (unit: % relative to the M).

Next, a partial sensitivity analysis was performed to test the sensitivity of the model results to changes in parameter values. This is done in several sets of analyses, in which we changed a selection of the more than 200 MIKADO parameters. First, we analysed the sensitivity of the environmental impact (M) to changes in model parameters (Sensitivity Analysis I). Second, we varied the values of a number of parameters that are associated with reduction options and their costs (Sensitivity Analysis II). Finally, we analysed parameters associated with the alloy mass flow (Sensitivity Analysis III). The parameters selected include emission factors, reduction factors, impact factors, activity rates or unitary prices. Model runs were performed for a lower and higher value for each of the parameters as indicated in Table 4.11. MIKADO results in terms of environmental impact (M) and total costs (C) were compared with the situation for the case in which the parameter values were not changed.

Table 4.11. Overview of Sensitivity Analysis cases. In Sensitivity Analysis II a reference is made to the associated reduction options.

		Associated reduction options	Range
Sensitivity Analysis I: Parameters associated with emission factors and characterisation factors			
SA1	Emission factor for cadmium on sub-process Melting	---	Based on several concentrations measured at the plant for each the minimum and maximum values are 0 and 0.49 mg/m^3.
SA2	Emission factor for nickel on sub-process Melting	---	Based on several concentrations measured at the plant for each the minimum and maximum values are 0.02 and 0.08 mg/m^3.
SA3	Emission factor for lead on sub-process Melting	---	Based on several concentrations measured at the plant for each the minimum and maximum values are 0.07 and 1.21 mg/m^3.
SA4	Emission factor for chromium on sub-process Melting	---	Based on several concentrations measured at the plant for each the minimum and maximum values are 0 and 0.08 mg/m^3.
SA5	Emission factor for copper on sub-process Melting	---	Based on several concentrations measured at the plant for each the minimum and maximum values are 0 and 0.94 mg/m^3.
SA6	Emission factor for hydrogen fluoride on sub-process Melting (related with desoxidation agent used)	---	Based on range of chemical composition of fluorine in desoxidation agent (20-50% Na_2SIF_6). Foseco (2002).
SA7	Emission factor for hydrogen fluoride on sub-process Melting (related with degassing agent used)	---	Based on range of chemical composition of fluorine in desoxidation agent (5-10% AlF_3). Foseco (2002).
SA8	Emission factor for non-methane volatile organic compounds on sub-process Melting	---	NMVOC emission factor range (0.2-4) kg/GJ for natural gas. EMEP/CORINAIR (2004).
SA9	Emission factor for NOx on sub-process Melting	---	NOx emission factor range (22 -350) kg/GJ for natural gas. EMEP/CORINAIR (2004).
SA10	Emission factor for lead on sub-process Casting	---	by + or - 20%
SA11	Emission factor for chromium on sub-process Casting	---	by + or - 20%
SA12	Emission factor for copper on sub-process Casting	---	by + or - 20%
SA13	Emission factor for non-methane volatile organic compounds on sub-process Casting	---	Based on several concentrations measured at the plant for each the minimum and maximum values are 2.7 and 3.4 mg/m^3.
SA14	Characterisation factor for cadmium	---	by + or - 20%
SA15	Characterisation factor for nickel	---	by + or - 20%
SA16	Characterisation factor for chromium	---	by + or - 20%
SA17	Characterisation factor for non-methane volatile organic compounds	---	by + or - 20%
SA18	Characterisation factor for NOx	---	by + or - 20%
SA19	Characterisation factor for lead	---	by + or - 20%
SA20	Characterisation factor for copper	---	by + or - 20%
SA21	Characterisation factor for zinc	---	by + or - 20%
SA22	Characterisation factor for hydrogen fluoride	---	by + or - 20%
Sensitivity Analysis II: Parameters associated with reduction options and their costs			
SA23	Reduction factor for hydrogen fluoride	Melting_WS_SC	by + or - 10% (maximum value=100%)
SA24	Reduction factor for heavy metals		by + or - 10% (maximum value=100%)
SA25	Reduction factor for copper		by + or - 10% (maximum value=100%)
SA26	Reduction factor for non-methane volatile organic compounds		by + or - 10% (maximum value=100%)
SA27	Change price of cost disposal (Sludge)		by + or - 50%
SA28	Thermal efficiency	Melting_CM	Range from 35% and 60%. EIPPCB (2005).
SA29	Natural gas price		by + or - 20%
SA30	Reduction factor for non-methane volatile organic compounds	Casting_WS_SC	by + or - 10% (maximum value=100%)
SA31	Reduction factor for zinc		by + or - 10% (maximum value=100%)
SA32	Reduction factor for heavy metals		by + or - 10% (maximum value=100%)
SA33	Price of cost disposal (Sludge)		by + or - 50%
SA34	Concentration of new mould release agent	Casting_nMA	Based on several concentrations measured at the plant for each the minimum and maximum values are 0.8 and 1.5%.
SA35	Mould release agent price		by + or - 10%
SA36	Powder agent used	Casting_PA	by + or - 10%
SA37	Price of powder agent		Data from product supplier for each the minimum and maximum values are 50 and 60€/kg. Klüber (2005). Personal communication
Sensitivity Analysis III: Parameters associated with alloy mass flow			
SA38	Runners' mass	---	by + or - 20%
SA39	Scrap rate in Casting	---	by + or - 20%
SA40	Scrap rate in Finishing	---	by + or - 20%
SA41	Emission factor for aluminium on sub-process Melting	---	Based on several concentrations measured at the plant for each the minimum and maximum values are 2.9 and 180.9 mg/m^3.
SA42	Amount of alloy in aluminium dross	---	by + or - 20%
SA43	Fraction of alloy drossed	---	by + or - 20%
SA44	Emission factor for aluminium on sub-process Casting	---	by + or - 20%
SA45	Fraction of material grinded	---	by + or - 20%
SA46	Fraction of material shot blasted	---	by + or - 20%
SA47	Fraction of material tumbled	---	by + or - 20%
SA48	Burrs fraction	---	by + or - 20%

In *Sensitivity Analysis I* a selection of 22 parameters from the sub-processes Melting and Casting is used, based on their relatively large contribution to M. The selection includes parameters that are related to human toxicity problems, because this is the largest environmental problem associated with Melting and Casting (Figure 4.4). In addition only parameters were selected that can be considered influential such as the characterisation factors used on the impact assessment method. Table 4.11 summarises the lower and higher values used in the sensitivity analysis.

In *Sensitivity Analysis II* a second set of 15 cases focuses on parameters associated with reduction options (Table 4.11). The parameters chosen are related with emissions from Melting and Casting that contribute to human toxicity problems, because these emissions have a large share in the overall environmental impact (M) of the plant. Only those parameters, that can be considered uncertain and influential within the set of the most effective reduction options, were selected. In each model run an individual reduction option was selected and a reduction option parameter made variable. MIKADO was used to calculate the value of M and the costs of emission control.

The S*ensitivity Analysis III* (SA38 to SA 48) focuses on parameters associated with alloy mass flow. These are included, because it is assumed that much of the environmental impact of the company is associated with the amount of alloy flowing through the company. Therefore, the parameters considered are part of all the sub-processes within the die casting production line.

The sensitivity analysis described so far focuses on the effects of changes in individual model parameters. To investigate the sensitivity of MIKADO to multiple changes, three cases were analysed in which the values of a selection of parameters was changed simultaneously. In other words, some of the cases of the three sensitivity analyses were combined. In each combination we included the most influential parameters. These parameters (Combined cases 1, 2 and 3) are presented in Table 4.12.

Table 4.12. Results of the sensitivity analyses: changes in the modelled overall environmental impact (M) and total costs (C) for a selection of cases. The table presents the cases with an impact on M of at least 1%. Only the sensitivity analysis results for changes in M related with the zero case are shown and the situation when reduction option(s) are implemented. The values presented in a range, are the results obtained for model runs, respectively, from the lower and higher case. In the table, the results for combinations of sensitivity analysis cases are also present (Combined Cases).

Sensitivity Analysis Cases	**Parameters in Sensitivity Analysis Cases (see Table 4.11)**	**Change in M related with zero case (%)**	**Change in M related with reduction option(s) (%)**	**Change in the Total Costs (C) (%)**
Sensitivity Analysis I	SA4	±1%	---	0%
	SA6	±5%	---	0%
	SA8	±2%	---	0%
	SA9	±2%	---	0%
	SA11	±5%	---	0%
	SA13	±2%	---	0%
	SA16	±5%	---	0%
	SA17	±4%	---	0%
	SA22	±2%	---	0%
Sensitivity Analysis II	SA23	---	+1%	0% [d)]
	SA24	---	+1%	0% [d)]
	SA28	---	-3%; +5%	+1% [d)]
	SA30	---	-2%; +3%	0% [d)]
	SA32	---	+4%	0% [d)]
	SA34	---	±3%	0% [d)]
Sensitivity Analysis III	SA38	-12%; +17%	---	-1%; +2%
	SA39	±2%	---	0%
	SA40	±2%	---	0%
	SA48	±1%	---	±1%
Combined case 1 *(cases from Sensitivity Analysis I)*	SA6+SA11+SA16 [a)]	-14%; +16%	---	0%
Combined case 2 *(cases from Sensitivity Analysis II)*	SA28+SA30+SA32+SA34 [b)]	---	-9%; +20%	±1% [e)]
Combined case 3 *(cases from Sensitivity Analysis III)*	SA38+SA39+SA40+SA48 [c)]	-16%; +23%	---	±3%

a) Combined case 1, includes cases from SAI for which the calculated change in M is larger than 5%.
b) Combined case 2, includes cases from SAII for which the calculated change in M is larger than 3%.
c) Combined case 3, includes all cases from SAIII resulting in any change in the calculated value of M.
d) The changes in total costs refer to the total costs for the situation when each associated individual reduction is used.
e) The changes in total costs refer to the total costs for the situation when all influential associated reduction options, shown in Table 4.11, are used.

For Sensitivity Analysis I the results, presented in Table 4.12, indicate that the MIKADO is most sensitive to variations in the emission factors used to calculate Melting-related emissions of HF, (case SA6, ±5% change in M relative to the zero case), and Casting-related emissions of chromium (SA11, ±5%). The model is also relatively sensitive to the characterisation factor (CF) for chromium (SA16, ±5% change in M relative to zero case). The other emission factors and CF have a relatively small effect (less then 5%) on M.

In Sensitivity Analysis II, it was observed that the MIKADO is sensitive to some, but not all parameters. For instance, the calculated value of M appears to be relatively sensitive to the variations of the parameter thermal efficiency, (case SA28: -3 to +5% change in M relative to the situation when the reduction option is implemented). Model results show that the calculated costs of emission control appear to be most sensitive to variations in the thermal efficiency parameter (case SA28) presenting a +1% cost variation. No effects on costs calculations are seen for the other parameters.

Sensitivity Analysis III indicates that the calculated overall environmental impact (M) is relatively highly sensitive to changes in the runners' mass (SA38, changing the value of M by -12% to +17% relative to the zero case). A comparatively minor effect is observed in the scrap rates from Casting (SA39) and Finishing (SA40) and burrs fractions (SA48) (as seen in Table 4.12).

In the Combined cases, the changes in the calculated values of M related to the *zero case* were investigated (Figure 4.5) for Combined Cases 1 and 3. Combined Case 1 shows a -14 to +16% change in M relative to the zero case. For Combined Case 3 this is -16% to +23%. In Combined Case 2 (Figure 4.6), the results indicate that the model is sensitive showing a change in M of -9 to +20%, when compared with M for the Combined case 2 (default case). Changes in total costs were analysed for the Combined Cases. Model runs show for Combined case 2 cost variation of ±1% when compared with the total costs for the situation when the associated reduction option were used, and for Combined case 3 a cost change of ±3% related with the zero case.

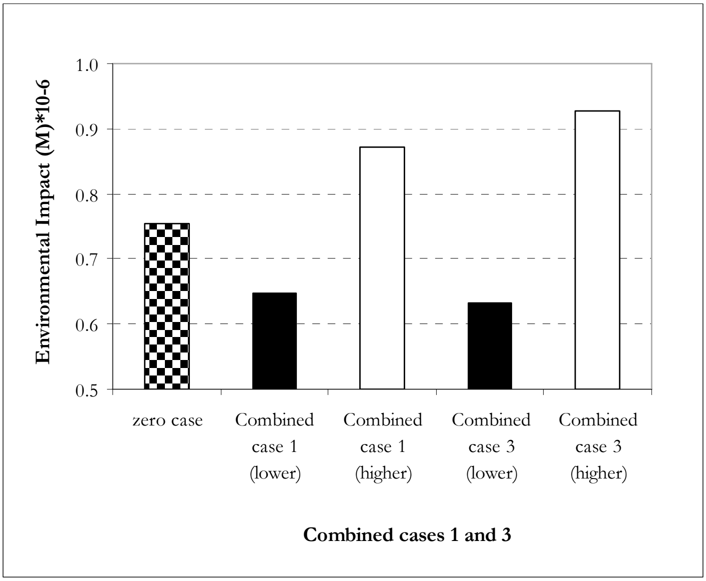

Figure 4.5. The calculated overall environmental impact (M) for two combined cases, in each of which was changed the value of a parameter to a lower or higher value, in order to test the sensitivity of the model results to changes in parameter values. The *zero case* uses parameter values as presented in earlier sections of this chapter. The valuation method used considers all environmental problems to be equally important.

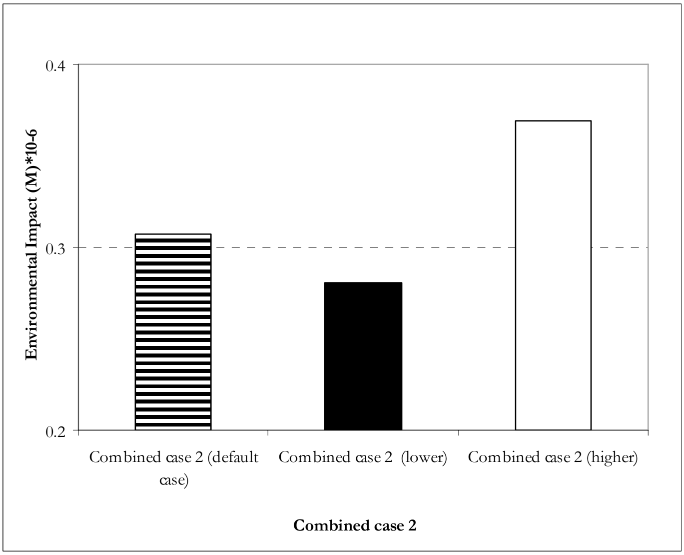

Figure 4.6. The calculated overall environmental impact (M) for Combined case 2, in each of which the value of a parameter was changed to a lower or higher value, in order to test the sensitivity of the model results to changes in parameter values. The calculation of M for *Combined case 2* (default case) uses the default parameters for the situation when the reduction options were implemented. The valuation method used considers all environmental problems to be equally important.

The results of the sensitivity analysis (Table 4.12) indicate that MIKADO appears to be relatively sensitive to changes associated with alloy mass flow. The parameter SA38 (runners' mass, this parameter is strictly related with the increase of metal yield) has an effect on the majority of model results (such as alloy mass entering the process and the activities rates), as seen in Table 4.5.

The same is true for the case where multiple combinations of parameters are used. Our analysis of the cases used leads to the conclusion that again a variation of the alloy mass flow related parameters (Combined case 3) gives rise to a relatively large change in M and in total costs.

Although outside the scope of this study, future studies may add to this partial sensitivity analysis by combining different parameters from SAI to SAIII. In addition, parameters related to other environmental problems other than human toxicity and from sub-processes other than Melting and Casting may be included in a sensitivity analysis.

4.5. Discussion and Conclusions

This study describes a model that assesses the potential environmental impact of emissions of environmental pollutants from a small to medium sized plant supplying car manufacturers with aluminium die casting products. The model also includes a number of options for emission reduction, and can be used to calculate their technical potentials to reduce the environmental impact as well as the associated costs. These calculations can be done for individual reduction options, or for combinations of options. Our study takes a company perspective. As a result, our model is an environmental decision support tool, meant to assist the management of the company in deciding on environmental policies. MIKADO can be used to perform scenario analysis to analyse the impact on the environment of different strategies, while taking into account both economical and ecological consequences of decision-making.

Our model results indicate that more than 90% of the environmental impact of the company is from the sub-processes Melting and Casting. Moreover, the results indicate that the environmental impact is mostly associated with human toxicity problems (caused by metal emissions, and emissions of ozone precursors), and the abiotic depletion of natural gas. This conclusion is relatively insensitive to the environmental impact assessment methods used. This may not be too surprising since the main compounds released by the plant are metals, including heavy metals, and some volatile organic compounds both contributing to human toxicity problems. The results of the sensitivity analysis indicate that variations in individual model parameters may change the calculated overall environmental impact only to a limited extent. Parameters to which the model is most sensitive include those related with alloy mass flow, and in particular, the ones highly related with the increase of metal yield (as the runners' mass).

As mentioned above, MIKADO takes a company perspective. This is apparent from the choice of (1) model components and (2) system boundaries, as well as (3) the selection of reduction options used in the model. In short, we modelled those parts of the production process that can be influenced by the company management. Below, we will elaborate on this.

First, the processes that are explicitly taken into account in the model are those that can be influenced by the company management to improve the environmental performance. The modelling approach taken acknowledges that the industrial system is primarily influenced by the process owner and therefore takes the process operator point of view. We modelled the production process, by zooming into its sub-process level. An insight into the sub-sub-process level allows for the identification of the intervention needed in terms of managing the environmental performance of the industrial process. This quantitative information may make it possible to prioritise environmental management decisions made by board managers (Wright et al., 1998). The model developed is based on specific data that was made available by the plant that served as a case study in our analysis.

Second, the system boundaries are chosen from a company perspective. We follow a limited chain analysis. This implies that we do not perform a full Life Cycle Assessment, but rather limit ourselves to those system elements that can be influenced by company management (Pineda-Henson et al., 2002). This implies, in accordance with other studies, that, in most cases, the system boundaries were set at the gates of the business concerned (Finkbeiner et al., 1998; Zobel et al., 2002; Backhouse et al., 2004). Although the activities outside the site may generate significant environmental impacts the possibilities that the facility has to influence or control them are limited (Zobel et al., 2002).

Third, we only included reduction options that can be taken by company management. We limited ourselves to existing and available abatement techniques. The options listed include both add-on techniques and more structural changes in the production process. The latter may best suit the company's pro-activeness. The method presented here is not a mere pollution oriented approach, since the model user may in the analysis select reduction options not only because of their potential in reducing pollution, but also due to the fact that these options may lead to a double goal on reduction pollution and simultaneously bring a cost benefit to the firm.

One of the strengths of MIKADO is the integrated approach that it takes in analysing, simultaneously, all the relevant environmental problems caused by the aluminium die casting plant. The compounds analysed contribute to several environmental problems including human toxicity, terrestrial ecotoxicity, aquatic toxicity, depletion of resources such as natural gas, acidification, global warming, emissions of ozone precursors and solid waste production. The model takes into account that some pollutants contribute to more than one problem, that some sub-processes emit more than one pollutant, and that some reduction options affect more than one pollutant. As a result, an analysis of the impact of the reduction options included in the MIKADO will reveal their integrated effect on the environmental performance of the company.

MIKADO is developed in such a way that a user can easily select options to be analysed (tailor-made structure), given the production line as defined in the model. Moreover, the model is transparent and understandable, making it reproducible. The data included in the model refer to consumption of energy and materials and the output data, besides the annual production, refer to the emissions and wastes. The model allows the user to analyse the causal chain of activities at the sub-process level and the associated environmental aspects.

An important feature of MIKADO is that it expresses the environmental performance of the company in one single indicator. This is done on the basis of Multi-Criteria Analysis (Pennington et al., 2004). We argue, in agreement with some authors, that this makes the model interesting for company management (Haes, 2000; Daniel et al., 2004; Krajnc and Glavič, 2005). Our approach is also in line with Olsthoorn et al. (2001) who propose a method for the aggregation of different environmental aspects in one single indicator. However, we realise that this approach includes a valuation step, in which the different environmental problems are weighed, that introduces subjectivity in the model: the question whether one environmental problem is more problematic than another is a political question, not a scientific one. Therefore, we included several valuation approaches in our model. More importantly, MIKADO is designed so that any user can change the valuation factors according to their own judgement (in line with Bengtsson and Steen, 2000).

In MIKADO, most emissions are quantified using a simple emission factor approach (IPCC Guidelines, 1997; Sakamoto and Tonooka, 2000; Winiwarter and Schimak, 2005). This implies that emissions are calculated as a function of a certain emission factor and activity rate (Pluimers, 2001). The reduction options may have an effect on the emission factor or on the activity level. The costs of reduction options are calculated as total annual costs. MIKADO allows the user to calculate the overall environmental impacts and the total costs of an individual reduction option or a combined strategy. This approach is appropriate, because it makes it possible to model a complex industrial process in a relatively simple way, while making it possible to take into account all the relevant interrelations between sub-processes, pollutants and reduction options.

MIKADO can only be used for scenario analysis, answering "what…if" type questions (e.g. 'What would the effect on the environment and the costs be if we would implement the following options?…). This model cannot be used for cost optimisation. Nevertheless, we consider the model flexible enough to allow the user to get a good overview of the cost-effectiveness of a large set of different scenarios. This way, the model creates a plausible possibility space that users can explore in order to identify the set of choices and trade-offs that they are willing to accept (in line with Carmichael et al., 2004).

Any model approach has its limitations. A weak point in our analysis is that by taking the company perspective, we do not account for the environmental impact of the production of raw materials, nor for the environmental impact of the use of the products after they leave the company. Another limitation of the model is the absence of electricity uses and its related consumption costs. Although it may contribute significantly for the cost assessment of the implementation of some reduction options, these data was not available from the company in a disaggregated level for the situation zero case. However, we consider this an inherent consequence of our modelling approach taken. Another weakness is the impact assessment methodology. More specifically, we used the amount of liquid effluent and the solid waste produced as indicators due to the lack of characterisation factors for aquatic toxicity and solid waste production. Also, the normalisation factors used are, because of lack of data, not based on the local situation, but on Western Europe. This, however, is justified by the fact that it is common practice in multi-criteria and Life Cycle Assessments (e.g. Hertwich and Hammitt, 2000; Huijbregts et al., 2003; Geldermann and Rentz, 2005). Another limitation of our study is that the model was not validated with independent data, because such data do not exist. However, we based our model on data from a specific plant and were able to simulate the processes in this plant in a satisfactory way. It should also be noted that although the model includes a large number of environmental problems, we do not take into account noise, vibration and odour.

The MIKADO approach is simple, but complete. It is based, among other environmental systems analysis tools, on relevant parts of life cycle impact assessment, environmental systems management and Multi-Criteria Analysis, which are well-developed tools in covering ecological aspects of decision-making (Finnveden and Moberg, 2005). Although several tools are available for assessment of the environmental performance of industrial processes, these methods may not be able to effectively evaluate the impacts associated with decision-making at the company level, nor provide opportunities to be more pro-active in environmental management (Kolk and Mauser, 2002). We consider our model an important step towards fulfilling the need for a tool that assesses both environmental and economic impacts of organisations.

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Chapter 5: Strategies to Reduce the Environmental Impact of an Aluminium Pressure Die Casting Plant: a Scenario Analysis

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Abstract

This study explores a model (MIKADO) to analyse scenarios for the reduction of the environmental impact of an aluminium die casting plant. Our model calculates the potential to reduce emissions, and the costs associated with implementation of reduction options. We first present model results for a situation in which no reduction options are assumed to be implemented (so-called zero case, reflecting the current practice in the plant). Second, we perform a systematic analysis of reduction options. Finally, seven types of reduction strategies are analysed, assuming the simultaneous implementation of different reduction options. These strategies are analysed with respect to their potential to reduce emissions, environmental impact and costs associated with the implementation of options. These strategies were found to differ largely in their potential to reduce the environmental impact of the plant (10 – 87%), as well as in the costs associated with the implementation of options (-268 to +277 k€/year). We were able to define eleven strategies, reducing the overall environmental impact by more than 50%. Of these, two have net negative costs, indicating that the company may in fact earn money through their implementation.

5.1. Introduction

Aluminium is a widely used metal, in particular in the automotive industry. The total mass of aluminium in a European car roughly doubled between 1990 and 2000 (EIPPCB, 2005), largely explaining the increased demand for aluminium products. This increase in the use of aluminium also affects the aluminium die casting industry. Aluminium pressure die casting is a manufacturing process in the non-ferrous industries, producing engineered aluminium alloy products, such as car components. Pressure die casting is a widely used casting process for aluminium alloys and about two-thirds of all aluminium castings are used in automotive industry (Brown, 1999).

The metal die casting industry contributes to air pollution problems through emissions of gases that contribute to acidification, human toxicity problems and global warming among other environmental problems. Aluminium pressure die casting also contributes to a number of environmental problems (Kim et al., 2003). It is in particular a source of metal emissions to the environment that may be toxic to humans and other organisms. Awareness of the need to reduce these environmental problems has been growing (EIPPCB, 2005; Tan and Khoo, 2005).

A wide range of environmental models exists to analyse the environmental impact of industrial activities, as well as the possibilities to reduce this impact (Castillo and Mora, 2000; Choi et al., 1997; Gäbel et al., 2004; Romero-Hernandez, 2005). However, the existing analytical tools do not typically take a company perspective in defining and evaluating pollution reduction strategies (Finnveden and Moberg, 2005). Therefore, we developed a model (MIKADO) that can be used to evaluate the environmental performance. In an earlier chapter (Chapter 4), we described the model structure and formulation (Neto et al., submitted). Our model assesses the potential environmental impact resulting from emissions of environmental pollutants from a plant supplying car manufacturers with aluminium die casting products. A plant in Portugal served as a case for the model building. MIKADO calculates the pollution reduction potential for a range of reduction options, as well as the associated costs. The model can be considered an environmental decision support tool that may assist management decide on environmental strategies to improve environmental performance.

As mentioned above, an important characteristic of MIKADO is that it takes a company perspective. This is reflected in the system boundaries (gate-to-gate analysis), the pollutants included (only those that can be managed by the company's management), the selected reduction options (only those that can be implemented by the company's management), and the costs of these options (only additional costs for the company) (Neto et al., submitted (Chapter 4)). The approach taken in the model building is different from many other models. Some models, for instance, are more focused on the level of the industrial sector but take the life cycle perspective (Gäbel and Tilmann, 2005), or include reduction options that cannot be taken by a single plant (e.g. Pluimers (2001)). Other models seem to focus more on the national level and take a policy perspective (e.g. the RAINS model (Alcamo et al., 1990)). Such models typically calculate the costs of environmental control for governments or economic sectors, rather than for individual companies. In a way, our model may be considered an Integrated Assessment (IA) model, because we take into account the causes of the environmental problem, the potential environmental impact and possible solutions, as well as the costs associated with impact reduction. MIKADO is designed as a tool for scenario analysis, answering "what….if" type of questions. This is different from some other IA models that can be used for optimisation analysis (e.g. Pluimers, 2001).

Here we present new results of the MIKADO model. We perform three different types of analyses. First, we analyse the environmental performance of the plant, assuming the current industrial process operation without implementing pollution reduction options. We refer to this situation as the zero case. We analyse the relative contributions of different industrial sub-processes and sub-sub-processes to the environmental impact.

Second, individual pollution reduction options are analysed systematically. We calculate their potential to reduce the overall environmental impact as well as their potential to reduce the different environmental problems considered. Net additional costs and the cost-effectiveness are also presented for the reduction options.

Third, we analyse cases in which a number of reduction options are assumed to be implemented simultaneously. To this end, we defined different strategies to combine reduction options. The reduction strategies may, for instance, aim for reducing a specific environmental problem, a specific activity, or a specific pollutant. Alternatively, a company may wish to combine the most cost effective options, or combine add-on techniques, or only more structural reduction options. We present a range of combinations, and analyse their effects on the plant's environmental performance, as well as the associated costs resulting from the implementation of these options.

5.2. Model Description

5.2.1. Model Formulation

MIKADO calculates the potential environmental impact resulting from emissions of environmental pollutants from a plant supplying car manufacturers with aluminium die casting products. The model calculates the effect of individual or combined pollution reduction options on the environmental impact. MIKADO models the main mass flows between the processes of the facility production chain and zooms into the sub-process and sub-sub-process that lead to environmental problems. The production line from the aluminium die casting company includes as main sub-processes: 1) Melting, 2) Casting, and 3) Finishing. The system also includes auxiliary sub-processes: 4) Internal Transports and 5) Auxiliary Burners. These two last sub-processes are considered to be independent of the annual production rate. Moreover, the facility owns two wastewater treatment plants, part of the die casting production line, which treats effluents from sub-processes Casting and Finishing.

The model includes all the important sources of pollutants resulting from all activities within the industrial process operations. So we perform a plant's gate-to-gate analysis.

MIKADO calculates the required input of materials and energy through the production rate concerning the process in question. The model inputs include raw materials (aluminium alloy ingots), energy (natural gas and other fuels used on internal transports and in auxiliary burners) and subsidiary materials such as the desoxidation and degassing agents, mould release agents, lubricants, water, steel shot, ceramic abrasives, detergent and other agents used in the wastewater treatment plants. These inputs, the so-called activity rates (Act), are quantified for specific activities (α) and include, for instance, the use of energy or a specific material. The activities rates are used to calculate emissions (E) of pollutants (x), using an emission factor (EF). Such emission factor approaches are relatively simple methods to quantify emissions, and are widely used in environmental studies of economic sectors (e.g. Pluimers, 2001; Winiwarter and Schimak, 2005) or by country (e.g. IPCC Guidelines, 1997; Zárate et al., 2000; Frey and Small, 2003). In MIKADO the emissions are directly linked to the materials and energy use in the facility sub-process or sub-sub-process and include air emissions (as aluminium (Al), zinc (Zn), cadmium (Cd), nickel (Ni), lead (Pb), chromium (Cr), copper (Cu) and iron (Fe)); natural gas combustion related emissions; hydrogen fluoride (HF) emissions resulting from the use of desoxidation and degassing flux; non-methane volatile organic compounds (NMVOCs) resulting from the mould release agent spraying technique; solid wastes (aluminium dross; ceramic lining, steel shot and ceramic abrasives), liquid effluents, oils and grease, sludge and fuel-related combustion emissions resulting from Internal Transports and Auxiliary Burners.

Important MIKADO outputs include emissions of pollutants (Ex), the potential environmental impact (Mz) for a number of environmental impact categories (z) and the overall potential environmental impact (M) resulting from the emission of these pollutants. The environmental impact assessment methodology used follows current approaches in Life Cycle Assessment and Multi-Criteria Analysis (e.g. Guinée, 2002; Pennington et al., 2004). The calculation of Mz and overall environmental impact (M) resulting from the operation of the industrial process is described in detail in section 5.2.2. .

MIKADO includes 18 pollution reduction options (τ), each aiming at reducing the emissions of pollutants for a specific sub-sub-process within the plant. They can either be add-on techniques added to the process, a replacement of an existing technique or a change in process operation. The emission of a pollutant (x) may change due to changes in either the activity or the emission factor. The pollution reduction options (see Table 5.2 for an overview) are associated in types. The individual reduction options are, within a type, mutually exclusive. The defined types include add-on techniques (fabric filters and wet scrubbers); the replacement of agents used; modification on the combustion process; the use of a different mould release application technique; the use of new die casting moulds; the use of electric equipment, etc. Some of the techniques/options are indicated as the best currently available for the industrial sector of the aluminium pressure die casting (EIPPCB, 2005).

The model can also be used to calculate the cost associated with the implementation of pollution reduction options. These costs are regarded as additional costs for emission abatement options (following Gelderman and Rentz (2004)). The net additional costs (C_{na}) are calculated by the sum of annualised capital costs (CI), operational costs (CO) and the variable costs (CV) of a certain option or a combination of options, when the zero case costs were subtracted. Net additional costs (C_{na}) may be negative if the implementation of a reduction option brings revenue for the facility by comparison with the situation for a zero case, in which no reduction options are assumed to be implemented.

5.2.2. Environmental Impact Assessment methodology

The environmental impact (M) of the plant is assessed for depletion of natural resources, emissions of pollutants to the atmosphere, solid waste production and liquid effluents from the industrial plant. Eight environmental impact categories (z) are considered in MIKADO: the potential environmental impact (Mz) is calculated as a human toxicity potential (HTP), abiotic depletion potential (ADP), global warming potential (GWP), solid waste production (SW), acidification potential (AP), terrestrial ecotoxicity potential (ECP), photochemical ozone formation potential (POCP) and aquatic toxicity potential (ATP).

Following current practice in Life Cycle Assessment and Multi-Criteria Analysis, the environmental impact assessment in MIKADO includes three steps (e.g. Guinée, 2002; Pennington et al., 2004): 1) Characterisation, 2) Normalisation and 3) Weighting. The last step is also referred to as Valuation. By using this methodology the potential environmental impact is expressed in terms of one indicator, which is calculated from the total amount of pollutants emitted per year.

The first step (Characterisation) is based on characterisation factors (CF), expressing the relative contribution of each pollutant (or natural resources) to specific impact categories (z). Thus, all emissions contributing to a specific environmental impact category are aggregated in one single value by multiplication by a characterisation factor (CF). We used the characterisation methodology by Guinée (2002). The resulting indicators are expressed in kilograms 1.4- dichlorobenzene (DCB) equivalent for human toxicity and ecotoxicity, in kilograms antimony equivalents for depletion of abiotic resources, in kilograms CO_2 equivalents for global warming, in kilograms of SO_2 equivalents for acidification and in kilograms of ethylene equivalents for photochemical ozone formation. Natural resources depletion refers to the consumption of energy (natural gas) resources by the plant, and the aquatic toxicity refers to the potential damage caused by the liquid effluent produced. Although liquid effluents and solid waste are subject to off-site treatment, MIKADO considers the total amount of waste or liquid effluent produced as a potential environmental problem.

In step 2 (Normalisation), normalisation factors (NF) are used, relating each of the indicator for an environmental impact category to a reference situation. Based on these, the potential environmental impacts (Mz) of the plant are calculated. Thus, in the normalisation step, the potential impact for each environmental problem (resulting from step 1) is divided by the potential impact of a reference situation. This way, we relate the impact of the plant to that of a reference situation (e.g. region, country or the whole world). The normalisation factors (NF) in MIKADO use Western Europe in 1995 as a reference (following Huijbregts et al. (2003)). Exceptions are the NF for aquatic toxicity and solid waste; for these categories the normalisation factors reflect emissions from Western Europe for the period 1990-1994 (Blonk, 1997). For the NF of solid waste we use the upper limit of the range given by Blonk (1997).

In the last step (Weighting), the overall environmental impact (M) is calculated by weighting all the specific impact categories by using four different valuation methods. This way, we are able to express the overall environmental impact (M) of the aluminium die casting plant in one indicator. The four different methods for the weighting used in MIKADO include: a) a method considering all environmental problems equally important, b) Panel method I (Kamp, 2005), c) Panel method II (Kortman et al., 1994) and d) a distance to target method (Goedkoop, 1995). In addition, the model user may define alternative sets of valuation factors for the environmental problems. The details on the impact factors used and the impact assessment calculation method is described in Neto et al. (submitted, (Chapter 4)).

5.3. Analysis of the zero case

We first analyse a zero case, in which we assume that no reduction options are implemented by the plant. Clearly, human toxicity problems have the largest share in the calculated overall environmental impact in the zero case (Figure 5.1). The second most important problem is the depletion of natural gas. These two environmental impact categories (human toxicity and depletion of abiotic resources) account for about 75% of the overall environmental impact M. This conclusion holds for all valuation methods used.

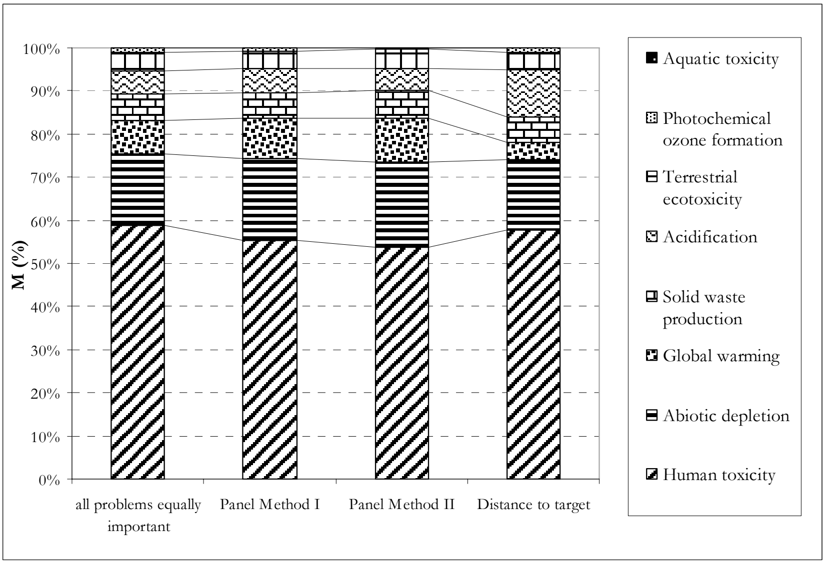

Figure 5.1. The relative contribution (%) of environmental impact categories (z) to the overall environmental impact (M) of an aluminium die casting plant for the zero case. Results are shown for four multi-criteria analyses (MCA) using different valuation methods: All problems equally important; Panel Method I (Kamp, 2005); Panel Method II (Kortman et al., 1994); and Distance to target (Goedkoop, 1995). (units: % relative to M).

Next, the relative contribution of sub-processes (p_i) to the overall environmental impact (M) is analysed. Melting and Casting are found to contribute by more than 90% to the calculated environmental impact, independent of the valuation method used (Figure 5.2). The environmental impact of Melting is largely associated with human toxicity problems and the depletion of abiotic resources (Table 5.1). Referring to the two above-mentioned environmental problems, the emissions of hydrogen fluoride

(HF) from Melting alone are responsible for 9% of the calculated overall environmental impact M, while chromium emissions account for 6% and non-methane volatile organic compounds (NMVOC) account for 2% (Table 5.1). Natural resources depletion refers to the consumption of natural gas. The use of natural gas for Melting accounts for 17% of the overall environmental impact (M). Within the sub-process Casting, the emission of compounds (chromium) with a potential human toxicity from the Holding Furnaces contributes by 21% to M. In the Pressure Die Casting the emissions of compounds with a potential human toxicity effect (NMVOC) contributes by 18% to M (Table 5.1).

It may be clear from the above that there are four relatively large sources of environmental pollution in the aluminium die casting plant: emissions of chromium and NMVOCs from Casting, the use of natural gas in Melting and emissions of HF from Melting. These four are responsible for about two-thirds of the overall environmental impact.

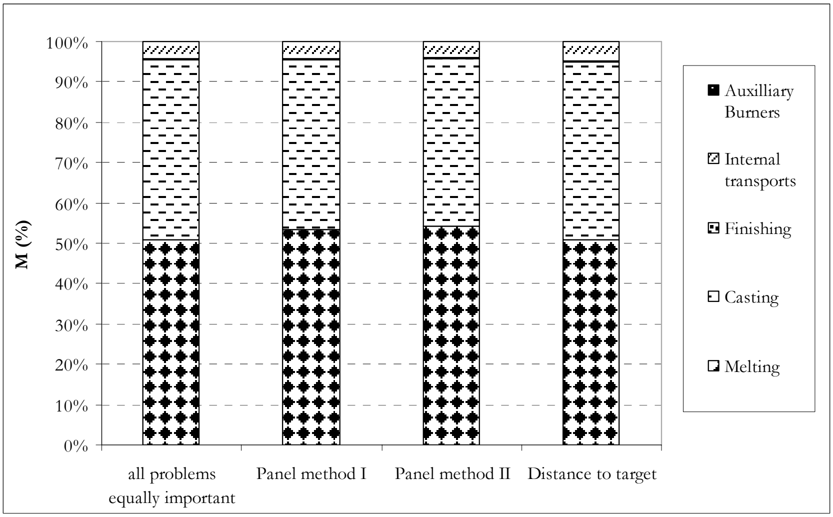

Figure 5.2. The relative contribution (%) of sub-processes (p_i) in an aluminium die casting plant to the overall environmental impact (M) for the zero case. Results are shown for four multi-criteria analyses (MCA) using different valuation methods: All problems equally important; Panel Method I (Kamp, 2005); Panel Method II (Kortman et al., 1994); and Distance to target (Goedkoop, 1995). (units: % relative to M) Note that the sub-process Casting includes several sub-sub-processes (Holding Furnaces and Pressure Die Casting) and that the sub-process Finishing includes Trimming, Surface treatment (Grinding, Shot Blasting and Tumbling) and Cleaning and Degreasing (Neto et al., submitted (Chapter 4)).

Table 5.1. The relative contribution of the emissions of an aluminium die casting plant to the overall environmental impact (M) by sub-sub-process and for the zero case. (Valuation method: All problems equally important) (units: % relative to the M for zero case).

Process (p)	**sub-process (p_i)**	**sub-sub-process (p_{ij})**	**Environmental impact categories(z)**	**Pollutants / Liquid effluent / Solid wastes (x) associated with the environmental impact categories**	**Contribution to M (%)**
Die Casting company	Melting (i=1)	Melting	Human toxicity	HF Cr NMVOC Cd + Ni + Pb + Cu + NMVOC	9% 6% 2% <1%
			Abiotic depletion	Natural gas [a)]	17%
			Global warming	CO_2	7%
			Solid waste production	Aluminium dross	4%
			Acidification	NOx HF	2% 2%
			Terrestrial ecotoxicity	Cr Cd + Ni + Pb + Cu + HF+NMVOC	2% <1%
			Photochemical ozone formation	CO + NMVOC + NOx	<1%
	Casting (i=2)	Holding Furnaces	Human toxicity	Cr Zn + Pb + Cu	21% <1 %
			Terrestrial ecotoxicity	Cr Zn + Pb + Cu	4% <1 %
			Solid waste production	Ceramic lining	<1%
		Pressure Die Casting	Human toxicity	NMVOC	18%
			Terrestrial ecotoxicity	NMVOC	<1%
			Solid waste production	Oils & Grease Sludge	1% 1%
			Photochemical ozone formation	NMVOC	<1%
			Aquatic toxicity	Liquid effluent	<1%
	Finishing (i=3)	Shot Blasting	Solid waste production	Steel Shot	<1%
		Tumbling	Solid waste production	Ceramic Abrasives Sludge	<1% <1%
			Aquatic toxicity	Liquid effluent	<1%
		Cleaning and Degreasing	Solid waste production	Sludge Oils and Grease	<1% <1%
			Aquatic toxicity	Liquid effluent	<1%
	Internal Transport (i=4)	Fork-lift Truck on Diesel and LPG	Human toxicity	NMVOC NOx + SO_2 + Particulates	2% <1%
			Global warming	CO_2	<1%
			Acidification	NOx SO_2	1% <1%
			Terrestrial ecotoxicity	NMVOC	<1%
			Photochemical ozone formation	CO + NMVOC + NOx + SO_2	<1%
	Auxiliary Burners (i=5)	Oxyacetylene and Butane burners	Human toxicity	NMVOC + NOx + Particulates	<1%
			Global warming	CO_2	<1%
			Acidification	NOx	<1%
			Terrestrial ecotoxicity	NMVOC	<1%
			Photochemical ozone formation	CO + NMVOC + NOx	<1%

[a)] The natural gas consumption contributes to the impact category - depletion of natural resources.

5.4. Systematic analysis of individual pollution reduction options

The environmental impact of industrial activities can be reduced by end-of-pipe technologies or by changes in the operation process (Beaumont and Tinch, 2004; Moors, 2006). We identified 18 options to reduce the potential environmental impact for the die casting plant (see Chapter 3, section 3.3.3.). These options are implemented at the sub-sub-processes level. We organise the options in different types (Table 5.2). Within the types we consider the options to be mutually exclusive (e.g. a fabric filter cannot be applied with another option that, simultaneously, is part of the same sub-sub-process and the same type "filters and scrubbers"). For each option the potential to reduce emissions is estimated, as well as the costs involved (see Chapter 3, section 3.3.3.). The options considered were described in the literature or were proposed by the managers of the plant that serves as a case in this study. Thus, the options may be considered up-to-date techniques to be used by any company in the aluminium pressure die casting sector. Most options affect more than one pollutant and most compounds are affected by more than one option (Table 5.2).

MIKADO includes options for all the sub-processes within the plant and includes end-of-pipe techniques (such as fabric filters), as well as more structural reduction options (Table 5.2). An example of a more structural option is replacing the desoxidation agent by a less polluting agent (granular desoxidation agent). Other examples include using a different technique for a) degassing of the molten alloy (Impeller station), b) the combustion process (air enrichment with oxygen or oxyfuel firing), c) mould release (by use of a lower concentrated agent maintaining the technique or changing the technique by using a powder agent). Yet another example is d) an alternative metal loading (compact metal load in melting furnaces), which may improve the thermal efficiency, by introducing in the furnaces a more compacted material in substitution to the remains of casting.

The model also includes options aiming at increasing the metal yield (where metal yield is the ratio of production to molten alloy). These options either reduce the mass of runners in the die casting moulds or reduce the scrap rate produced in the sub-processes Casting and Finishing. The metal yield increases due to the reduction of the mass of aluminium alloy that feeds the melting furnaces and hence the energy needed. Thus, these options not only reduce the amount of aluminium that is recycled internally, but also decrease the use of subsidiary materials that are directly dependent on the amount of molten alloy. As a result, many emissions will be reduced.

Table 5.2. Overview of pollution reduction options for a die casting plant (from Neto et al., submitted (Chapter 4)). See Chapter 3 (section 3.3.3.) for a description of the reduction options.

sub-process (p_i)	sub-sub-process (p_{ij})	Types of Options	Reduction Options (τ)	Abbreviation	Compounds reduced
Melting (i=1)	Melting	Filters and scrubbers	Fabric Filter. Reverse-air type [a)]	Melting_FF_RA	Heavy metals such as Cd, Ni, Pb, Cr
			Fabric Filter. Pulse-Jet type [b)]	Melting_FF_PJ	Heavy metals such as Cd, Ni, Pb, Cr
			Fabric Filter. Mechanical Shaker type [c)]	Melting_FF_MS	Heavy metals such as Cd, Ni, Pb, Cr
			Wet Scrubber. Impingement-Plate type [d)]	Melting_WS_IP	Heavy metals (Cd, Ni, Pb, Cr), Cu and HF
			Wet scrubber. Spray-chamber type [e)]	Melting_WS_SC	Heavy metals (Cd, Ni, Pb, Cr), Cu and HF and NMVOC.
		Alternative desoxidation agent	Granular desoxidation agent [f)]	Melting_GA	HF, Aluminium dross.
		Alternative degassing technique	Impeller station using N_2[f), k)]	Melting_IS	HF, Aluminium dross.
		Alternative metal loading in furnaces	Compact metal loading in furnaces [g)]	Melting_CM	CO_2, CO, NOx, and NMVOC (Natural gas combustion related emissions).
		Combustion process modification	Air enrichment with oxygen (30%O_2) [g)]	Melting_AE	CO_2, CO, NOx, and NMVOC (Natural gas combustion related emissions).
			Oxyfuel firing (100%O_2)[g)]	Melting_OF	CO_2, CO, NOx, and NMVOC (Natural gas combustion related emissions).
Casting (i=2)	Pressure die casting	Scrubbers	Wet Scrubber. Packed-Bed type [h)]	Casting_WS_PB	Heavy metals (Pb, Cr), Cu, Zn, NMVOC
			Wet scrubber. Spray-chamber type [e)]	Casting_WS_SC	Heavy metals (Pb, Cr), Cu, Zn, NMVOC.
		Alternative to mould release agent application	New mould release agent [g)]	Casting_nMA	NMVOC, liquid effluent, oils, grease and sludge.
			Powder agent [i), k)]	Casting_PA	NMVOC, liquid effluent, oils, grease and sludge.
		New die casting moulds	Reduce runners mass [j), *)]	Casting_rRR	Heavy metals (Cd, Ni, Pb, Cr), Cu, Zn, HF, CO_2, CO, NOx, and NMVOC, aluminium dross, oils, grease and sludge.
		Reduce scrap rate	Reduce scrap rate [k), *)]	Casting_rSR	Heavy metals (Cd, Ni, Pb, Cr), Cu, Zn, HF, CO_2, CO, NOx, and NMVOC, aluminium dross, oils, grease and sludge.
Finishing (i=3)	Trimming	Reduce scrap rate	Reduce scrap rate [k), *)]	Finishing_rSR	Heavy metals (Cd, Ni, Pb, Cr), Cu, Zn, HF, CO_2, CO, NOx, and NMVOC, aluminium dross, oils, grease and sludge.
Internal Transport (i=4)	Forklift Truck on Diesel (I and II) and LPG	Electrical equipment	Use electric forklift trucks [g)]	IT_eFL	CO_2, CO, NOx, and NMVOC, SO_2 and Particulates.

a) to e) and h) USEPA Air pollution control technology fact sheet. EPA-CICA Fact Sheet. USEPA (2002). a) EPA-452/F-03-026; b) EPA-452/F-03-025; c) EPA-452/F-03-02;. d) EPA-452/F-03-012; e) EPA-452/F-03-016; f) Brown (1999); g) Pedro (2005). Personal communication; h) EPA-452/F-03-015; i) Klüber (2005); j) INETI (2000); k) EIPPCB (2005).

*) These reduction options may change the value of the metal yield. For some reduction strategies, where these three reduction options were used, the runners' mass and scrap rates were modified leading to values of metal yield equal to 57% (EIPPCB, 2005).

5.4.1. Effectiveness of reduction options in reducing the environmental impact

The potential to reduce the overall environmental impact differs largely for the total 18 reduction options analysed (Figure 5.3). The two most effective options are found to be two wet scrubbers associated with Casting (Casting_WS_PB and Casting_WS_SC), each of which may reduce the overall impact by about 40% (Figure 5.3, Table 5.3). This reduction is mainly achieved by a reduction in emissions of toxic compounds.

The two least effective reduction options are calculated to reduce the overall impact by less than 1%. These include more structural reduction options, such as the use of an impeller station for degasification (Melting_IS), and using a small percentage of oxygen for the fuel combustion (Melting_AE).

The other 14 reduction options have more intermediate results, reducing M from 4 to 20%. A reduction in M of about 20% is calculated for wet scrubbers in Melting (Melting_WS_SC) as a result of reducing emissions of hydrogen fluoride, chromium and NMVOC. The option to use powder release agents (Casting_PA) in Casting, may reduce M by 20% as a result of a decrease in NMVOC emissions. A smaller reduction is observed for the options that compact the metal load (Melting_CM, 17% reduction in M), the new die casting moulds (Casting_rRR, 15% reduction in M) and the new mould release agent (Casting_nMA, 11% reduction in M). The other options reduce M by less than 10%.

It can be concluded that the choice of the valuation method has a small effect on the calculated effect of options on the overall environmental impact M (Figure 5.3). Therefore, in the following we only analyse the results for the valuation factors that consider all environmental problems equally important.

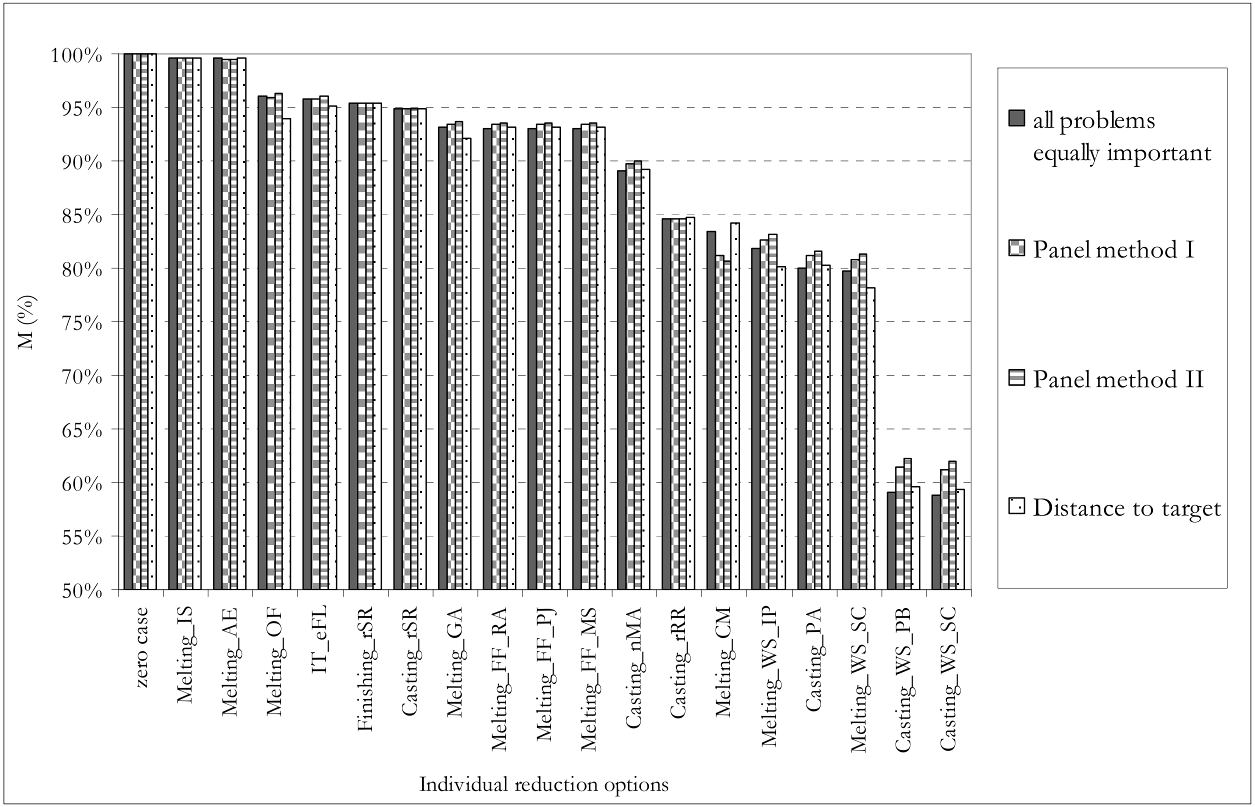

Figure 5.3. Overall environmental impact (M) of the plant for the zero case and for alternative cases in which one reduction option is assumed to be implemented. The overall environmental impact (M) is calculated for four multi-criteria analyses (MCA) using different valuation methods: All problems equally important; Panel Method I (Kamp, 2005); Panel Method II (Kortman et al., 1994); and Distance to target (Goedkoop, 1995). (units: % relative to M for the zero case). See Chapter 3 (section 3.3.3.) for a description of the reduction options.

Table 5.3. Relative contribution of sub-processes (p_i) and sub-sub-processes (p_{ij}) to the overall environmental impact (M) for the zero case and for alternative cases in which a single reduction option is assumed to be implemented. (the valuation method used is the one that considers all problems equally important) (units: % relative to M for the zero case). See Table 5.2 for an explanation of the abbreviations.

			Reduction Options (τ)																	
sub-process (p_i)	**sub-sub-process (p_{ij})**	**Zero case**	**Melting_IS**	**Melting_AE**	**Melting_OF**	**IT_eFL**	**Finishing_rSR**	**Casting_rSR**	**Melting_GA**	**Melting_FF_RA**	**Melting_FF_PJ**	**Melting_FF_MS**	**Casting_nMA**	**Casting_rRR**	**Melting_CM**	**Melting_WS_IP**	**Casting_PA**	**Melting_WS_SC**	**Casting_WS_PB**	**Casting_WS_SC**
(1) Melting	Melting	51%	51%	50%	47%	51%	48%	48%	44%	44%	44%	44%	51%	43%	34%	33%	51%	31%	51%	51%
(2) Casting	Holding Furnaces	24%	24%	24%	24%	24%	23%	23%	24%	24%	24%	24%	24%	20%	24%	24%	24%	24%	1%	0%
	Pressure Die Casting	20%	20%	20%	20%	20%	19%	19%	20%	20%	20%	20%	9%	17%	20%	20%	0%	20%	2%	3%
(3) Finishing	Surface Treatment: Shot Blasting	<1%	<1%	<1%	<1%	<1%	<1%	<1%	<1%	<1%	<1%	<1%	<1%	<1%	<1%	<1%	<1%	<1%	<1%	<1%
	Surface Treatment: Tumbling	<1%	<1%	<1%	<1%	<1%	<1%	<1%	<1%	<1%	<1%	<1%	<1%	<1%	<1%	<1%	<1%	<1%	<1%	<1%
	Cleaning and Degreasing	<1%	<1%	<1%	<1%	<1%	<1%	<1%	<1%	<1%	<1%	<1%	<1%	<1%	<1%	<1%	<1%	<1%	<1%	<1%
(4) Internal Transports	Fork-lift Truck on Diesel (I and II) and LPG	4%	4%	4%	4%	0%	4%	4%	4%	4%	4%	4%	4%	4%	4%	4%	4%	4%	4%	4%
(5) Auxiliary Burners	Oxyacetylene and Butane burners	<1%	<1%	<1%	<1%	<1%	<1%	<1%	<1%	<1%	<1%	<1%	<1%	<1%	<1%	<1%	<1%	<1%	<1%	<1%
Overall Contribution (M)		100%	100%	100%	96%	96%	95%	95%	93%	93%	93%	93%	89%	85%	83%	82%	80%	80%	59%	59%

Next, the effects of single reduction options on the calculated potential impact per environmental impact category (Mz) are investigated (Figure 5.4). The model includes 15 options to reduce emissions of compounds with a high human toxicity. Their calculated potential to reduce the environmental impact (Mz for HTP) ranges from 2 to 65%. The most effective options are the two different types of wet scrubbers located in Casting (Casting_WS_PB and Casting_WS_SC). These two options are calculated to reduce Mz by about 65% each.

Six reduction options were analysed for decreasing natural gas use. The most effective reduction option (Melting_CM) may reduce the calculated environmental impact (Mz for ADP) by about 60%. The other options have a smaller effect on natural gas use, and lead to a 2-15% reduction in the environmental impact (Mz). The least effective (2% reduction) is the option to reduce the oxygen concentration in combustion (Melting_AE).

A reduction in the greenhouse gas emissions (contributing to global warming) was calculated for seven options. A relatively large reduction (more than 50%) in Mz (for GWP), is calculated for the option to compact the metal load (Melting_CM). A smaller reduction (15%) is calculated for the option to use new moulds in the die casting process (Casting_rRR). Reductions smaller than 10% are calculated for options associated with Internal Transport (IT_eFL), reducing scrap rate (Casting_rSR and Finishing_rSR) and the use of oxygen in combustion (Melting_AE and Melting_OF).

The environmental impact from solid waste production (Mz for SW) may be reduced by up to 30% by the options analysed. On the other hand, some add-on techniques, meant to reduce other emissions may, as a side effect, increase the production of waste. This is true for options collecting dust that lead to an increase of the amount of waste (in particulate form or sludge) that needs to be disposed of. The largest reduction (about 30%) in SW is calculated for the option to use a powder mould release agent (Casting_PA). The use of die casting moulds (Casting_rRR) and of new mould release agents (Casting_nMA) may reduce Mz by about 15%. The other options reduce Mz by less than 5%.

We include eleven options to reduce acidification in our analyses. These are meant to reduce the impact for acidifying compounds (Mz for AP). The most effective reduction option (Melting_OF), may reduce Mz by over 45%. The other options reduce the calculated Mz by 1% such as (Melting_IS and Melting_AE) to 35% (Melting_WS_IP and Melting_WS_SC).

In total, ten options were analysed to reduce emissions of compounds contributing to terrestrial ecotoxicity problems (Mz for ECP). The two most effective are add-on techniques for the sub-process Casting and include two different types of wet scrubbers (Casting_WS_PB and Casting_WS_SC). These are calculated to reduce Mz by about 75% each. The other options have intermediate results ranging from 5% (for all the options reducing scrap rate) to 20% for all the add-on techniques in Melting.

Twelve options to reduce emissions of tropospheric ozone precursors were analysed. They may reduce the environmental impact (Mz for POCP) by 1% (Melting_AE) to 40% (Casting_PA, Casting_WS_PB and Casting_WS_SC). Eight intermediate options are found to reduce emissions of ozone precursors from 5% to 30%.

Five options to reduce emissions of compounds contributing to aquatic toxicity (Mz for ATP) were analysed. The largest reduction was found for the option to use powder agent (90% reduction in ATP). The option to use a new mould release agent (Casting_nMA) reduces this Mz by 40% while the other options from 5 to 15%.

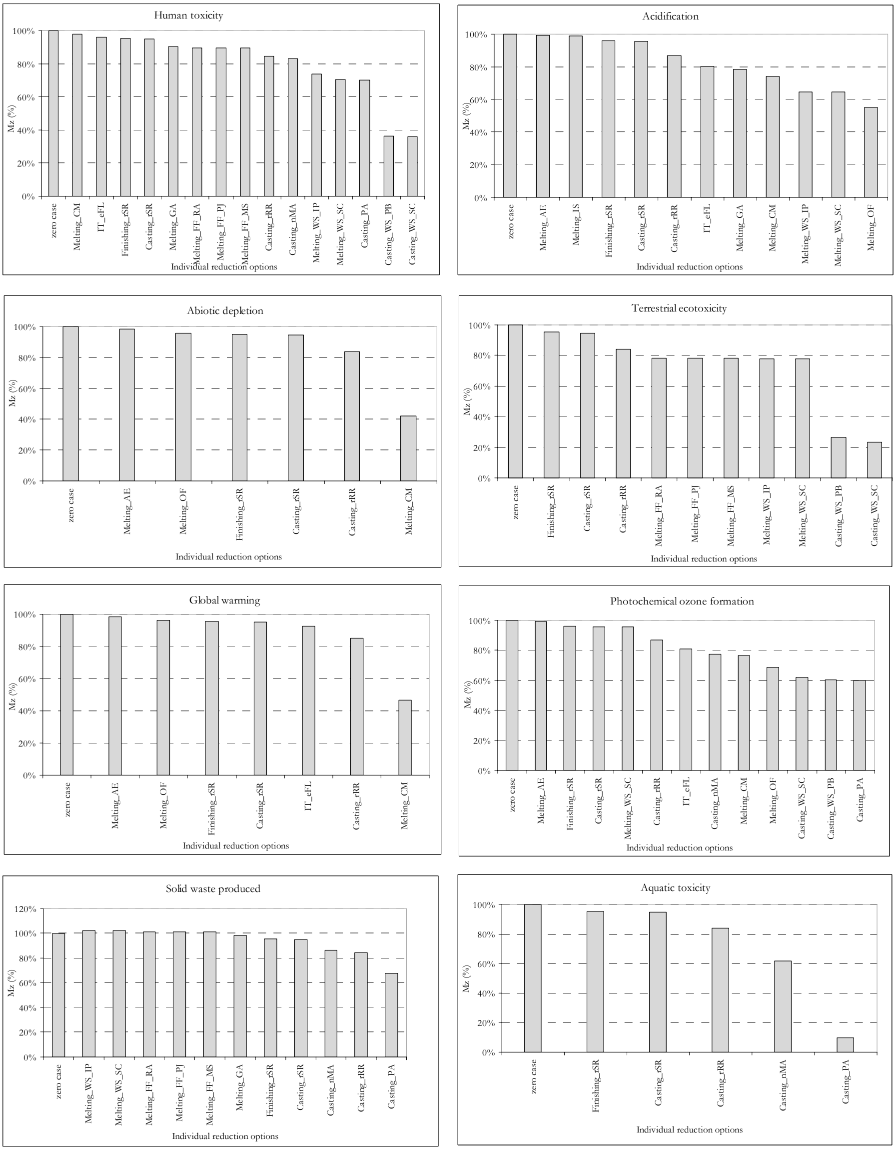

Figure 5.4. As figure 5.3, but for each environmental impact category (z). The results are only presented for options affecting the Mz in question, and for the valuation factor that considers all environmental problems equally important (units: % relative to Mz for the zero case).

5.4.2. Costs of reduction options

The implementation of pollution reduction options results in costs for the company. The total costs for each individual reduction option include fixed cost (equipment investment and the fixed operational cost) and variable costs (dependent on the equipment or materials use). In another chapter (Chapter 4) (Neto et al., submitted), we provide details on the cost parameters used in the analysis. In line with Geldermann and Rentz (2004) the costs are considered in terms of net additional cost for each reduction option. The calculated net additional costs for an option reflect the extra costs or savings (in some cases the company saves money by implementing an option) associated with the implementation of a reduction option, relative to the zero case. Thus, these costs may be negative if the implementation of a reduction option brings revenue for the company.

The calculated net additional costs (C_{na}) of reduction options range from -128 k€/year, for the option to compact metal load (Melting_CM), to +224 k€/year for the option when to implement oxyfuel firing in Melting (Melting_OF) (Figure 5.5).

Six reduction options are calculated to have negative costs, indicating that by implementing these options, the company, in fact, may earn money. These include the options to use a granular desoxidation agent (Melting_GA, -0.24 k€/year), some of the options to increase the metal yield (Casting_rSR, -30 k€/year, and Finishing_rSR, -36 k€/year), the use of electric forklift trucks in internal transports (IT_eFL, -39 k€/year) and options using a new mould release agent (Casting_nMA, -58 k€/year). The largest savings are calculated for the option to compact the metal load (Melting_CM, -128 k€/year).

The four most costly reduction options include the use of oxyfuel firing (Melting_OF, 224 k€/year), a wet scrubber in Casting (Casting_WS_PB, 195 k€/year), the use of powder mould release agent (Casting_PA, 146 k€/year) and the use of new moulds on Casting (Casting_rRR, 119 k€/year). Among the non-paying options are eight options with costs below 100 k€/year.

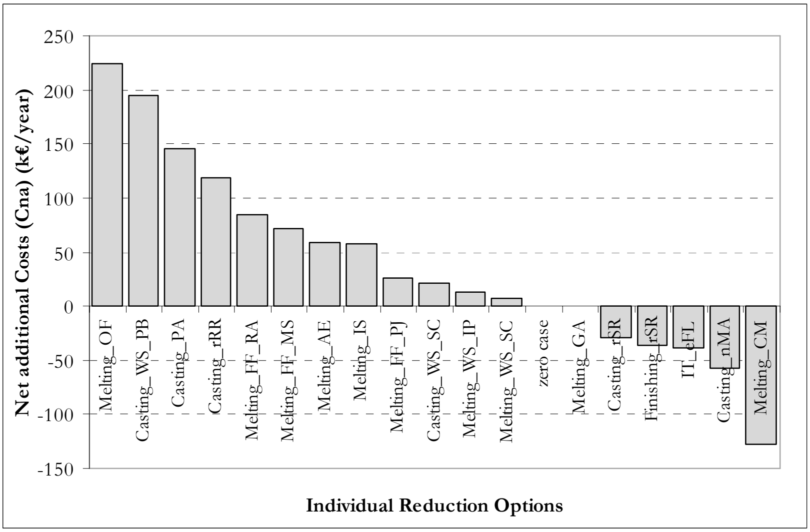

Figure 5.5. Net additional Costs (C_{na}) for the aluminium die casting plant for cases in which it is assumed that one of the reduction options is implemented. See Table 5.2 for an explanation of reduction options.

We also calculated the cost-effectiveness (CE) of reduction options. We define cost-effectiveness as the net additional costs (C_{na}) per avoided overall environmental impact (M) (Equation 1, following Pluimers (2001)). The cost-effectiveness for the reduction options is also calculated for each impact category (Mz) (Equation 2).

$$CE_{\tau,M} = \frac{C_{na}}{\left(M_{zerocase} - M_{zerocase+\tau}\right)} \qquad \text{(Equation 1)}$$

$$CE_{\tau,M_z} = \frac{C_{na}}{\left(M_{z,zerocase} - M_{z,zerocase+\tau}\right)} \qquad \text{(Equation 2)}$$

Where,

$CE_{\tau,M}$	=	Cost-effectiveness of option (τ) regarding the overall environmental impact (M). It expresses the net cost per avoided overall environmental impact *in* (€ / % avoided overall environmental impact).
CE_{τ,M_z}	=	Cost-effectiveness of option (τ) regarding the environmental impact per impact category (Mz). It expresses the net cost per avoided specific impact category *in* (€ / % reduced emission of pollutants with a potential to a certain environmental impact category (z)).
C_{na}	=	Net additional costs, expressing the difference in the total costs for the implementation of one reduction option when the costs for zero case are subtracted *in* (k€/year).
$M_{zerocase}$	=	Overall environmental impact for zero case *in* (%, $M_{zerocase}$=100%).
$M_{zerocase+\tau}$	=	Overall environmental impact in the alternative cases, i.e., when a reduction option τ is implemented *in* (%). Expresses the overall environmental impact when option (τ) is implemented.
$M_{z,zerocase}$	=	Environmental impact from a specific impact category (z) in the zero case *in* (as % 1.4 dichlorobenzene eq. (for human toxicity and ecotoxicity), % antimony eq. (for depletion of abiotic resources), % CO_2 eq. (for global warming), % solid waste produced , % SO_2 eq. (for acidification), % ethylene eq. (for photochemical ozone formation), % liquid effluent, $M_{z,zerocase}$= 100%).
$M_{z,zerocase+\tau}$	=	Environmental impact from a specific impact category (z) in the alternative cases *in* (%). It expresses the environmental impact per impact category, relative to the zero case, when a reduction option is implemented.

The calculated values for CE can be positive or negative. A negative CE results from a negative net cost (C_{na}), because for all options $M_{zero\ case}$ either equals or exceeds $M_{zero\ case+\tau}$. A negative value of CE implies that the option is beneficial to the company, thus options with a lower CE are more cost effective. A cost-effectiveness analysis can be used to compare options. We consider an option cost effective if it, compared to other options, results in a lower overall environmental impact at the same or lower cost, or if it has an equal overall impact but at a lower cost. Equation 1 applies only to options that reduce the environmental impact (M). The options not affecting the environmental impact are considered to be not cost effective and therefore not included in the cost-effectiveness analysis. Similarly, Equation 2 only applies to options that are calculated to decrease the environmental impact for the impact category (Mz) in question. Equations 1 and 2 cannot be used for comparing options with the same negative cost (C_{na}). However, these options do not exist in our study. Equations 1 and 2 also cannot be used for options that are calculated to have a zero cost (C_{na}). Similarly, our study does not include any options calculated to have a net additional cost equal to zero.

For six options we calculate negative values of CE in reducing the overall impact M (CE ranging from -0.03 to -9 k€ per % of M avoided (Table 5.4). It is interesting to note that these options differ considerably in their effectiveness to reduce the overall impact M (4 to 17%; Table 5.4). The most promising option seems to be to compact the metal load (Melting_CM), reducing the environmental impact by 17% at net negative costs. For the other options, the cost-effectiveness ranges from 0.4 to 57 k€ per % M avoided. Of these, the most interesting options are those with relatively low CE, and a relatively large potential to reduce the environmental impact M. For instance, wet scrubbers in the sub-process Casting are relatively cost effective (Casting_WS_SC, CE = 1k€/% avoided M), while reducing the environmental impact by up to 41% (Table 5.4).

The cost-effectiveness of the options in reducing M for a specific impact category (z) is also presented in Table 5.4. It is interesting to note that the six options that are most cost effective in reducing the overall environmental impact M, are also the most cost effective in reducing M for a specific impact category z. Again, the option to compact the metal load in the furnaces is found to be one of the most promising options, considering its cost-effectiveness and its potential to reduce several emissions simultaneously. Other highly cost effective options that may reduce several pollutants simultaneously include the use of new mould release agents in Casting (Casting_nMA), a reduction of the scrap rate (Casting_rSR, Finishing_rSR) and the use of electric forklift trucks (IT_eFL).

Table 5.4. Cost-effectiveness (CE) of reduction options (τ) and their potential to reduce the environmental impact (% M avoided). CE is calculated as the net additional annual costs per % of environmental impact avoided (k€ / % M or Mz avoided) (Equations 1 and 2, see text). Results are shown for the overall environmental impact (M) and for each environmental impact category (z). See Table 5.2 for an overview of the reduction options.

Reduction Options (τ)	Results for Overall Environmental Impact (M)		Results for different impact categories (Mz)															
			Human toxicity		Abiotic depletion		Global warming		Solid waste production		Acidification		Terrestrial ecotoxicity		Photochemical ozone formation		Aquatic toxicity	
	CE	% M avoided	CE	% Mz avoided	CE	% Mz avoided	CE	% Mz avoided	CE	% Mz avoided	CE	% Mz avoided	CE	% Mz avoided	CE	% Mz avoided	CE	% Mz avoided
Melting_FF_RA	12	7	8	10	n.e.	0	n.e.	0	increase	-1	n.e.	0	4	22	n.e.	0	n.e.	0
Melting_FF_PJ	4	7	3	10	n.e.	0	n.e.	0	increase	-1	n.e.	0	1	22	n.e.	0	n.e.	0
Melting_FF_MS	10	7	7	10	n.e.	0	n.e.	0	increase	-1	n.e.	0	3	22	n.e.	0	n.e.	0
Melting_WS_IP	1	18	0.5	26	n.e.	0	n.e.	0	increase	-2	0.4	35	1	22	n.e.	0	n.e.	0
Melting_WS_SC	0.4	20	0.3	30	n.e.	0	n.e.	0	increase	-2	0.2	35	0.3	22	2	4	n.e.	0
Melting_GA	-0.03	7	-0.02	10	n.e.	0	n.e.	0	-0.16	1	-0.01	21	n.e.	0	n.e.	0	n.e.	0
Melting_IS	n.e.	0	n.e.	0	n.e.	0	n.e.	0	n.e.	0	n.e.	1	n.e.	0	n.e.	0	n.e.	0
Melting_CM	-8	17	-63	2	-2	58	-2	53	n.e.	0	-5	26	n.e.	0	-5	24	n.e.	0
Melting_AE	n.e.	0	n.e.	0	n.e.	2	n.e.	1	n.e.	0	n.e.	1	n.e.	0	n.e.	1	n.e.	0
Melting_OF	57	4	n.e.	0	54	4	58	4	n.e.	0	5	45	n.e.	0	7	32	n.e.	0
Casting_WS_PB	5	41	3	64	n.e.	0	n.e.	0	n.e.	0	n.e.	0	3	74	5	40	n.e.	0
Casting_WS_SC	1	41	0.3	64	n.e.	0	n.e.	0	n.e.	0	n.e.	0	0.3	77	1	38	n.e.	0
Casting_nMA	-5	11	-3	17	n.e.	0	n.e.	0	-4	14	n.e.	0	n.e.	0	-3	23	-2	38
Casting_PA	7	20	5	30	n.e.	0	n.e.	0	4	33	n.e.	0	n.e.	0	4	40	2	90
Casting_rRR	8	15	8	15	7	16	8	15	8	16	9	13	7	16	9	13	7	16
Casting_rSR	-6	5	-6	5	-6	5	-6	5	-6	5	-7	4	-6	5	-7	4	-6	5
Finishing_rSR	-8	5	-8	5	-8	5	-8	4	-8	5	-9	4	-8	5	-9	4	-8	5
IT_eFL	-9	4	-10	4	n.e.	0	-5	8	n.e.	0	-2	20	n.e.	0	-2	19	n.e.	0

Note: n.e. = no effect, implying that this reduction option is not included in the cost-effectiveness analysis because $M_{zero\ case} - M_{zerocase+\tau} = 0$ or $M_{z,\ zero\ case} - M_{z,\ zerocase+\tau} = 0$. See Figures 5.3 and 5.4.

Note: "increase" indicates that this option is considered not cost effective because it leads to an increase in the potential impact (Mz), (i.e., $M_{z,\ zero\ case} - M_{z,\ zerocase+\tau} < 0$).

5.5. Reduction Strategies (combination of options)

So far, we analysed options as if they would be implemented individually. In practice, however, a company will most likely select a number of options and implement these simultaneously. Therefore, we define a number of reduction strategies, in which selected reduction options are combined. The strategies analysed aim at reducing the environmental impact of the plant relative to the zero case. We analyse the effectiveness of reduction strategies on emissions of specific pollutants (x), environmental impacts for specific impact categories (Mz) or the overall environmental impact (M). In addition, the costs associated with the combination of reduction options are calculated.

We analyse seven types of Reduction Strategies (Table 5.5). These strategies reflect different objectives of environmental management. For instance, Reduction Strategies of type I aim at reducing the largest environmental problem (in this case human toxicity). The second type (Reduction Strategies II) aim at reducing a specific activity rate (in this example the natural gas use), Reduction Strategies III focus on the reduction of a specific pollutant (as an example we take chromium emissions). Reduction Strategies IV combine the most cost effective reduction options, while Strategies V combine only add-on techniques. Alternatively, one may prefer to combine the more structural reduction options (Reduction Strategies VI) or to combine reduction options aiming at increasing the metal yield (Reduction Strategies VII).

Table 5.5. Description of the seven types of reduction strategies reflecting different combinations of reduction options. Results shown include the calculated reduction in overall environmental impact (M), and the associated net additional costs (C_{na}) for the company. See Table 5.2 for an overview of the reduction options.

Reduction Strategy	Combination of Reduction Options	Reduction Potential for M (%)	Net additional costs (C_{na}) (k€/year)
Reduction Strategies I: aiming at the reduction of the largest environmental problem (human toxicity)			
I-A	Casting_WS_SC + Casting_PA	44%	168
I-B	Casting_WS_SC + Casting_PA + Melting_WS_SC	64%	175
I-C	Casting_WS_SC + Casting_PA + Melting_WS_SC + Casting_rRR	69%	277
I-D	Casting_WS_SC + Casting_PA + Melting_WS_SC + Casting_rRR + Melting_GA	70%	277
I-E	Casting_WS_SC + Casting_PA + Melting_WS_SC + Melting_GA + Metal yield (MY=57%) [a)]	70%	258
I-F	Casting_WS_SC + Casting_PA + Melting_WS_SC + Melting_GA + Metal yield (MY=57%) [a)] + IT_eFL	74%	219
I-G	Casting_WS_SC + Casting_PA + Melting_WS_SC + Melting_GA + Metal yield (MY=57%) [a)] + IT_eFL + Melting_CM	87%	118
Reduction Strategy II: aiming at the reduction of a specific activity rate (ex: reduce natural gas use)			
II-A	Melting_CM + Casting_rRR	29%	16
II-B	Melting_CM + Metal yield (MY=57%) [a)]	30%	0
II-C	Melting_CM + Metal yield (MY=57%) [a)] + Melting_OF	32%	97
Reduction Strategies III: aiming at the reduction of a specific pollutant (chromium emissions)			
III-A	Melting_WS_SC + Casting_rRR	32%	126
III-B	Melting_WS_SC + Casting_WS_SC + Casting_rRR	67%	148
III-C	Melting_WS_SC + Casting_WS_SC + Metal yield (MY=57%) [a)]	67%	130
Reduction Strategy IV: aiming to combine the most cost effective reduction options			
IV-A	Melting_CM + Casting_nMA + Casting_rSR + Finishing_rSR + IT_eFL + Melting_GA	45%	-268
IV-B	Melting_CM + Casting_nMA + Casting_rSR + Finishing_rSR + IT_eFL + Melting_GA + Melting_WS_SC + Casting_WS_SC	84%	-239
IV-C	Melting_CM + Casting_PA + Casting_rSR + Finishing_rSR + IT_eFL + Melting_GA + Melting_WS_SC + Casting_WS_SC	86%	-51
Reduction Strategy V: aiming to combine add-on techniques			
V-A	Melting_WS_SC + Casting_WS_SC	61%	29
Reduction Strategies VI: aiming to combine more structural reduction options			
VI-A	Casting_nMA + Melting_CM + Melting_GA + IT_eFL	39%	-224
VI-B	Casting_nMA + Melting_CM + Melting_GA + IT_eFL + Melting_OF	40%	-113
VI-C	Casting_PA + Melting_CM + Melting_GA + IT_eFL	48%	-21
VI-D	Casting_PA + Melting_CM + Melting_GA + IT_eFL + Melting_OF	49%	91
Reduction Strategy VII: aiming at the increase of metal yield			
VII-A	Metal yield (MY=53%) [b)]	10%	149
VII-B	Metal yield (MY=55%) [c)]	12%	134
VII-C	Metal yield (MY=56%) [d)]	15%	118
VII-D	Metal yield (MY=57%) [a)]	16%	101

a) This "option" is the result of a combination of the reduction options leading to an increase on metal yield. These comprehend the options that reduce scrap rate and the runners' mass. The parameters in these options were varied resulting on a calculated metal yield (MY) of 57% (EIPPCB, 2005).

b) Metal yield equals 53%.

c) Metal yield equals 55%.

d) Metal yield equals 56%.

Reduction Strategies I: reducing the largest environmental problem (human toxicity)

The environmental impact of the plant is largely caused by emissions of compounds contributing to human toxicity (see section 5.3). Different combinations of nine reduction options are defined to decrease the emissions of these compounds. The reduction strategies (I-A to I-G) include options having a relatively large reduction potential (Figure 5.4, Table 5.5). For instance, strategy I-A combines the two most effective options (Casting_WS_SC and Casting_PA) reducing the company's contribution to human toxicity by 65% and 30%, respectively. The results indicate that reduction strategies of type I, although focusing on human toxicity problems only, may be relatively effective in reducing the overall environmental impact (M) (Figure 5.6). The overall environmental impact of the plant is reduced by 44% (I-A) to 87% (I-G) relative to the zero case (Figure 5.6, Table 5.5). The costs associated with these strategies range from 118 k€/y (I-G) to 277 k€/y (I -C and I-D).

Reduction Strategies II: reducing natural gas use

Although natural gas is a relatively clean fuel, it is non-renewable, so using it contributes to abiotic depletion, which is the second largest environmental problem caused by the company (see section 5.3). Three reduction strategies (II-A to II-C) are defined to reduce the use of natural gas (Figure 5.4, Table 5.5). For these strategies we calculate reductions in natural gas use around 65%, and a reduction in the overall environmental impact (M) of about 30% (Figure 5.6, Table 5.5). It is interesting to note that although these three strategies have similar impacts on the use of natural gas, their costs differ largely, ranging from 0 k€/y (II-B) to 97 k€/y (II-C).

Reduction Strategies III: reducing chromium emissions

Emissions of chromium contribute by about one-third to the overall environmental impact (M), followed by NMVOC emissions (22% contribution to M) and HF emissions (11% contribution to M) (Table 5.1). We analyse three different strategies to reduce chromium emissions (III-A to III-C) which combine options that increase the metal yield with the most effective emission abatement techniques. These reduction strategies are calculated to reduce chromium emissions by 34% (III-A) to 99% (III-B and III-C). The overall environmental impact is reduced by 32% (III-A) to 67% (III-B and III-C) (Figure 5.6, Table 5.5). The cost associated with these strategies ranges from 126 k€/y (III-A) to 148 k€/y (III-B). Clearly, the potential to reduce emissions of chromium is large, but the associated costs are relatively high.

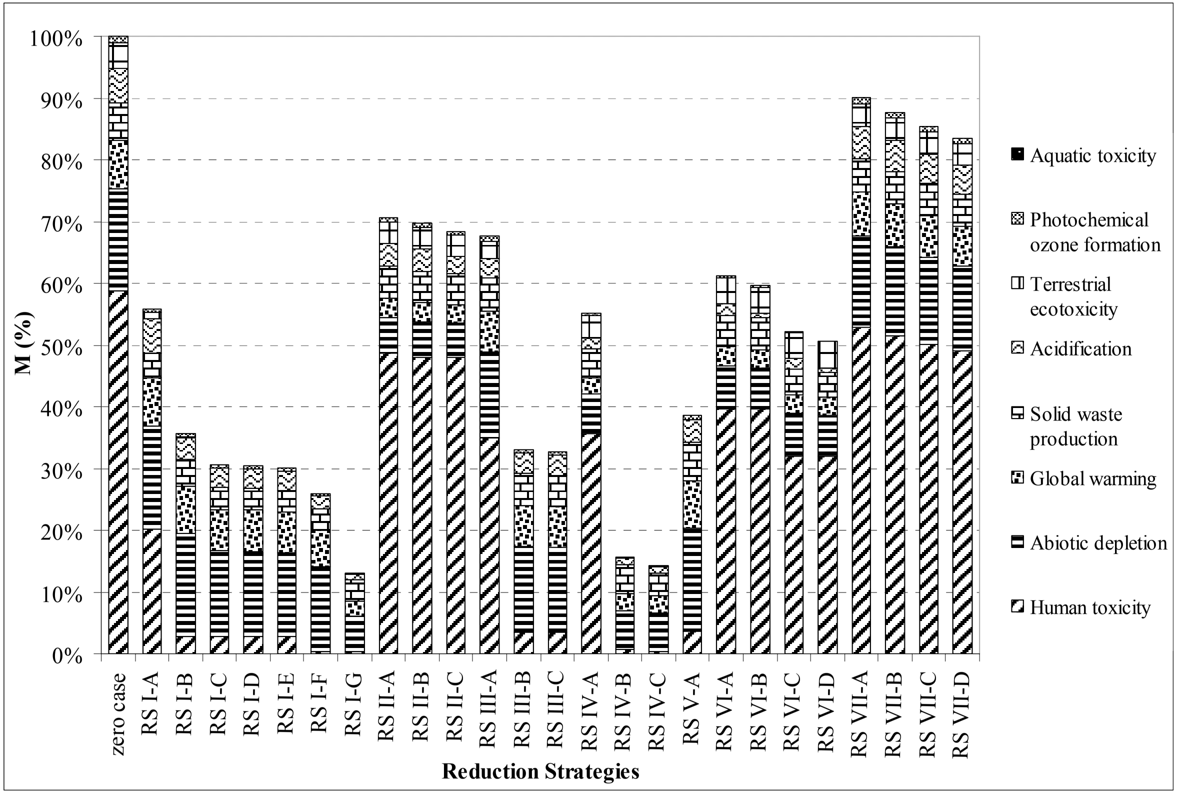

Figure 5.6. Overall environmental impact (M) for the zero case and for the alternative reduction strategies. The valuation method used on the overall environmental impact assessment considers that all environmental problems to be equally important. See Table 5.5 for a description of the reduction strategies. (unit: % relative to M for the zero case).

Reduction Strategies IV: combining the most cost effective options

Combining the most cost effective options is probably the most interesting from a company perspective. In reduction strategy IV-A, we combine the six options reducing M and having simultaneously, a net negative costs (Melting_CM, Casting_nMA, Casting_rSR, Finishing_rSR, IT_eFL and Melting_GA). In strategies IV-B and IV-C we also consider options having relatively low costs, but that are relatively effective in reducing the environmental impact (Melting_WS_SC, Casting_WS_SC and Casting_PA) (Table 5.4). The overall impact is calculated to be reduced by 45% (IV-A) to 86% (IV-C) (Figure 5.6, Table 5.5). The cost associated with these strategies are calculated to be negative ranging from -268 k€/y (IV-A) to -51 k€/y (IV-C). These results indicate that relatively large reductions (up to 85%) in environmental impact are possible while gaining money.

Reduction Strategies V: combining add-on techniques

Some add-on techniques are known to have a relatively large potential to reduce emissions of specific compounds. We selected relatively effective options that also have relatively low cost (Figure 5.3, Figure 5.5). These options include two wet scrubbers (Melting_WS_SC, Casting_WS_SC). Reduction strategy V-A is calculated to reduce the overall environmental impact (M) by 61% at an associated cost of 29 k€/y (Figure 5.6, Table 5.5).

Reduction Strategies VI: combining more structural reduction options

Four different combinations of more structural reduction options are analysed (VI-A to VI-D). The options increasing the metal yield are analysed separately (see Reduction Strategies type VII). The reduction strategies are calculated to reduce the overall environmental impact by 39% (VI-A) to 49% (VI-D) relative to the zero case (Figure 5.6, Table 5.5). The costs associated with these strategies range considerably from -224 k€/y (VI-A) to +91 k€/y (VI-D). Clearly, strategy VI-A is the most interesting, given the negative costs.

Reduction Strategies VII: increasing the metal yield

Increasing the metal yield is generally considered an important strategy to reduce pollution from the metals sector industry and in particular to the case plant studied. Here we selected options that aim to decrease the alloy mass inputs returning to melting furnaces and as such reduce all materials and energy needed in the die casting process. Options that increase the metal yield (MY) are those that reduce the scrap rate (Casting_rSR and Finishing_rSR) and those that reduce the runner's mass by using new die casting moulds (Casting_rRR) (Table 5.2). Four different reduction strategies (VII-A to VII-D) are defined to increase the metal yield (for comparison: the MY in the zero case is 47%). These strategies were calculated to reduce the overall environmental impact from 10% (VII-A) to 16% (VII-D) (Figure 5.6, Table 5.5). The costs associated with these strategies range from 149 k€/y (VII-A) to 101 k€/y (VII-D). It is interesting to note that increasing the metal yield, although generally considered an important strategy, is not very effective in reducing the environmental impact, and is relatively costly. Compared to the other strategies that we analysed, increasing the metal yield is perhaps not the first choice.

Comparing the different strategies

From the above, it may be clear that the different strategies that we analysed differ largely in their potential to reduce the environmental impact of the company (10 – 87%) as well as in the costs associated with the implementation of options (-268 to +277 k€/year). We were able to define 11 strategies reducing the overall environmental impact by more than 50%. Of these, two have net negative costs, indicating that the company may in fact earn money by implementing them. The largest effect on the environment (87% reduction in M) is calculated for strategy I-G, which in fact focuses on reducing the human toxicity. This is mainly because compounds with a human toxicity effect have the largest share on the overall impact (M), making strategy I-G very effective to reduce the overall impact. However, this strategy, is rather costly (118 k€/year). A similar reduction (86%) could be obtained while gaining 51 k€/year for reduction strategy IV-C, which is a combination of relatively cost effective options. If we combine only the highly cost effective options, the savings are even larger (-268 k€/year) while reducing the environmental impact by almost 45% (IV-A).

5.6. Discussion and Conclusions

This study explores a model (MIKADO) that assesses options to reduce the environmental impact of a plant supplying car manufacturers with aluminium die casting products. MIKADO includes a number of options for emission reduction, and can be used to calculate their technical potentials to reduce the environmental impact as well as the associated costs. We analysed individual reduction options, as well as reduction strategies, in which options are combined. MIKADO may support environmental decision making, by assisting the management of the company in answering "what …if" type questions (e.g. 'What would the effect on the environment and on the costs be if we implement the following options?).

First, we analysed the so-called zero case, assuming that none of the reduction options is implemented. The overall environmental impact of the plant is mostly associated with human toxicity (caused by metal emissions and emissions of ozone precursors), and abiotic depletion of natural gas. These two environmental problems account for about 75% of the overall environmental impact. This may be not too surprising since the main compounds released by the industry are metals, including heavy metals and some volatile organic compounds, both contributing to human toxicity problems. More than 90% of the overall environmental impact of the company comes from the sub-processes Melting and Casting. More specifically, we conclude that there are four relatively large sources of environmental pollution in the aluminium die casting plant: emissions of chromium and NMVOCs from Casting, the use of natural gas in Melting and emissions of hydrogen fluoride from Melting. These four are responsible for about two-thirds of the overall environmental impact.

Second, the 18 individual reduction options were analysed systematically with respect to their potential to reduce the environmental impact of the company, and the associated costs. The individual options may reduce the environmental impact by up to 40%. The largest reductions in environmental impact were calculated for two different types of wet scrubbers in Casting. These scrubbers are particularly effective in reducing emissions having a large effect on human toxicity. The cost associated with the implementation differs largely for the 18 options. Six options have net negative costs, implying that the company may in fact earn money by implementing them. These include the option to compact the metal load; the use of a new mould release agent, the use of electric fork-lift trucks, the reduction of the scrap rates and the use of a granular agent. These options are also the most cost effective options. Of these, compaction of the metal load may be the most interesting, given its relatively large effect on the environment (17% reduction of M).

We defined seven different types of reduction strategies in which reduction options are combined. The strategies defined include combinations of reduction options that aim I) to reduce the largest environmental problem (human toxicity); II) to reduce the use of natural gas, III) to reduce a specific pollutant emission (chromium); IV) to combine the most cost effective reduction options; V) to combine only add-on techniques; VI) to combine more structural reduction options or VII) to increase the metal yield. These strategies differ largely in their environmental impact (10 – 87% reduction) and net additional costs (-268 to +277 k€/year) (Table 5.5). The most effective strategy is a combination of options to reduce human toxicity problems (I-G). This strategy reduces the overall environmental impact by 87%, however at relatively high costs (118 k€/y). A similar reduction in M (86%) can be obtained by combining relatively cost effective options (IV-C), at net negative costs (-51 k€/y). The best paying strategy (IV-A) is reducing the environmental impact by 45% while gaining 268 k€/year.

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Chapter 6: Conclusions and Discussion

6.1. Introduction

The overall objective of this thesis was to develop a decision support tool (DST) to analyse options to reduce the environmental impact of an industrial company. A model was developed that allows for the assessment of the potential environmental impact resulting from emissions of environmental pollutants, as well as the effectiveness of reduction options and the associated costs. In this chapter the conclusions are drawn.

In section 6.2. conclusions are drawn from the answers to the four research questions as well as with respect to the overall objective of this thesis. We also address the stepwise systems analysis procedure taken, and the applicability of the methodological approach to other industries.

Section 6.3 includes a discussion of the results of the study. This discussion focuses on the environmental systems analysis approach taken (6.3.1), the uncertainties involved (6.3.2) and the implications of our DST for industry in general (6.3.3.).

The chapter ends with recommendations for future studies (6.4.).

6.2. Conclusions

In Chapter 1 we have formulated four research questions in order to meet the objectives of the thesis. In the following, we present the research questions and our conclusions.

Research question 1: "What existing environmental systems analysis methods and tools can in principle be combined in a decision support tool (DST) and used to analyse the environmental performance of a plant from a company perspective?".

- It can be concluded that careful selection of environmental systems analysis tools is important. In this thesis, selection of tools was based on the desired characteristics of the DST to be developed.

- We aim for an analysis that: 1) takes a company perspective; 2) includes environmental and economic aspects of decision making, 3) includes a complete coverage of the potential environmental impacts and 4) allows for an assessment of the consequences of a set of alternative strategies on pollution reduction.

- We conclude that for such analysis a DST is needed that i) considers a gate-to-gate approach; ii) considers the processes within the company that are relevant for the assessment of the environmental impact; iii) uses company's specific data easily available from the process owner; iv) considers up-to-date and company specific pollution reduction options; v) provides information on the cost-effectiveness of the reduction options; vi) can be used to express the company's environmental performance in one overall indicator; and lastly vii) may be used to explore possible user-defined pollution reduction strategies.

- Based on these characteristics, we conclude that the following seven ESA tools form a good basis for our DST: Life Cycle Assessment (LCA), Substance Flow Analysis (SFA), Multi-Criteria Analysis (MCA), Technology Assessment (TA), Sensitivity Analysis (SA), Scenario Analysis (ScenA) and Cost-Effectiveness Analysis (CEA).

Research question 2: "Which technical pollution reduction options are available for reducing the environmental impact of an aluminium pressure die casting plant? What are their technical potentials to reduce this impact, and the associated costs for the plant?"

- We conclude that in an analysis of the environmental performance of an aluminium die casting company, it is important to consider five main sub-processes: 1) Melting, 2) Casting, 3) Finishing, 4) Internal Transports and 5) Auxiliary Burners. Each sub-process includes a series of process operations here referred to as sub-sub-processes.

- Eighteen technical reduction options have been identified that could be applied by the aluminium pressure die casting plant. The options aim at reducing the different pollutants emitted by a specific sub-sub-process level within the company. The emissions of pollutants include air emissions, liquid effluents or solid wastes. The options considered may be typical end-of-pipe solutions (including fabric filters and scrubbers) or be more structural and use of alternative agents or techniques; modify the combustion process; use new die casting moulds; reduce the scrap rate and use electrical equipment.

- We conclude that the technical potentials to reduce the environmental impact vary for the different types of options. Relatively large reduction potentials exist, for example, for fabric filters or wet scrubbers which reduce emissions of heavy metals by 99% (e.g. cadmium and nickel). Some options affect a more than one pollutant. This may happen in different ways. Options may reduce the use of materials that cause environmental problems (e.g. new mould release agent); or replace materials by less pollutant ones (e.g. the use of granular desoxidation agent and the use of nitrogen in the impeller station) or modify the production process (e.g. compact metal load or the use of oxygen) and consequently decrease the use of natural gas. Some options have side effects such as the use of additional materials, energy or the production of additional pollutants, or both. Examples include filters and scrubbers (additional electricity use and production of waste).

- The associated implementation costs vary with the type of option. Some options are more expensive than others: calculated net additional costs vary from -128 to 224 k€/year. The net additional costs are calculated as the sum of annualised capital costs with fixed and variable costs of a certain option. Net additional costs may be negative if the implementation of a reduction option brings revenues for the facility.

Research question 3: "How can a model be developed that can be used from a company perspective to analyse options to reduce the environmental impact of aluminium pressure die casting?"

- We conclude that developing a model from a company perspective requires careful definition of system boundaries, processes considered and reduction options included.

- The model developed (MIKADO) calculates the main mass flows within the production chain as well as sub-processes and sub-sub-processes that lead to environmental problems. Only those processes are considered that can be managed by the plant managers. Likewise, the pollution reduction options included are applicable by the plant management.

- The model calculates the required input of materials and energy based on the production rate. The model inputs include raw materials (aluminium alloy ingots), energy (natural gas and other fuels used on internal transports and in auxiliary burners) and subsidiary materials such as the desoxidation and degassing agents, mould release agents, lubricants, water, steel shot, ceramic abrasives, detergent and other agents used in the wastewater treatment plants. These inputs, the so-called activity rates, are quantified for specific activities and include, for instance, the use of energy or a specific material. The activities rates are used to calculate emissions of pollutants, using an emission factor.

- In MIKADO the emissions are directly linked to the materials and energy use in the facility sub-process or sub-sub-process and include air emissions (as aluminium (Al), zinc (Zn), cadmium (Cd), nickel (Ni), lead (Pb), chromium (Cr), copper (Cu) and iron (Fe)); natural gas combustion related emissions (CO_2, CO, NOx, NMVOC); hydrogen fluoride (HF) emissions resulting from the use of desoxidation and degassing flux; non-methane volatile organic compounds (NMVOCs) resulting from the mould release agent spraying technique; solid wastes (aluminium dross; furnace linings, steel shot, ceramic abrasives and burrs), liquid effluents and fuel-related combustion emissions resulting from Internal Transports and Auxiliary Burners.

- From a company perspective is important that the model output is transparent and relevant. Important MIKADO outputs include emissions of pollutants, the potential environmental impact for a number of environmental impact categories and the overall potential environmental impact resulting from the emission of these pollutants. The environmental impact assessment methodology used follows current approaches in Life Cycle Assessment and Multi-Criteria Analysis.

- MIKADO can be used to calculate emission reduction and costs associated with the implementation of pollution reduction options. These costs are regarded as additional costs for the company. For industrial users of the model it is essential that the implementation costs of pollution reduction for the company are quantified.

- For model users it is important to have insight in the robustness of the model results. Therefore, a partial sensitivity analysis was carried out for MIKADO. We conclude that variations in individual model parameters change the calculated overall environmental impact only to a limited extent. Parameters to which the model is most sensitive include those related with alloy mass flow, and in particular, the ones related with the increase of metal yield (as the runners mass).

Preliminary model runs were performed for a case in which no reduction options are assumed to be implemented (so-called zero case) and for a systematic analysis of the implemented individual reduction options. The results obtained allow for the following conclusions:

- More than 90% of the environmental impact of the plant comes from Melting and Casting. Moreover, the results indicate that the environmental impact is mostly associated with human toxicity problems (caused by metal emissions, and emissions of ozone precursors), and the abiotic depletion of natural gas. These two environmental problems account for about 75% of the overall environmental impact. The main compounds released by the industry are metals, including heavy metals, and some volatile organic compounds both contributing to human toxicity problems. Another conclusion is that about two-thirds of the overall environmental impact is caused by emissions of chromium and NMVOCs from Casting, the use of natural gas in Melting and emissions of hydrogen fluoride from Melting. This conclusion is relatively insensitive to the valuation of the environmental impacts.

- The environmental impact may be reduced by up to 40% by implementing single reduction options. The largest reductions in environmental impact were calculated for two different types of wet scrubbers in Casting. These scrubbers are particularly effective in reducing emissions having a large effect on human toxicity. The costs associated with the implementation differ largely for the eighteen options. Six options have net negative costs, implying that the company may in fact earn money by implementing them. These include the option to use granular desoxidation agent; to compact the metal load; the use of a new mould release agent, the use of electric forklift trucks and the reduction of the scrap rates. These options are also the most cost effective options. Of these, compaction of the metal load may be the most interesting, given its relatively large effect on the environment (17% reduction of environmental impact).

Research question 4: "How do different strategies to combine pollution reduction options improve the environmental performance of an aluminium pressure die casting plant, and what are the associated costs for the plant?"

- Seven types of reduction strategies were developed and analysed. The strategies aim to reflect different management options to reduce the environmental impact and simultaneously the associated cost. They aim: I) to reduce the largest environmental problem (human toxicity); II) to reduce the use of natural gas, III) to reduce a specific pollutant emission (chromium); IV) to combine the most cost effective reduction options; V) to combine only add-on techniques; VI) to combine more structural reduction options, or VII) to increase the metal yield.

- The seven strategies types differ largely in their calculated reduction of the environmental impact (10 – 87%) and net additional costs (-268 to +277 k€/year). The most effective strategy is a combination of options to reduce human toxicity problems (I-G). This strategy reduces the overall environmental impact by 87%, however at relatively high costs (118 k€/y). A similar reduction in the environmental impact (86%) can be obtained by combining relatively cost effective options (IV-C), at net negative costs (-51 k€/y). The least effective strategy is related with metal yield increase (VII-A). This strategy reduces the calculated overall environmental impact only by 10% at an associated cost of 149 k€/y. Eleven strategies could be defined which reduce the overall environmental impact by more than 50%. Of these, two have net negative costs, indicating that the company may in fact earn money through their implementation.

- The most paying strategies are to combine cost effective options. The most paying strategy (IV-A) reduces the environmental impact by 45% while gaining 268 k€/yr. Other combination of options may reduce the impact by 84% (IV-B) at a net cost of –239 k€/y or reduce the impact by 86% at a net cost of -51k€/y. The most costly strategies (I-C and I-D) are related with the reduction of the largest environmental impact (human toxicity). These strategies reduce the impact of about 70% at a net cost of 277 k€/y.

- Strategies to increase the metal yield do not have a large potential to reduce the environmental impact. Strategies to reduce natural gas use (II-B) or combinations of more structural options (VI-A to C) have a larger potential to reduce the environmental impact at a zero or net negative costs. For the reduction strategy that reduces natural gas us (II-B) we calculate a 30% reduction in the overall environmental impact at zero costs and for the strategy that combines more structural options (VI-C) a 48% reduction in the impact at a cost of -21 k€/y. The remaining strategies have reduction potentials ranging from 49% (for a strategy combining structural options; VI-D) to 87% (for a strategy focusing on human toxicity problems; I-G). These are associated with higher costs of 91 k€/y (VI-D) and 118 k€/y (I-G), respectivelly. We conclude that it is possible to substantially decrease the environmental impact by using end-of pipe techniques but at a relatively high cost, except when costs of add-on techniques are compensated by benefits of paying options. For combining the most cost effective options (strategy IV-C) a large reduction in the impact (86% reduction) is calculated while gaining 51 k€/y.

- *Concluding remarks*

In the following, we address some novel aspects of this thesis, including: 1) the company perspective; 2) the involvement of plant managers; 3) the environmental systems analysis research strategy (sequence of ESA steps and iterations), and 4) the selection of ESA tools.

We conclude that taking a company perspective is valuable and essential for ensuring the usefulness of our DST MIKADO. The company perspective is reflected by the definition of system boundaries, the production processes included and the pollution reduction options considered. Knowing the point of view of the company helped in defining these important model characteristics. The DST considers the industrial processes that can be managed by the plant managers, plus the different types of environmental problems that the plant contributes to (air emissions, liquid effluents, solid wastes and natural resources used). The results from the DST help the company manager to decide where to focus on when reducing the overall environmental impact. For the plant studied here the focus should be on the Melting and Casting processes. These two processes contribute most to the overall environmental impact through causing human toxicity problems (through heavy metals emissions) and depletion of energy resources (through the use of natural gas).

We conclude that regular contact with plant managers during the model development was essential for ensuring that the DST fulfils their expectations on the assessment of the environmental performance of the plant. A result of these contacts is, for instance, that only those options are included in the DST that managers are able to control. A major strength of the DST to plant managers is its flexibility. The tool is flexible because users can define their own scenarios for environmental management. Furthermore, the priorities of the plant manager in the environmental management can be taken into account in the model. This is because the user of the DST can decide on the valuation of the environmental problems caused by the plant. Finally, the DST is flexible in that model parameters can be easily adjusted. All this contributes to the willingness of the plant manager to use our DST to analyse possibilities for environmental management in the plant.

This environmental systems analysis consisted of a unique sequence of steps and iterations, considered the most appropriate for this study. From experience we can conclude that systems analysis is useful to assist decision making in finding solutions for complex environmental problems. Complex problems require integrated studies in which knowledge from different disciplines is combined. The stepwise procedure provides a basis for the analysis of environmental problems from the industrial plant. Moreover, the steps are not performed sequentially because in practice we experienced that iterations between steps are needed. We conclude that environmental systems analysis as performed in this thesis may assist industrial plant managers in analysing options to reduce the environmental impact of an industrial company. This may also hold for other plants than the one studied here.

We conclude that the procedure to select ESA tools followed in this thesis was important to meet the thesis overall objective. This procedure and the resulting combination of the tools may serve as an example for other studies. We conclude that the combination of environmental systems analysis tools, as used in the thesis, can assist company management in the analysis of possible strategies to improve a company's environmental performance.

6.3. Discussion

6.3.1. Discussion of the environmental systems analysis approach

The research approach followed in this thesis is based on Checkland (1979), Wilson (1984), Findeisen and Quade (1997), and Pluimers (2001). The procedure followed six steps: 1) Problem definition; 2) Evaluation and selection of existing Environmental Systems Analysis Tools; 3) Identification of pollution reduction options; 4) Model building (includes sensitivity analysis); 5) Model application (includes the analysis of model performance) and 6) Evaluation of the methodological approach. A detailed description of the steps can be found in Chapter 1.

- *Iterations*

Even though this study is based on existing ESA studies, its approach is unique with respect to the sequence of ESA steps and the iterations as schematised in Figure 6.1. In the literature, these six steps are often presented as sequential. However, in practice iterations are useful and needed, as also shown by Findeisen and Quade (1997), Pluimers (2001) and Jawjit (2006). In this study, we have performed four iterations that proved to be useful. The iterations occurred from *model building* (Step 4) to *problem definition* (Step 1); from *model building* (Step 4) to *evaluation and selection of ESA tools* (Step 2), from *model building* (Step 4) to *identification of pollution reduction options* (Step 3) and lastly from *model application* (Step 5) to *model building* (Step 4).

The iteration from *model building* (Step 4) to *problem definition* (Step 1) appeared necessary to refine the problem formulation and to better define the system from a company perspective. In this thesis, the problem definition includes not only the formulation of research objectives, but also the definition of the system. We aimed for a tool that takes a company perspective, and focused on a specific aluminium pressure die casting plant. Most of the existing studies in the literature rather focus on industrial sectors as a whole than taking a company perspective (e.g. Rabah (1999), Kim et al. (2003), Dalquist and Gutowski (2004), Backhouse et al. (2004), Tan and Khoo (2005)). In this thesis, the system was first defined for the example plant and an initial model was designed and, after consultation with experts in the plant, redesigned. The eventual system boundaries were set at the plant gates. The flows of materials and energy outside the plant were not included in our system. These choices were in part made after several iterations with the plant experts, leading to redefinition of both the problem and the model set-up. One may argue that our final system excludes significant environmental problems outside the plant gate, but associated with the plant processes (e.g. the transport of the raw materials (aluminium ingots) to the plant). We consider our analysis to be complete in terms of the potential influence of the management on the environmental problems caused by the plant. Some potential environmental problems were not included in the model, while we initially considered including them. They are the nuisance, odour, vibration, heat wasted and desiccation.We argue that these are minor issues, and difficult to assess. Although there is plant-specific data available on noise caused by the industrial process (EMAS organisations, 2006), it is difficult to assess the environmental impact caused by noise. The same holds for vibration, wasted heat and desiccation. Our analysis also did not take into account emissions that may occur during plant maintenance operations or in emergency situations. The choices to include or exclude processes from the DST were made during the model building and after redefining the problem. A similar iteration is also performed by Jawjit (2006), however, for a slightly different purpose. His purpose was to assure that the model meets all the research objectives. Here, the iteration was mainly driven by discussions with the company management.

The next iteration was from *model building* (Step 4) to *evaluation and selection of ESA tools* (Step 2). This appeared necessary to ensure that our model (DST) is based on a relevant set of ESA tools and to ensure that the model meets the purpose of the model user. The plant managers expressed their views on the environmental performance of the company. Based on the contacts with these envisaged model users we formulated four criteria for our DST that led to the final selection of the seven ESA tools (see Chapter 2). However, this took in part place during the model building step. The final set of tools used appears to be useful for modelling materials and energy flows in the industrial process (LCA and SFA); assessing a complete set of potential environmental problems (LCA); assessing the overall environmental impact in one aggregated indicator (MCA) and analysing the model sensitivity (SA). Technology Assessment (TA) proved to be useful to define pollution reduction options and was combined with the tools ScenA and CEA. This made it possible to analyse the possible scenarios for impact reduction and to assess the cost-effectiveness of the reduction strategies. Summarising, the selection of tools was done in iteration with the model building, and driven by the input from the potential model users.

The iteration from *model building* (Step 4) to *identification of pollution reduction options* (Step 3) appeared useful in finalising the list of pollution reduction options included in the model. The final list is based on knowledge gained during the model building process and discussions with the plant experts as the envisaged model users. The options are defined such that they cover relevant pollutants and activities and allow for calculating the associated costs to the plant. Some of the options were proposed by the plant managers after the initial model set-up had been designed. Others were added even later to the model. And a few were deleted from the original list (e.g. the lowering of the temperature in the holding furnaces, or the replacement of burners by electrical equipment). Again the boundaries of the system were refined by this iteration. The options considered were only included if they can be managed directly by the plant managers. This iteration is also considered by Findeisen and Quade (1997), for the purpose of adjusting model parameters.

A final iteration performed in this thesis is from *model application* (Step 5) to *model building* (Step 4). For example, after model application we observed that the overall environmental impact was not affected significantly by the four different valuation factors used for the different environmental problems. The results appear to be not sensitive to the valuation methods. Therefore we only use one set of factors to analyse the scenarios on pollution reduction strategies in the last chapters of the thesis. This iteration is also considered in the literature (Findeisen and Quade, 1997; Jawjit, 2006).

There are iterations mentioned in the literature which have not been performed in this thesis. A first example is the iteration from *model application* (Step 5) *to problem definition* (Step 1) as indicated by Findeisen and Quade (1997). They argue that this iteration is useful, because it is usually impossible to set the objectives and determine the constraints with precision before knowing their implications. In this thesis, the problem was not redefined after the model application. Rather, we presented seven different scenarios for pollution reduction strategies, reflecting different types of objectives for environmental management strategies. These strategies may be adopted by the plant management. In the future, these views may change giving rise to redefinition of scenarios or of the problem. A second example that was not performed here is from communication of the results (or results presentation) to *problem definition.* According to Findeisen and Quade (1997), presenting results of systems analysis to the users of the results often leads to reformulating the problem or to reconsidering constraints, objectives or criteria. We did not perform this iteration in this thesis. It may, however, be part of future work.

We argue that our stepwise procedure, including the four iterations performed, and the involvement of the plant managers resulted in a tool that is useful for assisting industrial managers to decide on environmental management. It takes a company perspective, as reflected by the system definition, processes and reduction options included and the results obtained.

An interesting characteristic of our approach is that there is no link between the steps *evaluation and selection of existing ESA tools* (Step 2) and the *identification of pollution reduction options* (Step 3). This implies that these two steps are applied simultaneously. They both aim for the consistency of the model with the wishes of the plant managers. The evaluation and selection of existing ESA tools (Step 2) serves the model building and ensures that the model indeed takes the company perspective. The identification of pollution reduction options (Step 3) also serves the model building and ensures that the model only includes relevant options. Therefore, the simultaneous application of these two steps seems to be a strong point of the approach taken.

Throughout the analysis industrial plant managers have been involved. We consider this a strong point of our approach. After the problem formulation, the management board contributed to the system definition (Step 1), the selection of the ESA tools (Step 2), the identification of some pollution reduction options (Step 3), the model building (Step 4) and to the model application (Step 5). The initial contact, during the problem formulation phase, was with the management board of the plant. After the plant directors agreed to provide data from the plant for our case study, a formal cooperation protocol was signed on the confidentiality of information about the plant. The cooperation protocol included the initial purpose of the research and a work plan. The consecutive contacts during the research were primarily with plant managers who helped to collect data for the inventory and who answered process related questions. These contacts assisted in learning the managers' point of view, which we used to formulate the DST characteristics. Moreover, preliminary results of the analyses were presented to plant experts. On average, plant managers, were contacted every four months, throughout the research period. Part of the data collection was done at the site of the plant. We agree with Findeisen and Quade (1997) that this type of feedback from the model users in each step is essential to ensure that the decision support tool is meeting the industrial managers' needs.

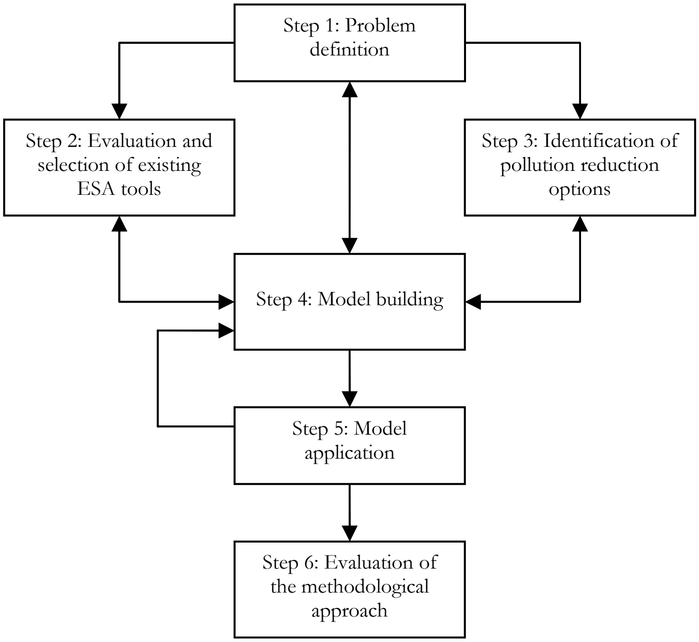

Figure 6.1. The procedure followed: a stepwise approach.

- *Stepwise approach*

Although the sequence of steps followed is based on other systems analysis approaches, there are some differences in the individual steps, between our approach and other studies. The number of steps considered is similar to the studies performed by Jawjit, (2006), Pluimers (2001) and Findeisen and Quade (1997), which are based on the studies by Wilson (1984) and Checkland (1979). However, we observe some differences between our stepwise approach and that of others. In the following, we discuss three of these differences.

The first difference is related to Step 2: *Evaluation and selection of existing ESA tools*. We do not know of other systems analyses in which the selection of analytical tools is described in this level of detail. Selection of tools is not explicitly mentioned as a step in the analysis by other authors describing the methodology of systems analysis (e.g. Findeisen and Quade (1997), Wilson (1984) and Checkland (1979)). Also authors applying environmental systems analysis only discuss the usefulness of the tools but not their selection. (e.g. Pluimers (2001) and Jawjit (2006)). Moreover, Finnveden and Moberg (2005) overview existing ESA tools and conclude that there is a lack of ESA tools that can assess both environmental and economic impacts of organisations and companies. Our approach for the selection of tools may be useful for other studies. It can serve as an example of how to successfully combine a selection of the currently available ESA tools, in order to assist companies in performing studies on environmental impacts of organisations. The characteristics of our DST also can serve as an example of a DST, fulfilling the expectations of companies, to assess environmental performance. We argue that a selection procedure of tools based on characteristics of the desired model is essential in any study aiming at environmental decision support.

The second difference is related to Step 5: *Model application*. In the work by Pluimers (2001), Wilson (1984) and Checkland (1979), the systems analysis includes an optimisation analysis. This results in a selection of the optimal system. For instance, Pluimers (2001) analysed cost-optimal strategies to reduce the environmental impact of greenhouse horticulture in the Netherlands. Our approach is different. We perform another type of systems analysis answering "*what if*" type of questions. This implies analysis of future trends by using the model. Some systems analysts advise to analyse future trends before building a model (Findeisen and Quade, 1997). Our approach is different, but in line with, for instance, Jawjit (2006). We aim at providing assistance in deciding on a limited number of alternatives (decision analysis). Therefore, we develop a model to analyse user-defined scenarios for pollution reduction by the industry. The model is used to analyse scenarios and thus the scenario analysis is carried out after model building. Advantages of MIKADO over other approaches include its flexibility, transparency and user-friendliness as scenario generator. The user can analyse various environmental management strategies, expressing alternative environmental objectives, and use it to assist decision making. By repetitive analyses, a user can decide on a preferred strategy. However, the model can not be used for optimisation analysis, aiming, for instance, at finding cost-optimal solutions. One may argue that this is a shortcoming of MIKADO. However, a disadvantage of optimisation analysis is the risk for theoretical optima while the results may be more difficult to interpret by the plant managers.

Thirdly we look at Step 6: *Evaluation of the methodological approach*. This step is not mentioned in the systems analysis literature. However, including it as a separate step, it ensures reflecting on the applicability of the approach to other industries or sectors. In this chapter (Chapter 6), we therefore explicitly address the environmental systems analysis approach in terms of iterations performed, the sequence of steps taken and the ESA tools used to the development of our decision support tool. We evaluate the model uncertainties and reveal the implications of the thesis results for industry in terms of the usefulness to combine the seven ESA tools, the identification of the eighteen pollution reduction options and the consequences of the results from the scenario analysis for the aluminium pressure die casting sector.

- *Comparison with other model studies*

Our DST MIKADO was built to be used by industrial company managers. This is different from many other models which are mostly meant to be used by environmental policy makers or environmental analysts. MIKADO focuses on the environmental management in an industrial plant. It can be classified as a deterministic model. An alternative would be a stochastic approach, which would have made a quantitative assessment of uncertainties possible. MIKADO is a steady-state model. No dynamics are described in emissions, environmental impact, nor in the demand for production. Further, it describes future trends by calculating (steady-state) results for different years. MIKADO also calculates the cost-effectiveness of pollution reduction and the environmental impact in physical units (e.g. €/unit CO_2 equivalents). Other models allow for cost benefit analysis (e.g. the MERGE model by Manne (1995)). MIKADO is also designed to perform scenario analysis and not for optimisation analysis, such as some others (e.g. Pluimers (2001), Brink (2003) and the RAINS model (Alcamo et al., 1990)). Instead, we aim for a flexible tool to analyse possible scenarios based on "what if" type of questions. A strong point of MIKADO is its capability to evaluate combinations of options, defined by the user, to reduce the environmental impact of an industrial plant. Our results may be expressed in terms of the overall environmental and the associated costs for the company of the pollution reduction strategy.

We have chosen to develop our DST MIKADO by combining a selected set of ESA tools, because individual tools are in itself not sufficient. We agree with Wrisberg et al. (2002) that combining tools is needed to overcome weaknesses of individual tools, and because single tools typically are not addressing all relevant questions. Moreover, our integrated environmental study requires combined knowledge from different scientific disciplines (as suggested by Huggett (1993)). Our DST combines parts of seven tools. However, other tools exist (see Chapter 2). As discussed earlier (Chapter 2, section 2.4) they were not included here as a first choice based on the criteria set to select the tools. Nevertheless, they may contain useful elements for studies at the company level. Potentially interesting are, for instance, environmental performance evaluation, cost benefit analysis and total cost assessment. These tools can provide additional information to the plant managers. However, we argue that our selection is sufficient regarding the nature of the plant, and the environmental problems at stake.

6.3.2. Uncertainties

Uncertainties in model-based decision support tools may be associated, among others, with model structure and model parameters (Van der Sluijs, 1997; Walker et al., 2003). In the following we address these categories of uncertainties for our DST MIKADO.

Uncertainties associated with the structure of MIKADO relate, for instance, to the system boundaries, the processes and pollutants included and the multi-criteria analysis used to assess the plant's overall environmental impact. Structural uncertainties may be due to incomplete knowledge of the system with respect to the potential environmental effect of the plant. Another source of uncertainty is the perspective of the plant manager that formed the basis for some model characteristics. Plant managers may have a narrow view on environmental management, because of current legislation, or simply by lack of knowledge. This could lead to an incomplete assessment of environmental issues in the model. In our case, we avoided such problems by considering not only production processes and pollution reduction options considered important by plant managers, but also those that appeared relevant from the literature. This resulted in a final structure for MIKADO different than initially defined. For instance, the plant managers initially did not consider *filters and scrubbers* and *alternatives to mould release agent application* relevant, because these options reduce pollutants for which environmental standards were already met. As a result, the plant managers did not consider these pollutants of primary interest. However, we decided to nevertheless include these options in MIKADO, because they have a large potential to reduction of the *overall* environmental impact of the plant. Moreover, implementing these may result in cost benefit for the company. The combination of *scrubbers, alternative mould release agent* and other more structural options is among the most cost effective strategies for pollution reduction. Another source of structural uncertainty relates to the multi-criteria methods used to assess the overall environmental impact. We used different sets of weighting factors that are not plant specific. This is on the one hand a strong point of the DST. Each set of weighting factors reflects a view on valuating environmental problems, and using several sets illustrates the relative importance of these views on the environmental assessment. However, the factors included in MIKADO do not necessarily reflect the preferences of the managers of the specific plant for which MIKADO was developed. Therefore, in future analyses we recommend that model users define their own sets of weighting factors. We also recommend using multiple multi-criteria methods, revealing the consequences of subjective choices.

A second category of uncertainties is associated with the values of parameters used in MIKADO. These include, for instance, the values used in the environmental impact assessment (i.e. characterisation and normalisation factors). For two environmental problems caused by the plant (aquatic toxicity potential and solid waste produced) no characterisation factors were available, and we therefore used the amount of liquid effluent and solid wastes produced as indicators. In addition, the normalisation factors are uncertain because they are not specific for the region where the plant is located. Rather, they were developed for Western Europe (adopted from Huijbregts et al. (2003)). Other parameter uncertainties are related to the description of the reference case (i.e. presenting the current practice in the aluminium pressure die casting plant) and the pollution reduction options. The uncertain values associated to MIKADO inputs include, for instance, emission factors, costs and pollution reduction factors. Parameters uncertainty may be caused by the system's inherent variability. This may cause extrapolation errors (e.g. emission factors for air emissions from metals and combustion emissions are extrapolated to annual values), measurement errors (e.g. aluminium alloy mass flows estimated by the company), reporting errors (e.g. reports of activity levels or annual air emissions by the company), or errors in technical developments (e.g. incomplete knowledge associated to reduction potentials, costs and side-effects of the new technologies to pollution reduction).

We have addressed the uncertainties of our DST MIKADO only partially by performing a sensitivity analysis. To this end, we analysed the influence of changes in the input parameter values to MIKADO results. The results in terms of environmental impact and costs were compared with the situation presenting the current industrial operation practice (i.e. for the case in which the input parameter values were not changed). This revealed which parts of the model are relatively robust, and which parts are more sensitive to uncertainties. The sensitivity analysis was performed in Chapter 4 and consisted of three sets of analyses in which we changed 48 of the more than 200 parameters. The three sets of analyses performed allowed for analysing (a) the model sensitivity to changes in model parameters for the current industrial operation practice; (b) the model sensitivity to changes in values of a number of parameters that are associated with reduction options and their costs; (c) and the model sensitivity to changes in parameters associated with the alloy mass flow. The partial sensitivity analysis shows that the modelled changes in environmental impact are relatively sensitive to changes in one parameter related to the mass of aluminium alloy recycled internally in the plant. However, the analysis performed could be more complete, as mentioned in Chapter 4 (section 4.4). Alternative sensitivity analyses could include, for instance, changes in model parameters related to other problems than human toxicity or be extended to other processes in the plant. Therefore, one of our recommendations for future studies is a more systematic analysis of model uncertainties that can make use of, for instance, Monte Carlo simulation (see section 6.4).

Various alternative methods to assess uncertainties exist, that were not applied here. These range from qualitative assessments of uncertainties to quantitative statistical approaches. Qualitative uncertainty analysis methods include, for example, data quality rating (such method, used in LCA studies, assigns alphabetical or numerical scores to inputs and parameters to express the uncertainty in a qualitative scale (high-low) (Björklund, 2002). Other methods for qualitative uncertainty analysis include expert's judgment and qualitative discussion. Quantitative uncertainty analysis include, among others, a comparison of model results with direct measurements (Van Aardenne, 2002), error propagation (this method provides a systematic way of obtaining the uncertainties in results of measurements and computations) (Morgan and Henrion, 1990), uncertainty importance analysis (used in LCA studies this method calculates how the uncertainty of different parameters contributes to the total uncertainty of the result) (Björklund, 2002), Finally, Monte Carlo simulation (also used in LCA studies) allows to generate random values for all uncertain parameters, so-called input scenarios, and for these input scenarios the model outputs are estimated (Kaplan et al., 2005).

The methods abovementioned were not explored in this thesis, but we agree that further analyses of the uncertainties are of utmost importance. It may improve the quality of our model or provide insights that can prioritise research needs for the plant's industrial sector. The exploration of uncertainties can focus on the relatively uncertain process input values, on a large set of parameters values or on the model structure. In summary, we consider that further studies on the decision support tools uncertainties could be done by including a more complete sensitivity analysis addressing the model inputs and model parameters. It may be, followed by a more systematic uncertainty analysis for the significant parameters (e.g. by performing Monte Carlo simulation). The results obtained could be useful for qualitative uncertainty analysis methods including expert's judgment and qualitative discussion on both the model parameters and model structure used in this thesis.

Finally, it can be argued that the stepwise approach taken in this ESA procedure, including the iterations performed, contributed to a reduction of uncertainties. We continuously aimed at using the most reliable sources of information and whenever available we confronted the plant data with industry specific data from the literature. Moreover, model results and parameters were discussed with experts from the plant or compared with actual measurements made in this plant. Nevertheless, uncertainties in the model can not be avoided, but we reduced the uncertainties by refining our DST MIKADO by carrying out several systems analyses iterations in the thesis. All in all, we consider our model adequate for its purpose. The model structure and the model parameters are in line with company specific information, or based on the most appropriate literature. MIKADO can therefore be considered up-to-date and makes use of the best quality data available.

6.3.3. Implications of the results for industry

We will now discuss the implications of the results of this study for the aluminium pressure die casting industry, as well as for the metals industry and other industry in general.

This study illustrates how the combined use of seven tools (Life Cycle Assessment, Substance Flow Analysis, Multi-Criteria Analysis, Technology Assessment, Sensitivity Analysis, Scenario Analysis and Cost-Effectiveness Analysis) is useful in assessing options to reduce the environmental impact of an industrial plant. The combination of these seven analytical tools proves to be a solid basis for a DST (MIKADO) that helps the company to consider environmental and economic aspects of decision-making.

MIKADO refers to a specific plant in Portugal. However, other industrial companies may also benefit from the results of this thesis. In particular, they may use the method applied here as a tool to improve the company's environmental management, and use the same tools to assess the company's environmental performance. We also argue that this method when applied for the same industrial sector may be a valuable instrument for comparison of environmental performances, among different plants. This may be possible by comparing, for instance, the cost-effectiveness of scenarios on pollution reduction, for different plants from same industrial sector.

MIKADO is not only useful for industry purposes, but also for other potential participants in environmental management assessments. First, the use of a DST like ours may be useful for environmental policy makers in providing information on the pollution reduction by available techniques that may be implemented in a plant. Second, environmental systems analysts may consider this combination of ESA tools as an interesting example. This study can serve as an example of how to select and combine tools.

- Pollution reduction

One of most interesting findings of this study for industry is that the aluminium die casting company studied here can earn money by implementing pollution reduction options. This may hold for similar companies as well. The analysis of single reduction options indicates that for some options the annual savings exceed the annual costs. In fact, a significant number of the options are paying options and thus are very promising. They include to *compact metal load*, the use of a *new mould release agent and* the *scrap rate reduction* in Casting and Finishing. Among these options, the ones that appear to be the most cost attractive are the *compact metal load* and the use of a *new mould release agent*. This can contribute to reduce the overall environmental impact while the company gains.

The other alternatives to pollution reduction are not paying options. In fact, some of the options are expensive, such as the add-on techniques *fabric filters* and *scrubbers*. However, these options also have a large reduction potential. Consequently, these costly options can not be ignored and may show to be useful as the environmental policies become more restrict in terms of limiting the amount of emissions released. Therefore, this study indicates that the companies in general and the plant studied in particular may benefit (environmentally and economically) from a proactive behaviour concerning environmental performance.

This study also showed that aluminium pressure die casting in general contributes to eight environmental problems, but the largest share of the overall environmental impact is associated with two problems. These two problems are human toxicity (caused by metals emissions and emission of ozone precursors) and abiotic depletion of natural gas. Furthermore, the majority of the overall environmental impact for this industry is caused by sub-processes Melting and Casting. These results suggest that the efforts of the industrial sector to reduce pollution should be focused on these two environmental problems. In addition, we have listed eighteen options to reduce the pollution that may be used by similar plants.

It is interesting to discuss the implication of the results for the Portuguese environmental policy makers. On the one hand, we have seen that there is ample opportunity to reduce pollution by the plant studied, but on the other hand, it should be noted that the plant studied meets the environmental regulations in terms of pollutants emissions. In addition, it should be noted that our model system focuses not only on the pollutants currently regulated, but also on other potential environmental problems including: several emissions, the depletion of natural resources, an in-depth analysis of the industrial production process, and a wide range of pollution reduction options. In summary, the model system goes far beyond the current national environmental policies and thus one may then consider that the current environmental policies are unlikely to effectively reduce the overall environmental impact of industry. Therefore, MIKADO can assist policy makers in deciding on future environmental policy, because MIKADO shows how the environmental perfornmance of an industrial plant that already meets current environmental standards can be further improved.

MIKADO can also be used as a communication tool. Companies may have different views on environmental management, and our DST can assist decision makers to illustrate the consequences of having different objectives. The seven different scenarios analysed in this thesis are examples of the types of studies that can be performed using MIKADO. They are useful for reflecting on consequences of different management strategies. They may also assist the dialogue between industry and the environmental authorities when the concern is the reduction of the environmental impact by a company or an industrial sector. MIKADO users can formulate other scenarios reflecting, for instance, user-defined combinations of reduction options. MIKADO could also be used as a communication tool by using it in participatory scenario analysis. In participatory scenario analysis the story lines of the scenarios can be formulated by stakeholders, which may include the plant managers, the national association for metals industry and representatives of national environmental authorities. MIKADO can then be used to quantitatively analyse these qualitative scenarios.

6.4. Recommendations for future studies

The overall objective of this thesis was to develop a decision support tool to analyse options to reduce the environmental impact of an industrial company. An integrated environmental assessment model (our DST MIKADO) was developed for calculating the effectiveness of reduction options and the associated costs for the industrial plant. In the following, some recommendations for further studies are presented.

Uncertainties in MIKADO may be reduced. For instance, experimental studies, on specific model parameters (e.g. emission factors) are needed. Such analyses may in particular focus on emissions that contribute significantly the overall environmental impact, such as emissions of hydrogen fluoride (so far estimated based on literature) and the emissions of chromium and non-methane volatile organic compounds (so far based on few samples monitored). In addition, the environmental impact assessment factors used in the model can be improved. To reduce model uncertainty, studies on more appropriate characterisation factors for some environmental problems and on site-specific normalisation factors for Portugal would be useful. These new factors would replace the currently used factors, which mostly came from Western Europe. Following that line, the number of the valuation methods used in MIKADO may be increased. This implies the need for a valuation method that can be easily implemented by the company. Or, as an alternative, the company may develop an internal valuation method itself. The resulting valuation factors preferably express the company's specific environmental management strategy. A more systematic analysis of model uncertainties is also recommended and can be performed by using, for instance, Monte Carlo simulation.

Future research may aim to make MIKADO more complete. This may hold, for instance, for the electricity used by the plant. We took into account the energy conservation in the plant by considering the reduction in the use of natural gas needed for melting. This can be achieved by efficiency improvement of the melting process. As discussed in Chapter 3, electricity used in the plant is not explicitly accounted for in our analysis. This is because of the choices made in terms of the system boundaries; we consider electricity production not manageable by the plant managers. The purpose of the tool is to assist environmental management *in* the company. Although the environmental problems outside the gates may in fact be significant, the ability of the management board to reduce these external effects is limited. For the same reason machining is now not included in MIKADO. In reality, raw products leave the plant to be machined, and then return to be cleaned by degreasing. As this process takes place outside the gates of the plant, the pollution caused by it was not included in our analysis. Future analyses may, however, include these.

In addition, nuisance, odour, vibration, heat wasted and desiccation may be included, even though we assume that their contribution to the overall environmental impact is small. Likewise, the emissions that may occur during plant maintenance operations or in emergency situations, and that are not taken into account in the current version of our DST, may be include in future studies. One may even reconsider the system boundaries and include flows of materials or energy taking outside the plant. The current version of MIKADO only includes pollution reduction options that are currently available. With time, new options to reduce pollution could be included in the model. Alternatively, it would be interesting to analyse more user-defined scenarios with the current version of MIKADO.

Finally, MIKADO may serve as an example for other plants, including a wider range of potential industrial users. It should be noted that MIKADO requires first of all a user-friendly interface. Our model can be modified to make it applicable to other plants from the aluminium pressure die casting sector. This would require validation of plant-specific parameters for other plants, or perhaps the whole aluminium die casting sector. An equally interesting option would be to extrapolate MIKADO to the metals industry in general, or even other industries. This can be done by using the methodology underlying MIKADO and apply it to develop decision support tools for other industrial plants. This would reveal the general applicability of our decision support tool and provide a good basis to further explore the general usefulness of the analytical tools combined here, in the systems analyses of companies in general. This could result in different MIKADO versions, filling the current lack of analytical tools that assess both environmental and economic aspects of industrial managenent at the plant level.

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Summary

Industrial activities cause a variety of environmental problems. These are largely caused by emissions of air pollutants, the production of waste and depletion of natural resources. As a consequence, industrial managers face a complex problem when assessing the overall environmental pressure on the environment, and options to reduce this pressure. This complexity is associated with the range of activities taking place in industrial processes, the variety and complexity of their environmental effects, the number of available technologies for pollution control, and the costs of pollution reduction. Despite this complexity, pollution reduction in industry is not always based on systematic analyses, nor on clearly defined company priorities to environmental management. An important reason for this is a lack of integrated analyses of the environmental impact of industrial processes, the options to reduce this impact and the associated costs. An instrument to assist plant managers in deciding on environmental management is of utmost importance. However, a decision support tool that takes a company perspective and covers all relevant environmental issues as well as costs of environmental management is currently not available in the literature.

The overall objective of the thesis is to develop a decision support tool to analyse options to reduce the environmental impact of an industrial company. A model is developed for the assessment of the potential environmental impact resulting from emissions of environmental pollutants, as well as the effectiveness of reduction options and the associated costs. The tool aims to take a company perspective and to assist the company management in the analyses of possible strategies to improve the company's environmental performance. An industrial plant, supplying the automotive industry with aluminium pressure die casting products, located in Portugal, served as case study.

The following research questions are addressed:

1) What existing environmental systems analysis methods and tools can in principle be combined in a decision support tool and used to analyse the environmental performance of a plant from a company perspective?

2) Which technical pollution reduction options are available for reducing the environmental impact of an aluminium pressure die casting plant? What are their technical potentials to reduce this impact, and the associated costs for the plant?

3) How can a model be developed that can be used from a company perspective to analyse options to reduce the environmental impact of aluminium pressure die casting?

4) How do different strategies to combine pollution reduction options improve the environmental performance of an aluminium pressure die casting plant, and what are the associated costs for the plant?

Environmental systems analysis (ESA) is often used to assist decision making in finding solution to complex environmental problems. A systems analysis research strategy is followed to address the above formulated research questions. It is based on a stepwise

approach consisting of: 1) Problem definition; 2) Evaluation and selection of existing ESA tools; 3) Identification of pollution reduction options; 4) Model building; 5) Model application and finally 6) Evaluation of the methodological approach.

In this environmental systems analysis, seven analytical tools are combined. These are selected on the basis of criteria ensuring an analysis that takes a company perspective; includes environmental and economic aspects of decision making; includes a complete coverage of the potential environmental impacts and allows for an assessment of the consequences of pollution reduction strategies. The associated characteristics of the decision support tool to be developed are that it i) considers a gate-to-gate approach; ii) considers the processes within the plant that are relevant for the assessment of the environmental impact; iii) uses plant specific data easily available from the process owner; iv) considers up-to-date and plant specific pollution reduction options; v) provides information on the cost-effectiveness of the reduction options; vi) can be used to express the environmental performance in one overall environmental indicator; and vii) can be used to explore possible user-defined pollution reduction strategies. Based on these characteristics the following analytical tools are considered useful for the purpose of this study: Life Cycle Assessment, Substance Flow Analysis, Multi-Criteria Analysis, Technology Assessment, Sensitivity Analysis, Scenario Analysis and Cost-Effectiveness Analysis.

Next, 18 pollution reduction options are identified for the aluminium pressure die casting plant studied. For each option the potential to reduce the pollution and the costs associated with their implementation is estimated. The options include typical end-of-pipe solutions, as well as more structural changes in the industrial processes. The options are considered the best available for the current aluminium pressure die casting sector. The inventory shows that promising and effective opportunities exist for pollution reduction.

A model (MIKADO) is developed for and applied to the specific aluminium die casting plant. MIKADO is the *Model of the environmental Impact of an Aluminium Die casting plant and Options to reduce this impact*. The model includes material and energy flows in the plant that give rise to environmental problems. It considers the following sub-processes: Melting; Casting; Finishing; Internal Transports and Auxiliary Burners. MIKADO can be used to analyse future trends in the potential environmental impact of the aluminium pressure die casting plant and the effect of different pollution reduction strategies, as well as the costs for the company. One of the strengths of MIKADO is the integrated approach that it takes in analysing, simultaneously, all the relevant environmental problems caused by the aluminium die casting plant.

MIKADO results are first analysed for the situation that reflects the current practice in the plant. In addition, a partial sensitivity analysis performed to study the sensitivity of MIKADO results to changes in parameter values. The results indicate that more than 90% of the environmental impact of the company is from the sub-processes Melting and Casting. Moreover, the environmental impact caused by the plant is mostly associated with human toxicity problems (caused by metal emissions, and emissions of ozone precursors) and the depletion of natural gas. Four relatively larger sources of environmental pollution include the use of natural gas and emissions of hydrogen fluoride in Melting, and emission of chromium and non-methane volatile organic compounds from Casting. These four cause about two-thirds of the overall

environmental impact. MIKADO results show to be relatively insensitive to the valuation factors used to assess the overall environmental impact.

A systematic analysis of the pollution reduction options reveals that the potential to reduce pollution varies largely for the 18 options analysed. Individual options may reduce the overall environmental impact by up to 40%. The most effective single options, leading to the largest reductions, are found to be two wet scrubbers associated to Casting. The costs to implement reduction options differ largely. Six options have net negative costs, implying that the company may in fact earn money by implementing them. These include the use of a granular desoxidation agent, reduction of the scrap produced during Casting and Finishing, the use of electric forklift trucks in internal transport, a new mould release agent and compacting the metal load entering the melting furnaces. The last option is found to be the most paying.

Seven different types of reduction strategies are analysed, assuming the simultaneous implementation of different pollution reduction options. These strategies, reflecting different environmental management objectives, are analysed with respect to their potential to reduce the environmental impact and the costs associated with the implementation of options. The strategies differ largely with respect to their effect on the environmental impact (10 - 87% reduction) and costs (-268 to + 277 k€/year). The most effective strategy is a combination of options to reduce human toxicity, but this is also a relatively costly strategy. The least effective is related to metal yield increase. Combining the most paying options is an interesting strategy: it reduces the overall environmental impact by 45% at negative net costs (-268 k€/year). Eleven strategies could be defined which reduce the overall environmental impact by more than 50%. Of these two have net negative costs. It is also possible to reduce largely the environmental impact in the case in which the costs of add-on techniques are compensated by benefits of the paying options. This is, for instance, the case when most cost effective options are combined. Results show a large reduction in the overall environmental impact (86% reduction), while the company gains 51 k€/year.

Novel aspects of this thesis include: 1) the company perspective that it takes; 2) the involvement of plant managers throughout the research; 3) the environmental systems analysis research strategy (sequence of environmental systems analysis steps and iterations), and 4) the selection of environmental systems analyses tools.

The company perspective taken when developing MIKADO is reflected by the definition of system boundaries, the production processes included and the pollution reduction options considered in the model characteristics. The decision support tool only considers the industrial processes that can be managed by the plant managers, as well as the different types of environmental problems that the plant contributes to (air emissions, liquid effluents, solid wastes and natural resources used within the plant gates).
The involvement of plant managers during MIKADO development was essential for ensuring that the tool fulfils their expectations on the assessment of the environmental performance of the plant. A major strength of the tool is its flexibility. This flexibility contributes to the willingness of the plant manager to use MIKADO to analyse possibilities for environmental management in the plant.
The research strategy taken in this thesis includes a unique sequence of steps and iterations and is considered appropriate and useful for development of decision support

tools for environmental management in industrial companies. The environmental systems analysis procedure followed here may also be useful in assisting environmental decision making by other industries.
Finally, the procedure to select analytical tools as a basis for the model was helpful. The detailed description of the procedure followed may serve as an example for other studies. This also holds for the combination of seven different environmental systems analysis tools, as presented in this thesis.

Samenvatting

Industriële activiteiten veroorzaken verschillende milieuproblemen. De belangrijkste oorzaken daarvan zijn emissies van luchtvervuilende stoffen, de productie van afval en uitputting van natuurlijke hulpbronnen. Hierdoor is het voor industriële managers niet eenvoudig om de totale milieubelasting te overzien, en de mogelijkheden voor milieubeleid te beoordelen. De complexiteit van de problematiek hangt samen met de verscheidenheid aan activiteiten die plaatsvinden in industriële processen, de verscheidenheid en complexiteit van de daarmee gepaard gaande milieubelasting, het aantal beschikbare technologieën voor het terugdringen van de vervuiling, en de kosten van milieumaatregelen. Ondanks deze complexiteit, is het terugdringen van vervuiling door de industrie niet altijd gebaseerd op systematische analyses, noch op helder gedefinieerde prioriteiten van bedrijven ten aanzien van milieubeleid. Een belangrijke oorzaak hiervan is het gebrek aan geïntegreerde studies van de milieubelasting van industriële processen, de opties om deze milieubelasting te verminderen en de daarmee gepaard gaande kosten. Een instrument om managers van bedrijven te helpen in hun beslissingen over milieubeleid is daarom uiterst belangrijk. Een beslissingsondersteunend systeem, opgezet vanuit bedrijfsperspectief, dat alle relevante milieuproblemen omvat evenals de kosten van milieubeleid, is echter thans niet beschikbaar in de wetenschappelijke literatuur.

Het doel van dit proefschrift is om een beslissingsondersteunend systeem te ontwikkelen om opties te analyseren voor het reduceren van de milieubelasting van een bedrijf. Een model is ontwikkeld voor de beoordeling van de milieubelasting van emissies van milieuvervuilende stoffen, evenals de effectiviteit van reductie opties en de daarmee gepaard gaande kosten. Dit instrument beoogt het bedrijfsperspectief weer te geven en managers van een bedrijf te helpen bij het analyseren van mogelijke strategieën om de milieuperformance van een bedrijf te verbeteren. Een hogedrukgieterij in Portugal, die de auto-industrie voorziet van aluminium hogedrukgietproducten dient hierbij als casus.

De volgende onderzoeksvragen worden beantwoord:

1) Welke bestaande milieusysteemanalytische methoden en *tools* kunnen in principe gebruikt worden voor het analyseren van de milieuperformance van een bedrijf vanuit bedrijfsperspectief?

2) Welke technische milieumaatregelen zijn beschikbaar voor het reduceren van de milieubelasting van een aluminium hogedrukgieterij? Wat is het technische potentieel van deze opties om de milieubelasting terug te dringen, en de daarmee gepaard gaande kosten voor het bedrijf?

3) Hoe kan een model worden ontwikkeld dat gebruikt kan worden vanuit een bedrijfsperspectief om opties te analyseren voor het reduceren van de milieubelasting van een aluminium hogedrukgieterij?

4) Hoe verbeteren strategieën waarin verschillende milieumaatregelen worden gecombineerd de milieuperformance van een aluminium hogedrukgieterij, en wat zijn de daarmee gepaard gaande kosten voor het bedrijf?

Milieusysteemanalyse (MSA) wordt vaak gebruikt om beleidsmakers te helpen bij het vinden van oplossingen voor complexe milieuproblemen. Dit onderzoek is uitgevoerd volgens een systeemanalytische onderzoeksstrategie. Deze is gebaseerd op een stapsgewijze benadering: 1) Probleemdefinitie; 2) Evaluatie en selectie van bestaande MSA methoden; 3) Inventarisatie van opties om de milieuvervuiling terug te dringen; 4) Modelbouw; 5) Modeltoepassing en tenslotte 6) Evaluatie van de methode.

Zeven analytische *tools* zijn gecombineerd in deze milieusysteemanalyse. Deze *tools* zijn geselecteerd op basis van criteria die een analyse vanuit bedrijfsperspectief garanderen, evenals een analyse van zowel de milieukundige als de economische aspecten van beleid, een analyse die alle potentiële milieueffecten in beschouwing neemt en een beoordeling mogelijk maakt van de consequenties van strategieën om de vervuiling terug te dringen. Het te ontwikkelende beslissingsondersteunende systeem heeft de volgende eigenschappen: i) de poort van het bedrijf bepaalt de systeemgrens (een *gate-to-gate* benadering); ii) processen in het bedrijf die relevant zijn voor de beoordeling van de milieu-impact worden in beschouwing genomen; iii) er wordt gebruik gemaakt van bedrijfsspecifieke data, voor zover deze relatief eenvoudig te verkrijgen zijn; iv) de beschouwde opties om vervuiling terug te dringen zijn *up-to-date* en bedrijfsspecifiek; v) het systeem verschaft informatie over de kosteneffectiviteit van opties om vervuiling terug te dringen; vi) het kan gebruikt worden om de milieuperformance in een indicator uit te drukken en vii) het biedt de gebruiker de mogelijkheid om strategieën voor reductie van vervuiling te definiëren en vervolgens te analyseren. Op basis van deze eigenschappen worden de volgende *tools* het meest bruikbaar geacht voor het doel van deze studie: levenscyclusanalyse, stofstroom analyse, multicriteria analyse, technologie beoordeling, gevoeligheidsanalyse, scenario analyse en kosteneffectiviteitanalyse.

Vervolgens zijn 18 opties om de vervuiling terug te dringen geïdentificeerd voor de bestudeerde aluminium hogedrukgieterij. Voor elke optie is geschat in welke mate deze de vervuiling kan terugdringen (het reductie potentieel) en wat de implementatiekosten zijn. De opties betreffen typische *end-of-pipe* maatregelen, evenals meer structurele veranderingen in de industriële processen. De opties worden de best beschikbare geacht voor de huidige aluminium hogedrukgieterij. Uit deze inventarisatie blijkt dat veelbelovende en effectieve opties beschikbaar zijn.

Een model (MIKADO) is ontwikkeld voor en toegepast op de hogedrukgieterij. MIKADO staat voor *Model of the environmental Impact of an Aluminium Die casting plant and Options to reduce this impact*. Het model beschrijft stofstromen en energiestromen in het bedrijf die ten grondslag liggen aan milieuproblemen. Dit betreft de volgende subprocessen: smelten, gieten, afwerking, intern transport, en branders (smelten, gieten, afwerken, intern transport en hulpbranders). MIKADO kan gebruikt worden voor de analyse van toekomstige trends in potentiële milieueffecten van de aluminium hogedrukgieterij en de effecten van strategieën om de vervuiling terug te dringen, evenals de kosten daarvan voor het bedrijf. Een van de sterke punten van MIKADO is de integrerende benadering: het analyseert gelijktijdig alle relevante milieuproblemen die worden veroorzaakt door de hogedrukgieterij.

De resultaten van MIKADO zijn allereerst geanalyseerd voor de huidige praktijk in het bedrijf. Tevens is een gedeeltelijke gevoeligheidsanalyse uitgevoerd, waarmee de gevoeligheid van de modelresultaten voor veranderingen in parameterwaarden is onderzocht. Meer dan 90% van de milieueffecten van het bedrijf blijkt te worden veroorzaakt door de subprocessen smelten en gieten. De milieueffecten zijn vooral gerelateerd aan toxiciteitproblemen voor mensen (veroorzaakt door emissies van metalen en stoffen die bijdragen aan ozonvorming) en de uitputting van aardgas. Vier relatief grote bronnen van vervuiling zijn het gebruik van aardgas en emissies van waterstoffluoride tijdens het smelten en emissies van chroom en vluchtige organische stoffen (exclusief methaan) tijdens gieten. Deze vier bronnen van vervuiling veroorzaken ongeveer tweederde van het totale milieueffect. MIKADO resultaten blijken relatief ongevoelig voor de waarden van wegingsfactoren die gebruikt zijn om de totale milieu-*impact* te berekenen.

Uit een systematische analyse van de reductie opties blijkt een grote range in reductiepotentiëlen van de 18 opties. Individuele opties kunnen, volgens de berekeningen, de milieu-*impact* tot 40% verminderen. De meest effectieve opties, resulterend in de grootste reducties, zijn twee natte wassers die kunnen worden toegepast tijdens het gieten. De implementatiekosten verschillen ook aanzienlijk. Zes opties hebben negatieve kosten. Dit impliceert dat het bedrijf in feite geld kan verdienen door deze opties te implementeren. Deze opties zijn het gebruik van granulaire antioxidanten, een reductie van de hoeveelheid schroot die wordt geproduceerd tijdens het gieten en de afwerking, het gebruik van elektrische vorkheftrucks voor intern transport, een nieuw lossingmiddel en het compacter laden van de smeltovens. De laatste optie is het meest rendabel.

Vervolgens zijn zeven verschillende typen reductiestrategieën zijn geanalyseerd, waarin gelijktijdige implementatie van verschillende reductie opties is verondersteld. Deze strategieën zijn gebaseerd op verschillende management doelen. Ze zijn geanalyseerd met betrekking tot het potentieel om de milieu-*impact* terug te dringen en de implementatiekosten van de opties. Het milieu effect van deze strategieën verschilt aanzienlijk (10 - 87% reductie) evenals de kosten (-268 to + 277 kEuro/jaar). De meest effectieve strategie is een combinatie van opties om de toxiciteitproblemen voor mensen terug te dringen, maar dit is ook een relatief dure strategie. De minst effectieve strategie betreft het vergroten van de fractie van de grondstof (aluminium) die in het eindproduct terecht komt. Het combineren van de meest rendabele opties is een interessante strategie. Dit reduceert de totale milieu-*impact* met 45% tegen netto negatieve kosten (-268 kEuro/jaar). Voor elf strategieën is een reductie van meer dan 50% in de totale milieu-*impact* berekend. Van deze elf zijn er twee met netto negatieve kosten. Het is mogelijk de milieu-*impact* aanzienlijk te reduceren wanneer de kosten van *end-of-pipe* technieken worden gecompenseerd door de opbrengsten van rendabeler opties. Dit is bijvoorbeeld het geval wanneer de meest kosteneffectieve opties worden gecombineerd. Voor deze strategie wordt een grote reductie in de totale milieu-*impact* berekend (86% reductie), terwijl het bedrijf er 51 kEuro/jaar mee verdient.

Vernieuwende aspecten van dit proefschrift betreffen: 1) het bedrijfsperspectief van waaruit de analyse is uitgevoerd; 2) de betrokkenheid van de bedrijfsleiders gedurende het onderzoek; 3) de milieusysteemanalytische onderzoeksstrategie (volgorde van milieusysteemanalytische stappen en iteraties) en 4) de selectie van de milieusysteemanalytische *tools*.

Het bedrijfsperspectief van waaruit MIKADO is ontwikkeld, blijkt uit de definitie van systeemgrenzen, de productie processen die in beschouwing zijn genomen en de milieumaatregelen die zijn meegenomen in het model. Het beslissingsondersteunende systeem beschouwt slechts die industriële processen die beheerst kunnen worden door het management van het bedrijf, evenals de verschillende milieuproblemen waar het bedrijf een bijdrage aan levert (emissies naar lucht en water, vast afval en het gebruik van natuurlijke hulpbronnen binnen het bedrijf).

Het betrekken van de bedrijfsleiding bij de ontwikkeling van MIKADO was essentieel. Het garandeerde dat het beslissingsondersteunende systeem voldeed aan de verwachtingen met betrekking tot het beoordelen van de milieuperformance van het bedrijf. Een sterk punt van het ontwikkelde model is de flexibiliteit voor de bedrijfsleiding. Deze flexibiliteit vergroot de bereidheid van de bedrijfsleiding om MIKADO te gebruiken voor het analyseren van mogelijkheden voor milieumanagement in het bedrijf.

De onderzoeksstrategie waarvoor in dit proefschrift is gekozen betreft een unieke volgorde van stappen en iteraties, en wordt passen en bruikbaar geacht voor de ontwikkeling van beslissingsondersteunende systemen in industriële bedrijven. De hier gevolgde milieusysteemanalytische procedure zou ook bruikbaar zijn bij het ondersteunen van milieubeleid van andere industrieën.

Tenslotte bleek de procedure voor het selecteren van analytische *tools* als basis voor het model bruikbaar. De gedetailleerde beschrijving van de gevolgde procedure, en de resulterende combinatie van analytische *tools* zouden als voorbeeld kunnen dienen boor andere studies. Dit geldt ook voor de combinatie van zeven verschillende milieusysteenanalytische *tools* zoals beschreven in dit proefschrift.

Curriculum Vitae

Belmira Neto was born on 14th June, 1968 in Porto, Portugal. She graduated in metallurgical engineering in 1992 at the Engineering Faculty of Porto University. In 1993, after a six month training (graduation complement) in a Dutch company (Leiden), she worked as a research assistant at the Faculty of Engineering University in Porto University. In 1996 she obtained her MSc. degree in Materials Engineering from Porto University. In the same year she specialised in Environmental Engineering at the Engineering Faculty in Porto (branch of industrial waste treatment and management). From 1996 to 1998, she worked first as a quality systems manager, and later in a consultant agency specialised in production management. Belmira Neto has, since 1998, been a lecturer at the Engineering Faculty of Porto University.

In March 2002 she started her PhD research, supported through a post-graduation research scholarship by the Portuguese Foundation for Science and Technology. Most of the PhD research was carried out at the Environmental Systems Analysis Group of Wageningen University (The Netherlands). The research included a case study of an existing company from the aluminium die casting sector (located in Portugal). A formal agreement was signed with this company on the confidentiality of information and the plant-specific data used. The modelling of the environmental issues at stake was partly performed at, and assisted by TNO Built Environment and Geosciences (The Netherlands). In addition, she spent two months at the International Institute of Applied Systems Analysis (Austria) where she focused on the analysis of cost-effectiveness of pollution reduction options. The results of her PhD research were presented at the second Conference of the International Society for Industrial Ecology in Michigan (U.S.A). She participated in the SENSE Research School on the Socio-Economic and Natural Sciences of the Environment.

Currently Belmira Neto is coordinating two courses on *environmental decision support tools* and *industrial ecology* in the Environmental Engineering integrated master programme at the Engineering Faculty of Porto University (Portugal). Her fields of interest include environmental modelling, environmental management in industrial sites, environmental systems analysis tools and integrated environmental assessment.

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SENSE PhD courses:

- Research Context Activity: Essay on Multidisciplinarity of the PhD research project.
- Techniques for Writing and Presenting a Scientific Paper.

Other PhD courses:

- Full course in Environmental Engineering. Porto University, Portugal.

Other Activities:

- Training at IIASA (2003). Cost Effectiveness Analysis of Pollution Reduction. Laxenburg, Austria.
- Conference (2001). The Science and Culture of Industrial Ecology. Leiden, The Netherlands.

Presentations:

- Poster Presentation (2003). Symposium "Environmental Research at the Edge of Science and Society",Wageningen, The Netherlands.
- Oral Presentation (2003). Second International Conference of the International Society for Industrial Ecology, Ann Arbor, USA.
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