LIFE CYCLE ASSESSMENT IN FERROUS FOUNDRY INDUSTRY

A THESIS SUBMITTED TO
THE GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES
OF
MIDDLE EAST TECHNICAL UNIVERSITY

BY

ÇİSEM YİĞİT

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR
THE DEGREE OF MASTER OF SCIENCE
IN
ENVIRONMENTAL ENGINEERING

JANUARY, 2013

Approval of the thesis:

LIFE CYCLE ASSESSMENT IN FERROUS FOUNDRY INDUSTRY

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ABSTRACT

LIFE CYCLE ASSESSMENT IN FERROUS FOUNDRY INDUSTRY

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JANUARY, 2013, 102 pages

Foundries are most widely facilities all around the world, producing high amounts of castings. In this study, environmental impact of metal foundries was investigated toward a life cycle assessment (LCA) goal. Studies were conducted in two foundry plants in order to collect the inventory data. The difference between the plants regarding their processes was the application of secondary sand reclamation (SSR) in Plant 2. Application of SSR is indicated as a “best available technique-BAT” in the Reference Document for Foundries and Smitheries published by Integrated Pollution Prevention and Control (IPPC) Breau. In order to exhibit SSR’s environmental effects during its whole life cycle, firstly, environmental impact of conventional casting was evalauated by using LCA. Then, environmental impact of casting with SSR was assessed to see what if the SSR facility is applied after casting for Plant 1. The results of these two scenario (with and without SSR) were compared. In this framework, one ton of metal melted and one ton of mould and core production selected as functional units. The boundaries of the study selected as from cradle to grave for foundry processes, cradle to gate 2 for foundry products. SimaPro LCA software was used during calculations and impact assessment was conducted by using Impact 2002+ method. Additionally, several production scenarios (SSR magnetic seperation efficiency, amount of burned sand during molten metal pouring and different products) were analysed and compared to each other. Results showed that; among the sub-processes one ton metal melting has the highest environmental impact due to its high energy demand because of the production of inputs (e.g. pig iron and steel production) and energy required for melting the metal. For core and mould production, among the process without SSR and six scenarios with SSR, the process without SSR showed the lowest environmental impact. This was explained by the high energy demand of SSR. Also, it was investigated that phenol-resorcinol formaldeyhde resin production is the significant contributor of environmental impact during core and mould production. This study revealed that; application of SSR which is indicated as BAT in the literature, has more environmental effect in life cycle view.

Keywords: foundry, life cycle assessment, sand reclamation, SimaPro software

ÖZ

DEMİR DÖKÜM ENDÜSTRİSİNDE YAŞAM DÖNGÜSÜ ANALİZİ

Yiğit, Çisem

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Tez Yöneticisi: Prof. Dr. Filiz B. Dilek
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Ocak 2013, 102 sayfa

Yüksek üretim miktarlariyla dökümhaneler dünyada en çok bulunan tesislerdir. Bu çalışmada, demir dökümhanelerinin çevresel etkisi, yaşam döngüsü değerlendirmesi hedefine yönelik olarak incelenmiştir. Enventer verisini toplamak amacıyla iki farklı dökümhane tesisinde saha çalışmaları gerçekleştirilmiştir. Uyguladıkları proseslere yönelik olarak iki tesis arasındaki fark; ikinci tesiste ikincil kum geri kazanım uygulamasının olmasıdır. İkincil kum geri kazanım uygulaması Entegre Kirlilik Önleme Bürosu tarafından yayınlanmış olan Dökümhaneler için En İyi Refereans Doküman'da "Mevcut en iyi teknik" olarak belirtilmiştir. İkincil kum geri kazanım sisteminin çevreye olan etkisinin yaşam döngüsü süresince anlaşılabilmesi için ilk olarak normal bir döküm prosesinin çevreye olan etkisi hesaplanmıştır. Daha sonra, ikincil kum geri kazanım sisteminin çevreye etkisini görebilmek amacıyla kum geri kazanım sisteminin birinci tesiste uygulanması durumunda çevreye olan etkinin ne olacağı hesaplanmıştır. İki durumun sonuçları karşılaştırılmıştır. Bu çerçevede işlevsel birim olarak bir ton metalin eritilmesi ve bir ton maça ve kalıp kumunun üretilmesi seçilmiştir. Çalışmanın sınırları döküm proses için beşikten mezara, döküm ürünleri için beşikten ikinci kapıya kadar olarak seçilmiştir. Hesaplamalar SimaPro yazılımı kullanılarak yapılmış ve etki hesaplama yöntemi olarak Impact 2002+ seçilmiştir. Ek olarak, bir çok üretim senaryosu (ikincil kum rejenerasyon manyetik ayrışım verimi, ergimiş metalin dökülmesi esnasında özelliğini yitiren kum miktarı ve farklı ürünler) analiz edilmiş ve birbiriyle karşılaştırılmıştır. Sonuçlar; döküm alt-proseslerinden metalin ergitilmesnin, proses girdilerinin üretiminden kaynaklı yüksek enerji ihtiyacından (örneğin; pig demir ve çelik üretimi) ve metali ergitmek için ihtiyaç duyulan yüksek enerji miktarından dolayı, çevreye en yüksek etkisinin olduğunu göstermiştir. Maça ve kalıp kumunun üretilmesi için ise, ikincil kum rejenerasyonsuz ve altı senaryonun ele alındığı kum rejenerasyonlu proseslerden, kum rejenerasyonsuz prosesin çevreye etkisinin en az olduğu bulunmuştur. Bu durum, ikincil kum rejenerasyonlu sistemin enerji tüketim ihtiyacının fazla olması ile açıklanmıştır. Ayrıca, maça ve kalıp kumu üretiminde; fenol-resorcinol formaldeyhde reçine üretiminin çevreye etkide en yüksek katkısının olduğu görülmüştür. Bu çalışma; literatürde mevcut en iyi teknik olarak belirtilen ikincil kum geri kazanımı uygulamasının yaşam döngüsü açısından çevreye daha çok etkisi olduğunu göstermiştir.

Anahtar Kelimeler: döküm, yaşam döngüsü değerlendirmesi, kum geri kazanımı, SimaPro yazılımı

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CHAPTER 1

INTRODUCTION

1.1 General

Foundry sector in which casting technology is applied to process and give shapes to metals is one of the major industrial sectors. Casting is used for various products from jewellery to manufacturing of heavy industry products. In 2007, foundry production in Turkey (about 1,300,000 ton of casting with more than 1200 enterprises) ranked among the top five countries in Europe with Germany, France, Italy and Spain. In 2008, according to statistics of World Foundry Association, Turkish Foundries produced 1,265,800 ton of castings which are mainly iron and steel [1]. Since foundries melt ferrous and non-ferrous metals and alloys to give them desired shapes for products (i.e., casting). Mainly four types of metals are used for casting: pig/sphero/tempered iron, steel, copper and alluminium alloys. Foundry operation is energy intensive due to melting of metals. There are many installations in foundries with different type of technologies and unit operations depending on the type of products [2]. Main processes include: core and mould making, melting, casting, shotblasting and finishing. The main distinction within the sector is based on the type of feed, ferrous or non-ferrous, used. Another distinction is observed in the manufacturing of moulds. Some foundries use permanent moulding techniques like die casting, whereas others use traditional techniques like green sand moulding with chemicals which is also called as casting with lost moulds. Also, different types of furnaces for the melting of metals can be used in the foundries. In last decade, induction type furnaces have been gaining popularity due to their clean performance [2]. The pollution related to foundries are important due to their high potential risks to environment and human health. The main waste from casting is the spent foundry sand, which is generated at very large quantities during core and mould preparation [2]. This spent foundry sand is primarily recycled in most of the foundries. This practice reduces the amount of waste sand going to disposal to a certain extent. Additionally, there are other advanced techniques that recycle and reuse the primarily recycled sand, called secondary sand reclamation (SSR). These techniques generally consist of a magnetic seperation (seperation of mould sand from core sand) and reclamation drum, reduces the amount of waste sand up to 90% and the requirement of resin addition in order to prepare the sand for core making. However, additional energy is required for the application of these techniques.

Concioussness on resource depletion and environment degradation is gaining importance; therefore industries are trying to use clean processes to minimize their effects on the environment [3]. They are trying to improve strategies to increase their overall efficiencies while reducing risks to the humans and environment [4].

Since Turkey is currently in the harmonisation period with European Union (EU), Environmental Directives of EU are being transposed to Turkish national regulations. In addition, studies are being conducted to determine the best management practices of different waste forms. Directive 2008/98/EC defines the key concepts such as the definitions of waste, recovery and disposal. It also recommends a life cycle approach for waste prevention measures. This requires considering the environmental impacts of waste generation and waste management as well as the reuse and waste recovery [5]. Additionally, under Council Directive 96/61/EC, The European Integrated Pollution Prevention and Control (IPPC) Bureau has published “Best Reference Documents (BREFs)” for different manufacturing sectors that provide information about consumption and emission levels achievable by using each “Best Available Technique(BAT)” the costs and cross media issues associated with each technique, and the extent to which each technique is applicable [2].

Life cycle assessment (LCA) is a methodology used for estimating and assessing the environmental impacts of a product during its life [6]. According to Council Directive

96/61/EC concerning integrated pollution prevention and control, IPPC Directive manufacturing processes have several environmental impacts on environment [8]. Depending on the impact source and technical background of the installation, BAT selection which is useful for comparing and selecting specific production techniques in terms of their environmental impacts without changing products properties is useful [9]. During the calculation of environmental impacts, gathering the reliable and representative information on waste generation rates belonging to the product of concern is very important. Waste factors which are indicators of waste generation rates are helpful tools to describe environmental effects of products and processes, representing material flow analysis information and leading to develop alternatives for waste minimisation and reducing environmental impacts of waste. In this framework, by generating waste factors, the benefits of waste minimisation techniques and environmental impacts of any process can be assessed by using LCA methodology.

Regarding the LCA studies conducted on foundry sector, there is not a specific study relating LCA and foundry processes or products. The studies already conducted are generally about automative sector, including foundaries as a part of their study and comparing environmental effects of raw materials of automobile cylinders in their whole lfe cycle. Another LCA study that was conducted on foundry sector analyses and compares environmental impacts of water and alcohol based coatings applied to casting products. Also, there is a study conducted on foundaries is a mass balance study, which is a prerequisite for LCA study.

1.2 The Objectives and Scope of the Study

The main objective of this study was to assess the overall environmental impacts of foundry processes and products without and with the application of SSR technique by using LCA approach.

Studies were carried out in two ferrous metal casting plants in Turkey. The process flow schemes of the plants were examined; all the raw materials, products or by-products entering to the process and all the wastes and emissions generated during the process were determined. These plants have the similar production processes, except one has a SSR facility.

In the scope of the study, the following tasks were undertaken:

- LCA of foundry processes of “metal melting (including casting)” and “core and mould production”, without application of SSR technique (Process based LCA without SSR).
- LCA of foundry processes of “metal melting (including casting)” and “core and mould production”, with application of SSR technique for different secondary magnetic separation recycle ratios (10%, 30% and 50%) at different amount of resin burned (50% and 70%) during casting process (Process based LCA with SSR).

- Calculation of environmental impacts of foundry products with different metal to core ratios (1 to 8 and 1 to 16) applied for different sand recycle and resin burn ratios by using results gathered from above bullets (Product based LCA).

SimaPro version 7.2.4 software was used for LCA. The 2010 data of the plants were used for LCA. The boundary of the study was selected as cradle to grave including upstream processes, transportation, production processes and wastes of each process. Firstly, the functional unit was selected as 1 ton of metal melted for the melting process and 1 ton of “core or mould produced” for the core and mould process. Environmental impact assessments of products were calculated based on these functional units. Among the end-point methods used to conduct LCA, Impact 2002+ was selected for impact assessment. Interpretation and comparison of results were conducted by using normalization and single score results. LCA results, conventional sand casting with and without the application of sand reclamation option were compared to examine the effectiveness of the suggested BAT option (i.e. sand reclamation) on overall environmental impacts of foundries.

CHAPTER 2

LIFE CYCLE ASSESSMENT AND FOUNDRY PROCESS

2.1 LCA Concept

Life cycle assessment (LCA) is a methodology used for estimating and assessing the environmental impacts (e.g., climate change, stratospheric ozone depletion, tropospheric ozone (smog) creation, eutrophication, acidification, toxicological stress on human health and ecosystems, the depletion of resources, water use, land use, and noise—and others) of a product during its life [10]. This concept is different than the classical concept of manufacturing process pollution since it takes into account the “upstream” and “downstream” steps, not only the processes for the manufacture of a product [11]. In other words, it is used for evaluating the environmental performance of a product considering all the processes in the downstream and upstream [12].

Today, public is more conscious and interested in the resource depletion, environmental degradation, and environmental impact of their activities. In this framework, “greener” processes to produce “greener” products attract more attention. Many companies have been investigating the ways to minimize their effects on the environment. They use LCA for developing pollution prevention strategies and environmental management systems [13]. Figure 1 presents a simplified scheme of the product life concept which includes loops between the several life phases [10].

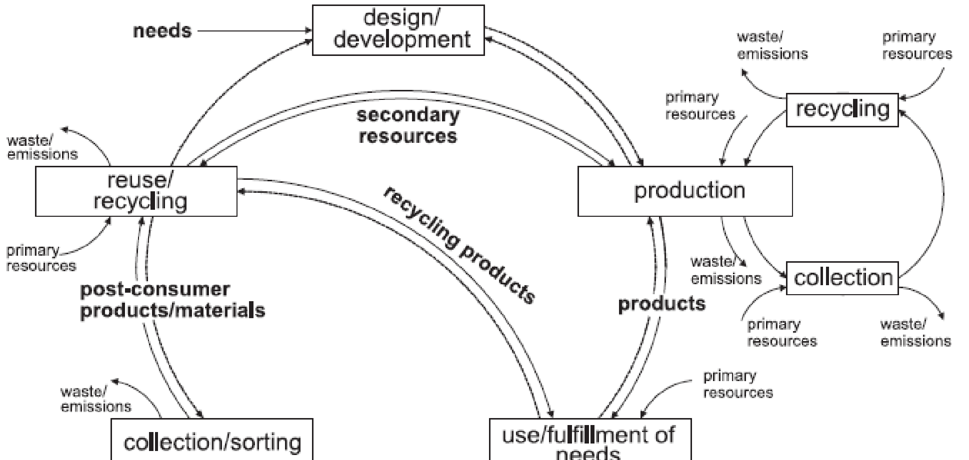


Figure 1. Schematic representation of a generic life cycle of a product (the full arrows represent material and energy flows, while the dashed arrows represent information flows) [10].

LCA includes upstream and downstream processes for a product, and is generally a “cradle-to-grave” approach for assessing industrial systems. Upstream processes begin with the gathering of raw materials from the earth to create the product and ends at the point when all materials are returned to the earth. LCA evaluates all the production stages independently from each other, and, is used for estimating the cumulative environmental impacts resulting

from all the production stages in the product life cycle, often including the impacts not considered in more traditional analyses (e.g., raw material extraction, material transportation, ultimate product disposal, etc.). LCA provides a comprehensive assessment of the environmental impacts of the product or processes, thus a more accurate picture of the overall environmental trade-offs in product and process selection [14].
Since LCA has become a more commonly used technique for environmental management, the International Organization for Standardization (ISO) has published a set of guidelines to standardize LCA [15]:

- ISO 14040 - Principles and framework (1997)
- ISO 14041 - Goal and scope definition and inventory analysis (1998)
- ISO 14042 - Life cycle impact assessment (2000)
- ISO 14043 - Life cycle interpretation (2000) [15].

ISO Standards indicates that LCA is a widely accepted procedure for "the compilation and evaluation of the inputs and outputs, and the potential environmental impacts of a product system throughout its life cycle", and the LCA methodology is divided into four stages [15]:

- Goal and scope definition
- Inventory analysis
- Impact assessment
- Interpretation

Brief explanations for these stages are presented in the following sub-sections.

2.1.1 Goal and Scope Definition

First step of an LCA is the goal and scope definition. In this step, the goal of the study under interest is determined with the functional unit, the reference flow, the product system(s) under study, and the breadth and depth of the study in relation to this goal. The goal are determined, the stakeholders and the target audience are identified. Next, the main characteristics of the intended LCA study (i.e. if it is to cover temporal, geographical and technology issues) are established [16]. System boundaries and functional unit should be defined clearly in the goal and scope definition. System boundaries define the limits of the system to be analyzed, and determine the processes to be included. During this step, the inputs and outputs of the process should be determined. According to Lindfords et al. [17], the inputs could be the whole inputs for production or could be limited to the input(s) to a single process; the same also applies to output(s). Different types of system boundaries, geographical boundaries and environmental load boundaries, can be considered for LCA [16].

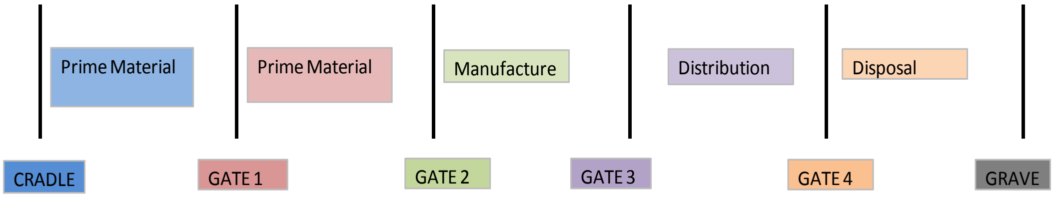


Figure 2.Product life-cycle span steps [16]

Different life cycle boundaries can be considered. If the entire life of a product is to be examined, it should begin with the prime material extraction and it should end with the final disposal of the product (Figure 2). These limits are defined as "cradle to grave" analysis. When the fate of a product is not known exactly at its end point, the analysis is concluded after the manufacturing stage. This is called "cradle to gate" analysis. In a comprehensive LCA study, each life-cycle step will carry out its own gate-to-gate analysis (Figure 2). If the 'cradle to grave' analysis of the process is in interest, all the inputs (strating from raw material extraction), and outputs (considering the disposals of wastes and emissions) should be taken into account. Cradle-to-grave process will be the cumulative result of the gate-to-gate systems [18]. Geographical boundaries consider geographic conditions for the establishment of product system. They can be considered as life-cycle boundaries when the different life-cycle steps need to be applied in different regions. In the case of site specific studies, this approach is recommended [18].

Regarding the environmental load boundaries; there are different types of environmental loads, namely, renewable and nonrenewable raw materials, air and liquid emissions, solid waste, energy losses, radiation and noise. LCA can be carried out considering the entire list of inputs and outputs (i.e., complete LCA) or taking into account some of them (i.e., partial LCA). In Figure 3, partial LCA 1 considers only air and liquid emissions and is carried out from the beginning (cradle) until gate 2. Partial LCA 2 takes into account only solid waste and energy losses and goes from gate 1 to end of life (grave) [11].

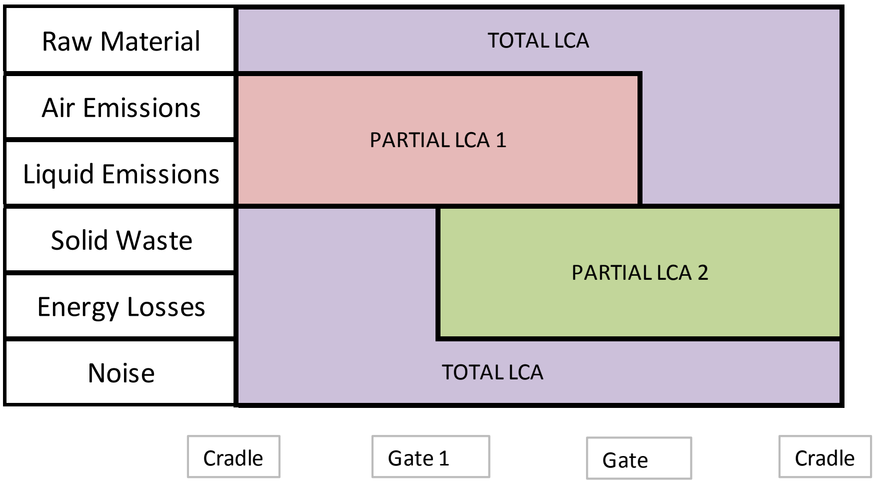


Figure 3. Boundaries of LCA [3]

A functional unit is a central and important concept in LCA. This unit is a base for the calculation. Functional units can be used to compare different systems for the same function. When different alternatives for the manufacture of the same product or providing the same service are possible, the functional unit must be well-defined and should enable an effective comparison of the options considered. Additionally, it must be measurable, and when two products with different life spans are compared, it is important that the period of use be considered for its establishment [11]. For example, treatment of a 1 kg waste with a defined composition, 1 kg milk production and transport of 1 ton waste over 1 km can be the functional units of LCA.

2.1.2 Inventory Analysis

Life-cycle inventory (LCI) is considered as the second step in which all the data regarding environmental loads (EL) or environmental effects generated by a product or activity during its life-cycle are identified and evaluated. ELs are the amount of substances, radiation, noises or vibrations emitted to or removed from the environment that cause potential harmful effects. ELs can be raw materials, energy consumption, air and water emissions, waste generation, radiation, noise, vibration, odors, etc- what is commonly known as environmental pollution. EL must be quantifiable. To prepare an LCI, each EL generated by the process must be added as material and energy inputs, and the outputs associated with it. In other words, the inventory which basically consists of an EL balance associated with a product, flow diagram of the process should be clearly established. The most time-consuming task in an LCA study is data collection, and establishing qualitative and quantitative information about inputs and outputs concerning the process. Data can be obtained from different sources: electronic databases, literature data, unreported data, measurements, and computation. According to Sonnemann et al. [11], data collection shows large differences in the availability of input and output data. Inputs are the most readily available because energy and raw material consumption are registered by the companies. Output data, with the exception of the main product and sometimes some by-products, are difficult to find. In many cases, this is due to the absence of registering all releases and the difficulty of allocating the existing data to the individual product. This feature is typically dependent on the size of the company in the study. Nevertheless, as recommended by Hauschild and Wenzel [21], the problem in the availability of output data may be solved in some cases by carrying out mass and energy balances using the inputs and calculating the output values.

2.1.3 Impact Assessment

The life cycle impact assessment (LCIA) is the third step of LCA. The purpose is to assess a product system's environmental significance and impact during its life cycle (raw material acquisition, production, use phase, disposal). Since, LCA provides a wide perspective of environmental and resource issues and affected impact categories, it establishes information for interpretation of the results. There are several methods for impact assessments in the literature which are given in APPENDIX A, Table A 1. In this step, for each impact category, impact potentials are selected and category indicator results are calculated. The collection of these results defines the LCIA profile of the product system, which provides information on the relevance of resource use and emissions associated with it [11].

There are several steps within the LCIA phase [16]:

i. Selection of impact categories
ii. Selection of characterization methods: category indicators, characterization models, and factors
iii. Classification (assignment of inventory results to impact categories)
iv. Characterization
v. Normalization
vi. Grouping
vii. Weighting

In step i, relevant impact categories with the system under study are defined. An impact category is defined as a class representing environmental issues of concern to which LCI results may be assigned. The following list illustrates typical impact categories used in LCA [16]:

- Depletion of resources (eg, subdivided into abiotic and biotic)
- Impacts of land use (eg, subdivided into land competition, loss of life support functions, loss of biodiversity)
- Climate change
- Stratospheric ozone depletion
- Human toxicity
- Ecotoxicity (sometimes subdivided into freshwater aquatic, marine aquatic, terrestrial)
- Photooxidant formation
- Acidification
- Eutrophication
- Impacts of ionising radiation
- Odor
- Noise
- Waste heat

There are several impact assessment methods in the literature; most frequently used ones are eco-indicator 99, eco-indicator 95, CML 1992, CML 2000, TRACI, IMPACT 2002+ etc. These methods differ in the impact categories, they consider and use different factors for the calculation of impacts. Additionally, some of the methods are mid-point methods considering emission, fate and exposure. Beyond mid-point methods, also there are end-point methods that consider effect and damage of the materials, like human health, extinction of species, availability of resources for future generation etc. [18]. Figure 4 illustrates the relationship between mid-point and end-point methods. As seen from the Figure, some mid-point results can have effect on the same endpoint, in this case, these impacts are added up. This can be done by conducting characterization and normalization on inventory data.

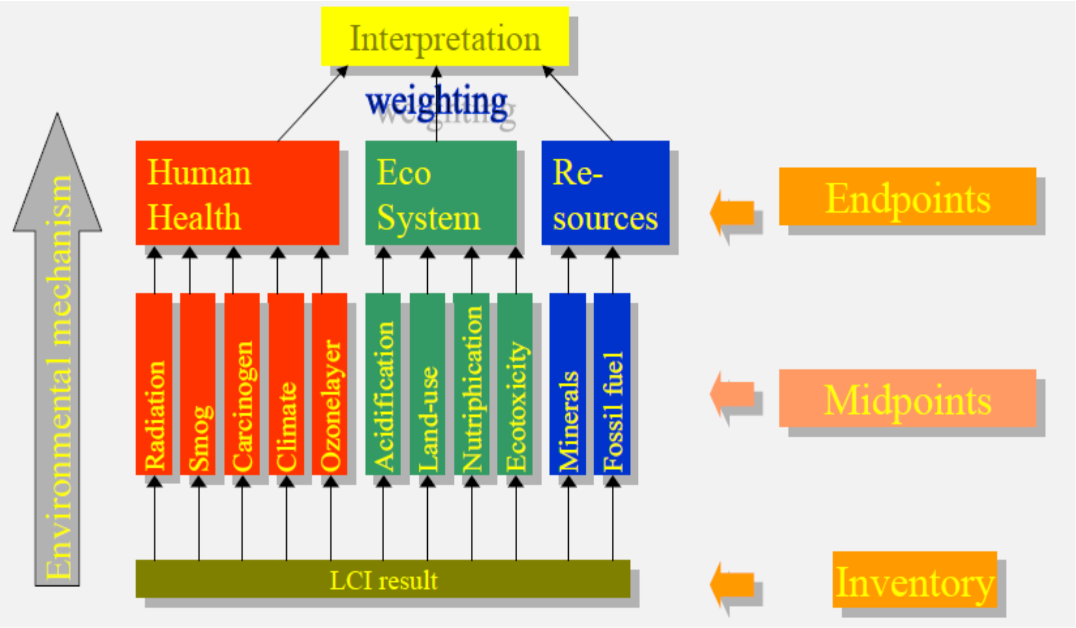


Figure 4. Schematic overview of the methodology proposed by Goedkoop & Spriensma [18]

Characterization factor is defined as the relative contribution of the substance for a selected impact category. For example, the characterization factor for CO_2 in the impact category climate change is equal to 1, while the characterization factor of methane is 21 which means that the release of 1 kg CH_4 causes the same amount of climate change as 21 kg CO_2. The total result is expressed as impact category indicators [18].

For the comparison of impact category indicator results, the impact category values are divided by the reference or normal value. This step is called normalization. A commonly used reference is the average yearly environmental load in a country or continent, divided by the number of inhabitants. However, the reference may be chosen freely [18].

One of the steps in impact assessment is weighting, where the (normalized) indicator results for each impact category assessed are assigned numerical factors according to their relative importance, multiplied by these factors, and possibly aggregated [16].

2.1.4 Interpretation

The last step of LCA is interpretation. In this step, results of the study are interpreted to evaluate environmental impact of the product or process under study. In this step, the actual assessment of the environmental profile of the product takes place according to the goal and scope of the study. [11].

Since large amounts of data are needed and some of these data may not have good quality at the same time, it is clear that the results of an LCA will not be completely certain. Additionally, cut-offs, simplifications and assumptions may have been introduced to make the analysis feasible. For some data items, there may be a range of values available, because different databases contradict each other. Methodological choices can be debated; the principles used for allocating multifunctional processes are just one example. All in all, the quality of the analysis and the robustness of the results is an essential part of sound decision making. For this reason, the interpretation phase is a place par excellence to address uncertainty. Sensitivity and uncertainty analysis address inherent uncertainties in data and different scenarios, assumptions, and choices. Typical forms may address [16]:

- Parameter variation, (i.e. the recalculation of results with modified data and/ or choices).
- Monte Carlo analyses (e.g. leading to results with error bars).
- Ranking of alternatives on the basis of the number of runs for which a certain alternative ranks best or worst.

A final activity in the interpretation is the drawing of conclusions and the making of recommendations. Although no formal methods can be specified here, the main concern in the LCA framework is to safeguard the consistency with the goal and scope of the study, the procedural embedding, and the justification of the conclusions and recommendations [16].

2.2 LCA Databases and Softwares

In order to calculate environmental impacts from LCA view easily, software tools were developed. There are various types of LCA software tools on the market. The most important and important property of a software tool is the price which vary between several thousand euros and free of charge. Price is generally dependent on the features of the software tool. Some are focused on a specific field of LCA like in waste management, while others are expert at different application fields of LCA. Also data quality have an effect on the price of a software tool. Depending on the purpose for which the user has selected the software, different LCA tools are more suitable for particular applications [31].

According to ISO; the main reason for using LCA is to calculate the environmental aspects and potential impact associated with a product [15]. Since, LCA is often data intensive; computers and adequate software tools are used to support the user in managing and editing these amounts of data. Environmental processes are often very complex and convoluted. This makes it difficult to model an LCA. Additionally, LCA software helps to structure the modeled scenario, displaying the process chains and presenting and analyzing the results. Also, processes that have a large impact on the environment, in other words environmental hot spots, can be identified. By this way, a more environmentally-friendly production process can thus be developed. LCA can also be used for a cleaner approach to production. It can help to improve and optimize resource management, which leads to a more efficient use of materials and energy. LCA therefore is used mainly for comparing different options and for deciding which option is best for the environment. LCA and LCA software are thus used as a support tool in decision taking [31].

A software tool generally consists of a database (Bousted Method, Euklid, Ecoinvent etc.) and a modeling module (GaBI, SimaPro, Umberto etc.). Data is stored separately from the modeling module as database or library. Apart from processes and flows, a database also contains modeled process chains, sub-layers in a process chain. The quality of data should be reliable and should be up-to-date and from a reliable source. More than one source can be used in order to limit the danger of making mistakes. The user needs to clearly define the conditions under which the data are valid as well as the region for which they can be applied which is named as data quality indicators. It can be helpful to include a data quality index to indicate the level of data quality. An automatic update should be provided as soon as new data or data of better quality are available [31].

There are specially designed programs for specific purposes of LCA. These programs are listed in
Table **1** together with their some important specifications.

Table 1. LCA Softwares and their specifications [11]

LCA Type	**Software name**	**Remarks**
LCI TOOLS	Bousted Model	MS_DOS based. Information from industries through questionnaires-23 countries data
	Euklid	methodology of ISO Standards-limited. "**S**tructured **Q**uery **L**anguage - SQL" database
	JEM_LCA	electronics sector
FULL LCA	EDIP LCA	for product development
	LCAiT	simple graphics based software that allows user to set up a product life cycle graphically and allows material input output balances.
	GaBI	life cycle balances covering environmental and economical issues-there are two databases and add-on modules
	LCAdvantage	graphical interface based on links, presenting material and energy inflows between modules that represent product components-also has a report generator
	PEMS	graphical flowcharts representing a product life in four units: manufacture, transport, energy generation and waste management, database allows user to insert new information
	SimaPro	transparent database (allows to see unit process inputs and outputs), program allows the results to be displayed in different formats such as after classification and characterization. Comes with extensive instruction material, including an operating manual for the program, database and methodology
	TEAM	extensive database, powerful and flexible structure that support transparency and sensitivity analyses of studies
	Umberto	capable of calculating material flow networks
ABRIDGED LCA	Eco-Indicator' 95	limited amount of data but allows simple LCA evaluation studies
	MET Matrices Method	for assessing and prioritizing environmental impacts of products or processes.
SPECIALIZED LCA TOOLS	ECO PACK 2001-06-22	packaging industry-data sets from Swiss EPA
	Ecopro 1.4	flow chart principle-user can add information to database

LCA Type	Software name	Remarks
	KCL ECO	operates on a process of modules and flows. Each flow consists of a number of equations that represent masses and energies moving between two modules-small products
	Repaq	packaging materials in US conditions
	WISARD	comparison of different waste management scenarios

2.3 Foundry Process

In foundries, the production is mainly divided into two parts: mould/core making, melting/casting. While moulds and cores are produced (valid for sand casting) at a designated area of the foundry the metal is melt in furnaces. Then, molten metal is transported to the place where pouring takes place-here molten metal is poured into pattern to fill the space between mould and core. Then, the cast product is removed in order to improve its surface appearance by grinding, shot blasting and coating. The burned sand is returned and recycled according to its physical properties if lost moulds are used [32]. Main processes that are included in foundries are: pattern, core and mould making, melting, casting, shot blasting and finishing. The steps of foundry production are shown in Figure 5 and are described below in detail.

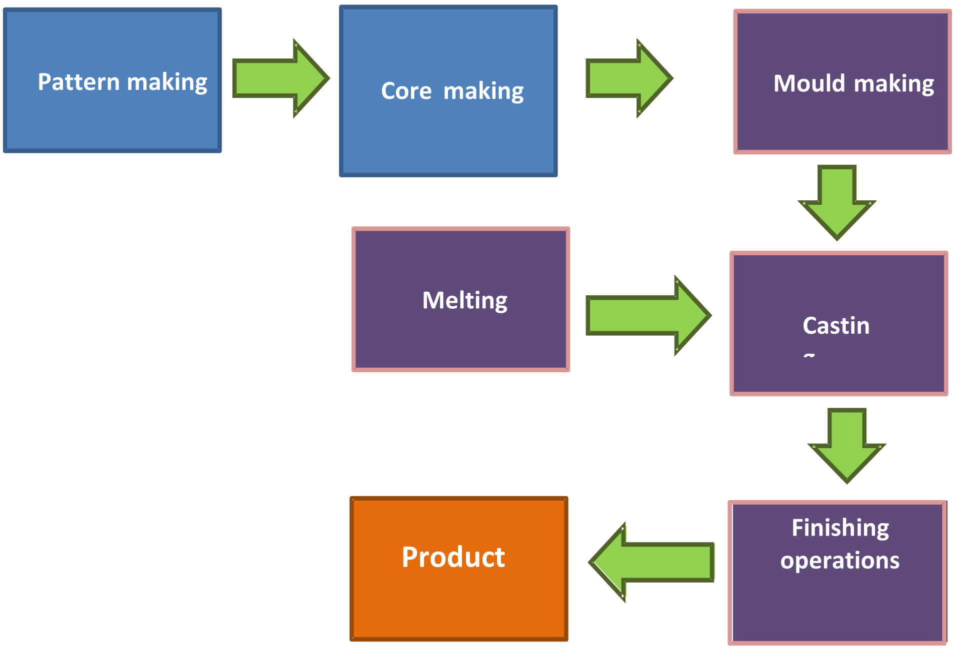


Figure 5. Foundry Process flowscheme

2.3.1 *Pattern, Mould and Core Making*

Pattern is the exact copy (positive shape) of a desired product. Therefore, pattern making is the critical step in the casting, since dimensions of the cast products are highly depends on the pattern. Dimensions of the patterns are very important and they are made by means of hand tools, universal machines, or by a CAD/CAM system on computer-numerical-controlled (CNC) machines [33].

The outer shape of the product is defined by the moulds, whereas the inner cavities in the product are shaped by cores. Amoount of core used is determined by the product shape. If the product has more inner cavities, then the amount of core is increased. Mould shape represents the “negative” of the product shape. Moulds in foundries can be either lost moulds or permanent moulds. Permanent moulds are used when gravity and low-pressure casting, pressure die-casting, and centrifugal casting are a part of a casting process and typically the moulds are metallic. Production of lost moulds are specific to each casting product. These moulds are generally sand. There are different types of lost moulding in practice, namely; moulding with natural gas, moulding with clay bonded sand, moulding with unbonded sand and moulding and core making with chemically bonded sand [33].

Cores should be resistant to heavy forces since, molten metal is poured into mould. Also, it should be easily removable through small passages after the solidification of molten metal. For that reason, cores are made from silica sand and chemical binders. Mixture of sand and binder is poured into a core box to introduce their shapes. The hardening of the core is achieved by a catalytic reaction, chemical or heat [33].

In order to produce good quality castings, the interactions between the mould and molten metal should be minimized. These interactions can be either sand expansion, metal penetration or chemical decomposition. To prevent these interactions and improve surface quality, moulds and cores are generally coated with refractory linings. These linings can be alcohol or water based coatings. [33].

2.3.2 Melting and Casting

Metal feed is prepared depending on the properties of the product. Iron and steel scrap, ferro-alloys can be added to meet the metallurgical properties of the product. Metal feed should be melted in order to be poured into moulds. There are different kind of furnaces that are used to melt metals, namely: cupola furnaces, electric arc furnaces, induction furnaces, radiant roof furnace, rotary furnace and hearth type furnaces [33].

The molten metal is poured into foundry ladles. Molten metal is carried with foundry ladles to the moulding line and it is poured into moulds with the help of foundry ladles.

2.3.3 Finishing and Post Casting Operations

Cleaning is to remove sand, scale, and excess metal from the casting. After the casting product is separated from the mould it needs to be cleaned. While cleaning burned-on sand and scale are removed. Metal burrs, wires etc. are cut off and surface improvement is performed [35]. Surface improvement can be done with different ways like shot blasting, heat treatment and coating.

2.3.4 Sand Regeneration Practice

For the spent sand which can not be primarily recycled (almost 90% of the used sand) can be subjected to advanced reclamation techniques in order to increase recycle of spent sand. These advanced techniques are called SSR. These systems have 5 basic steps: shake-out, crushing or lump reduction, cooling, scrubbing and classification [34]. Shake-out which is generally considered as a primary means of sand reclamation, separates the casting from the mold and/or the sand from the flask. It can be done by manual knockout, high energy impact vibrating shake-out, or by shot-blasting. In this step, magnetic separation can also be considered to remove rods, chills and other magnetic metals. For example, crushing or lump breaking can basically be done by three different actions: by impact in which a sharp instantaneous impingement of one moving object against another, by rubbing action or by compression or the process of compressing material between two surfaces. Because of the residual heat from the casting process, some type of cooling is often required in a sand reclamation system. The cooling unit can be placed before or after the scrubber. Some reclamation systems cool the sand by exhausting air through the various stages and transfer points such as elevators and belt conveyors. Scrubbing is usually done on the sand in the shake-out and lump breaking process. Pneumatic sand scrubbers may be used to do further cleaning on the sand grains. Classification is an important step in a sand reclamation system. The reclaimed sand screen analysis should be similar to the new sand used originally. The coarse grains and the fines must be removed to an acceptable level [34]. Implementation of sand reclamation which is suggested as BAT in foundries helps reducing raw material consumption including virgin sand and binder, and thereby decreasing the amount of waste sand to be disposed [34].

2.4 LCA Studies for Castings

In the literature, LCA studies on foundry sector are limited or may not be publicly published. As a matter of fact, Gutowski and Dalquist (2004) stated in their paper that complex products like semiconductors and cars are frequently subjected to LCAs as a part of or in conjunction with environmental impact analyses. However, for conventional processes like sand casting such an evaluation is uncommon [36]. So, LCA studies retrievable from the literature are those that have not been conducted directly on foundry sector, but have included the foundry sector (indirectly) as part of another sector LCA analysis. For example, there are some studies conducted for the automobile sector, in which motor engines were compared and LCA on metal casting were involved as a part. The main intention in these LCA studies, in fact, is to conduct the environmental impact analysis of producing light weighting vehicles, because automobile manufacturers are investing for light weighting vehicles since they have important environmental advantages like minimization in fuel consumption and emission reductions in their use phase. However; the advantages of using light weighting cars should be valid throughout lifetime of the vehicle [37]. Therefore, the environmental impacts of vehicles are investigated in the life-cycle aspect. As an example of such studies, Bonollo et al. [37], compared aluminum and cast iron cylinder blocks in the automotive industry whereas, Peaslee [39] used LCA, for the comparison of cast aluminum, cast iron and forged steel automotive parts. Similarly, Koltun [38] tried to investigate the advantages of using Mg components for light weighting cars. Bonollo et al.[37] and Koltun [38] used SimaPro Sofware for their study whereas Peaslee [39] used GaBI software . Since both Bonollo et al [37], and Peaslee [39] compared cast iron and cast aluminum parts, their results can be compared to each other. In Bonollo et al.'s study [37], Eco-Indicator 99 which is a damage oriented method was used whereas Peaslee [39] didn't mention about his method. The functional unit of the former study [37] was "C segment of 1600cc cylinder" whereas of the latter study [39] were "steering knuckle of front suspension of 6 cylinder minivan" for aluminum part and "steering knuckle of front suspension of 4 cylinder sedan" for cast iron part. Both studies indicated that Al made components has more effect on global warming potential than cast iron ones during production phase whereas global warming potential of cast iron is more than aluminum one during the use phase [37][39]. Additionally, Bonollo et al.'s study [37] revealed that Al components are more advantageous than cast iron ones, whereas Peaslee [39] says total impact from iron casting due to global warming potential is less than that of aluminum. Another study that is also mentioned above was conducted by Koltun [38] to investigate the advantages of using Mg components for light weighting cars. In this study, functional unit was selected as "one unit engine block" and cast iron, aluminum and magnesium engine blocks were compared in terms of their green house gas emissions. Different types of magnesium, aluminum and cast iron alloys were compared. It was found that, for all types of alloys, use stage is the highest contributor to global warming. In the use phase of all components, cast iron, magnesium and aluminum alloys have effect of global warming in respective orders [38]. These three studies are summarized in **Table 2**.

Table 2. Overview of LCA studies related with casting

	Bonollo et al. [37]	**Koltun et al. [38]**	**Peaslee et al. [39]**
Objective	To reduce environmental load by using Al cylinder blocks instead of cast iron blocks	To reduce GHG emissions by using Mg components in automotive industry and compare with cast iron and Al parts	To compare GHG emissions of cast Al, cast iron and forged steel automotive parts
Boundary	Cradle to grave (manufacture of metals, casting and assembly, use phase and end of life)	Cradle to grave (manufacture of metals, casting and assembly, use phase and end of life)	Cradle to grave (manufacture of metals, casting and assembly, use phase and end of life)
Functional Unit	C segment of 1600cc cylinder	Engine block	Steering knuckle of front suspension of 6 cylinder minivan” for aluminum part and “steering knuckle of front suspension of 4 cylinder sedan” for cast iron part
Software	SimaPro 6.0	SimaPro (version not mentioned)	GaBI (version not mentioned)
Impact Method	Eco-Indicator 99	Not mentioned	CML 2001
Results	• Al made components has more effect on global warming potential than cast iron ones during production phase whereas global warming potential of cast iron is more than aluminum one during the use phase. • Al components are more advantageous than cast iron ones.	• For all types of alloys, use stage is the highest contributor to global warming	• Al made components has more effect on global warming potential than cast iron ones during production phase whereas global warming potential of cast iron is more than aluminum one during the use phase. • Total impact from iron casting due to global warming potential is less than that of aluminum.

Apart from LCA studies conducted on foundry products, another LCA was carried out in foundries between the use of water and alcohol based coatings where BAT was the use of water based coatings. The study showed that when stove is used for drying the water based coatings, the reduced emissions are partly counterbalanced at LCA level by increased energy use [2].

Beyond LCA studies, as a first step requirement of LCA, mass balance studies or material flow analysis have been conducted in foundry sector. In a study by Dalquist and Gutowski [36], a manual mass balance on energy and material used in sand casting was conducted. In this study, waste factors for “sand that is sent to landfill or waste for per ton of product” or “water consumption for each ton of cast product” or “used energy for per ton of product” were calculated for U.S. and U.K. These factors are; U.S sends to waste 0.5 tons of sand per ton of cast metal whereas this value for U.K is 0.25 tons of sand per ton of cast metal to landfill. In U.K, 1.5 tons of water is consumed for each ton of cast product and U.S foundries used 14.6 million Btu per ton of saleable casting in 1998 [36]. Another material flow study on foundries was conducted in U.K., on the scope of “Biffaward Programme on Sustainable Resource Use” [40]. In this study, mass balances of different types of casting were conducted. According to their results, for all cast products 0.15% difference was apparent from input and output analysis, indicating that the balance is nearly satisfied.

Overall, as Dalquist et al [36] stated, because sand casting continues to be significant contributor to metal manufacturing techniques, its environmental impact must be better understood.

2.5 BAT vs LCA

2.5.1 General

According to Council Directive 96/61/EC of 24 September 1996 concerning integrated pollution prevention and control, Article 2(11); BAT is defined as the most effective and advanced stage in the development of activities and their methods of operation which indicate the practical suitability of particular techniques for providing in principle the basis for emission limit values designed to prevent and, where that is not practicable, generally to reduce emissions and the impact on the environment as a whole:

- 'Techniques' shall include both the technology used and the way in which the installation is designed, built, maintained, operated and decommissioned,
- 'Available' techniques shall mean those developed on a scale which allows implementation in the relevant industrial sector, under economically and technically viable conditions, taking into consideration the costs and advantages, whether or not the techniques are used or produced inside the Member State in question, as long as they are reasonably accessible to the operator,
- 'Best' shall mean most effective in achieving a high general level of protection of the environment as a whole [2].

There are several documents published on BAT’s of several sectors or economic activities called “Best Reference Documents - BREF” by European IPPC Bureau. These documents inform related institutions, industrial operators and public about operating the installation in environmentally friendly ways. There are 35 BREF documents that are published by European IPPC Bureau corresponding 35 different economic activities or sectors.

Since, LCA is a technique for assessing the environmental performance of a product, process or activity from `cradle to grave', i.e. from extraction of raw materials to final disposal, it covers BAT selection. However, BAT selection does not guarantee that your system minimizes overall environmental impacts during its life cycle. BAT is technique to minimize or eliminate waste production in the process or plant. As a matter of fact, Azapagic stated that, process selection must be based on considerations of the environment as a whole, including indirect releases, consumption of raw materials and waste disposal. This approach is more detailed than BAT generation and implies LCA approach. The study also mentions that it is possible to reduce the environmental impacts directly from the plant, but to increase them elsewhere in the life cycle [41]. In this framework, efficiency of sand reclamation plant was compared with respect to conventional process by using LCA approach. In this step of the study, results of LCA were compared and discussed whether it’s worth to apply selected BAT to foundries when LCA approach is considered.

2.5.2 BAT vs LCA in Foundries

One of the BREF's that are mentioned in Section 2.4??2.5?? are about foundries: "Reference Document on Best Available Techniques in the Smitheries and Foundries Industry" published in May, 2005 [2]. Applied processes in foundries, current emission and consumption levels in foundries, techniques to determine BAT and BAT for foundries are explained in detail in this document. Also, there are other documents that are about pollution prevention and waste minimisation in foundries. "Guideline Beneficial Re-Use of Ferrous Foundry By-Products —Draft Guideline" is published by Environmental Protection Agency and gives information about foundry by-products and their reuse options. Also, there are several handbooks and guidelines related on pollution prevention technologies and waste minimisation in foundries. Since foundries make intensive use of sand as an inert primary material, the regeneration or re-use of this sand is an important point of consideration as part of its environmental and economic performance. Various techniques are applied for regeneration of the sand (i.e. treatment and internal re-use as core andmoulding sand), the selection of which depends on the binder type and the sand flow compostion. If sand is not regenerated, then external re-use may be considered in order to prevent the need for its disposal. In these documents, one of BAT's suggested for foundries are use of SSR plant. By regenerating used sand, the plant reduces the consumption of binder and virgin sand thus the amount of sand going to landfill is decreased. However, the system needs more energy [2].

2.6 Summary of Key Findings

- LCA is a technique to assess the environmental aspects and potential impacts associated with a product, process, or service.
- A life-cycle assessment provides an overview of the environmental benefits and costs of the different management options and makes it possible to compare the potential environmental impacts of these options.
- Foundries are important faciilities due to their high production rates. The main markets served by the foundry industry are the automotive (50 % of market share), general engineering (30 %) and construction (10 %) sectors.
- LCA on foundries has not been directly conducted. Available LCA's are product based and conducted for casting automobile parts. The main objective of these studies are to reduce environmental impacts of engines while reducing fuel consumption. In this framework, use of several materials (iron, magnesium, aluminium, steel) were subjected to LCA and comparisons were made.
- In this framework, this study aims to evaluate overall environmental impact of foundry process by using LCA approach.
- As indicated in the IPPC Directive 96/61/EC, BAT's are used by industries in order to reduce their environmental impacts to the environment. However, their overall impact at LCA level to the environment are not known.
- Use of sand reclamation plant is one of BAT's suggested in the literature. It's contribution to the overall impact of the foundry process has not yet been evaluated.
- In this framework, efficiency of SSR plant needs to be assessed and compared with base scenario.

CHAPTER 3

METHODOLOGY

3.1 Study Approach

In this study, environmental impacts of foundries were assessed using LCA approach, with particular emphasis on the effect of having a SSR facility on the impacts. Two different iron foundaries (Plant 1 and Plant 2), located in Turkey, were selected to conduct field studies during which detailed process examination and data gathering were performed. Both plants apply the same production process with traditional green sand moulding using induction type of furnaces and primary sand regeneration involving shake out and primary magnetic separation. Plant 1 and Plant 2 have a production capacities around 10,000 ton/year and 50,000 ton/year, respectively. Also, the products of these plants differ from each other resulting different sand consumptions for each product. The general information regarding these processes are provided in Sections from 2.2.1 to 2.2.4. In one of the plants, namely Plant 2, additionally, a SSR facility is present, where cold mechanical regeneration using an impact drum type is used for the separation of bentonite, resin and coal dust around the sand (Figure 6). These binders are separated by friction of sand particles to each other, and crash of the scrubbers and sand particles. As moulding sands exhibit magnetic property due to Fe_2O_3 content of bentonite, they are separated by magnetic separators together with the core sands. As presented in Figure 6, after magnetic separation, two types of sand are obtained: magnetic sands with higher bentonite content are used following the reclamation drum stage for mould making whereas non-magnetic sands with less bentonite content are used as core sand. In practice, core which is non-magnetic sand constitutes about 10-50% of total spent foundry sand depending on the dimension sensitivity requirement of the product. The remained sand goes to reclamation drum as magnetic sand.

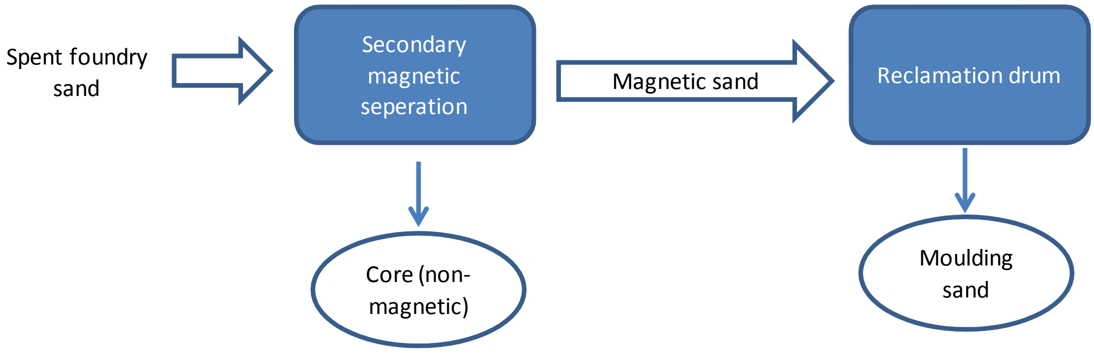


Figure 6. SSR plant (cold mechanical regeneration using an impact drum type) flow scheme in Plant 2.

During LCA runs, process and capacity data belonging to Plant 1 (withou SSR) was primarily taken into consideration. Inventory data for Plant 2 did not allow to differentiate the ones belonging to SSR facility only. In other words, the inventory data were for the whole plant; it was not possible to differentiate the fractions of resources used and the wastes generated in the SSR facility, only. It was also not possible to extrapolate the normalized data (according to capacity) from Plant 1 and then use in Plant 2 as such to represent the data excluding the SSR in Plant 2, since the production in plants were not necessarily following the same patterns, exactly. Therefore, it was not possible to gather the inventory data from Plant 2, which would allow the separation of SSR data from the whole plant data. So, inventory data extracted for Plant 1 were used and the analysis were conducted to see what if the SSR facility of Plant 2 had been available in Plant 1.

In an attempt to explore the effect(s) of having the SSR facility in the plant, on environmental performance of the foundaries, LCA results with and without SSR cases were assessed and compared. In case with SSR, different secondary magnetic recycle ratios (10, 30 and 50%) and different resin burned ratios (50 and 70%) were evaluated (Table 3). Further details regarding the inputs and outputs considered are given in the following sections. Additionally, two different product scenarios; metal to sand ratio 1:8 and metal to sand ratio 1:16 were analysed for their environmental impacts by using the results of each scenario that is presented in Table 3.

Table 3. Scenarios evaluated

Scenario	Secondary magnetic recycle ratios	Resin burned ratios
A	10	50
B	10	70
C	30	50
D	30	70
E	50	50
F	50	70

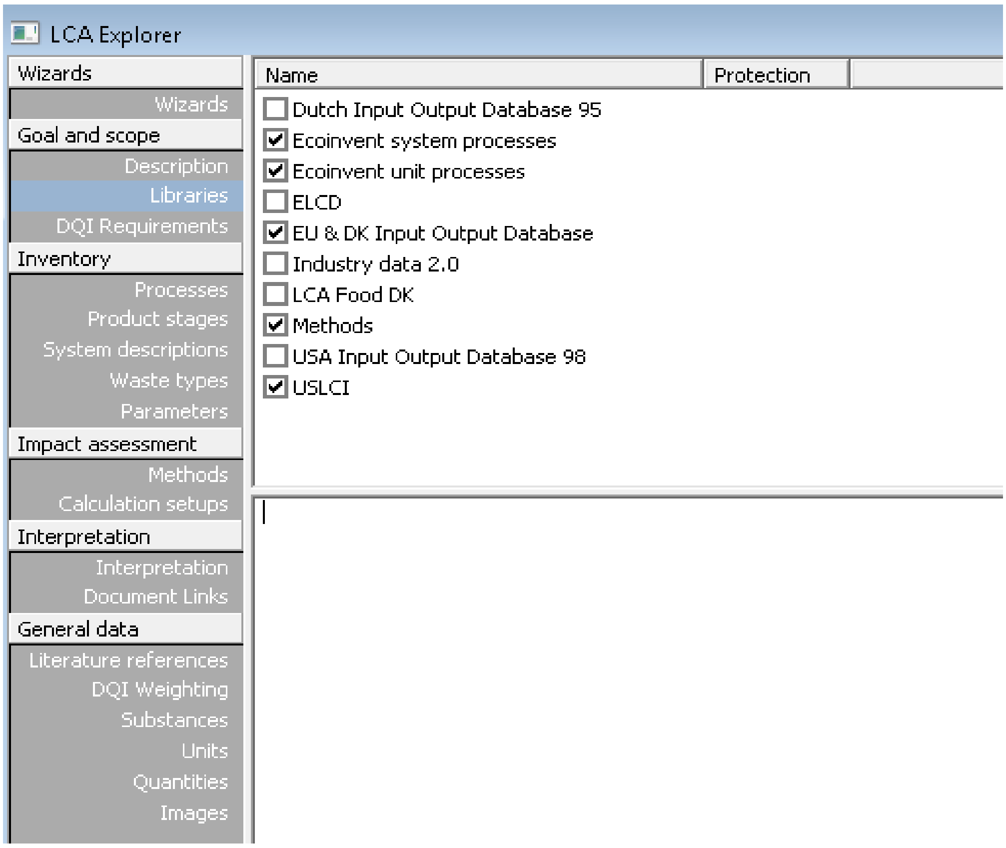
3.2 LCA Methodology

This LCA study was conducted by using SimaPro ver. 7.2.4 software that is developed by PRé Consultants [24]. As described in Chapter 2, conducting a LCA study requires some certain steps that should be followed:

3.2.1 Goal and Scope Definition

The goal of the study was to achieve a cradle to grave analysis of current environmental impacts of the traditional sand casting process, and to compare these impacts with those of with having SSR plant. by using LCA approach. The functional units of this study were based on foundry sub-proccesses which are 1 ton of metal melted for metal melting (including casting) process and 1 ton of sand for core and mould production process. Environmental impacts of different product scenarios for different metal to core ratios were also calculated in the content of this study.

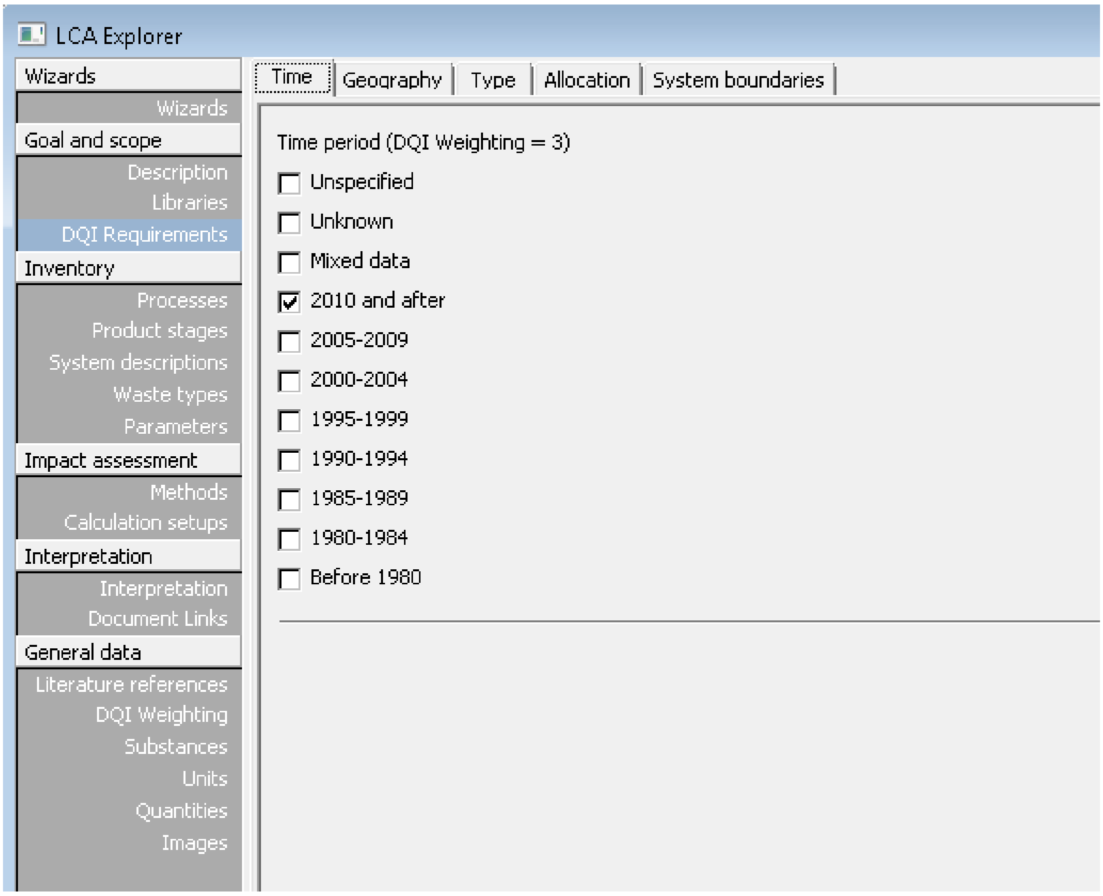
In the scope of this study, all the raw materials entering to the casting process and outputs were determined by considering upstream and downstream processes. The upstream processes are extractions of raw materials, energy production and auxiliary materials. Environmental impact due to transportation of raw materials was also considered in this study. The information regarding to raw material acquistion, energy and auxiliary materials could not be obtained from the facility. Therefore, this information was taken from databases of SimaPro. The selected databases were presented in Figure 7. Primarily Ecoinvent database was preferred; in case the information was not available in this database, the other databases were used. Also, some data was adapted from the database for Turkey conditions such as energy generation profile. All the inputs and outputs of the sub-prosesses and their amounts entered to SimaPro is given in APPENDIX B.



☐ Dutch Input Output Database 95
☑ Ecoinvent system processes
☑ Ecoinvent unit processes
☐ ELCD
☑ EU & DK Input Output Database
☐ Industry data 2.0
☐ LCA Food DK
☑ Methods
☐ USA Input Output Database 98
☑ USLCI

Figure 7. Databases used in SimaPro

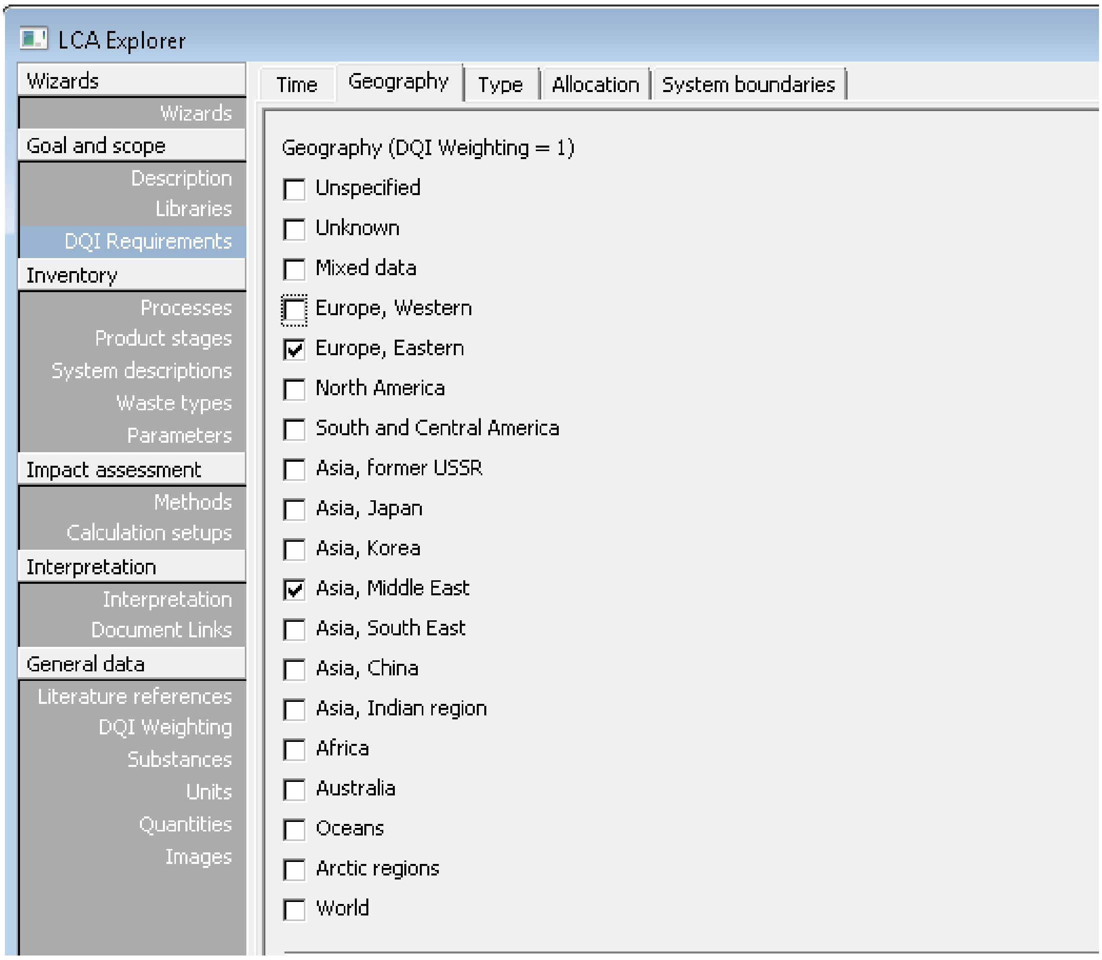
Data quality indicator requirements (time, geography, type of technology and representativeness of the data, etc.) should be identified in the goal and scope definition step. These requirements are important since they specify the adequacy of inventory data to be used in the study. The data quality indicator requirements can be selected in SimaPro based on the inventory data year, geography and type of the data. In this case, the inventory data belongs to the 2010 data of two facilities in Turkey. Therefore, “time” was selected as “2010 and after” (Figure 8); and “geography” was “Eastern Europe” and “Middle East Asia” (Figure 9). In Figure 10, information regarding to “technology and representativeness” of the data is presented. Both “average” and “modern” technology options were selected according to technologies used in the plants. For the representativeness of the data, several data types were used. Since real data from the plants were used, “data from specific plant and company” option was selected. Also, since the studies were conducted in two different plants, in some cases “average from a specific process” and “average from processes from similar outputs” selections were also used.



Time period (DQI Weighting = 3)

☐ Unspecified
☐ Unknown
☐ Mixed data
☑ 2010 and after
☐ 2005-2009
☐ 2000-2004
☐ 1995-1999
☐ 1990-1994
☐ 1985-1989
☐ 1980-1984
☐ Before 1980

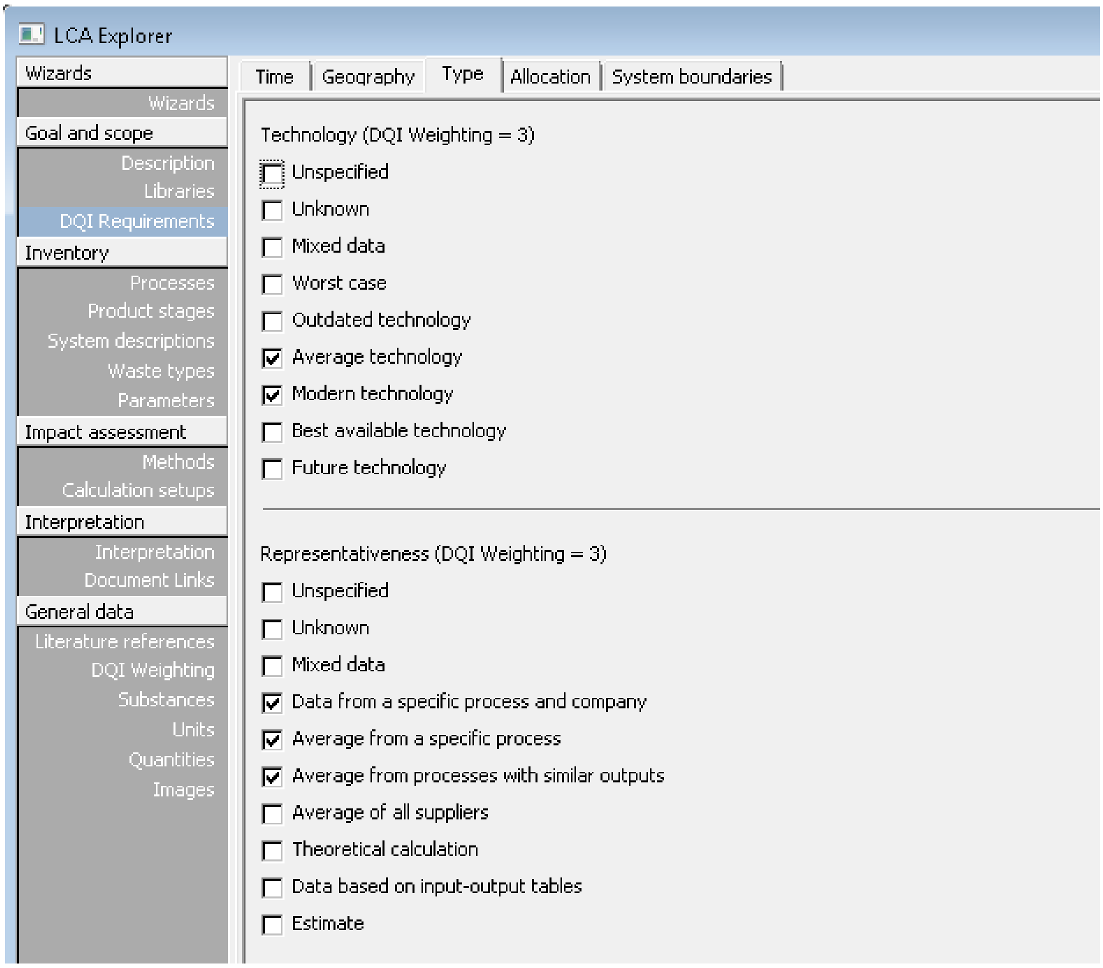
Figure 8. Data quality indicator requirements of LCA: Time



Geography (DQI Weighting = 1)

- ☐ Unspecified
- ☐ Unknown
- ☐ Mixed data
- ☐ Europe, Western
- ☑ Europe, Eastern
- ☐ North America
- ☐ South and Central America
- ☐ Asia, former USSR
- ☐ Asia, Japan
- ☐ Asia, Korea
- ☑ Asia, Middle East
- ☐ Asia, South East
- ☐ Asia, China
- ☐ Asia, Indian region
- ☐ Africa
- ☐ Australia
- ☐ Oceans
- ☐ Arctic regions
- ☐ World

Figure 9. Data quality indicator requirements of LCA: Geography



Technology (DQI Weighting = 3)

- ☐ Unspecified
- ☐ Unknown
- ☐ Mixed data
- ☐ Worst case
- ☐ Outdated technology
- ☑ Average technology
- ☑ Modern technology
- ☐ Best available technology
- ☐ Future technology

Representativeness (DQI Weighting = 3)

- ☐ Unspecified
- ☐ Unknown
- ☐ Mixed data
- ☑ Data from a specific process and company
- ☑ Average from a specific process
- ☑ Average from processes with similar outputs
- ☐ Average of all suppliers
- ☐ Theoretical calculation
- ☐ Data based on input-output tables
- ☐ Estimate

Figure 10. Data quality indicator requirements of LCA: Type

3.2.2 Inventory Analysis

Since the boundary of the study is “cradle to grave” for foundry processes and “cradle to gate 2” for foundry products, all the necessary data including downstream and upstream processes of casting should be available. For collecting the data, an inventory analysis was conducted for casting process. “Gate to gate” part of this analysis is specific to the foundry data for Turkey. However, when the data was absent or unavailable, several other databases (Figure 7) which are available in SimaPro were used for filling the missing data. Also, due to difficulty in gathering the data for all the downstream and upstream processes (cradle to grave), again SimaPro databases were utilized for “cradle to gate-1” and “gate-2 to grave” part of the study. Following casting process analysis, wastes arising from the process were determined. All the inputs and outputs of each sub-process were described as presented in Figure 12. The inputs were in the form of raw material or energy while the outputs were products and wastes. At this step; wastes and their generation points together with their classifications were described. After the determination of all wastes, their origins, and chararacteristics, for all production steps mass balances were described.

Also, treatment, reuse and recycle options for the wastes arising from the processes were examined in detail. The amounts of each waste stream were determined and entered to SimaPro software.

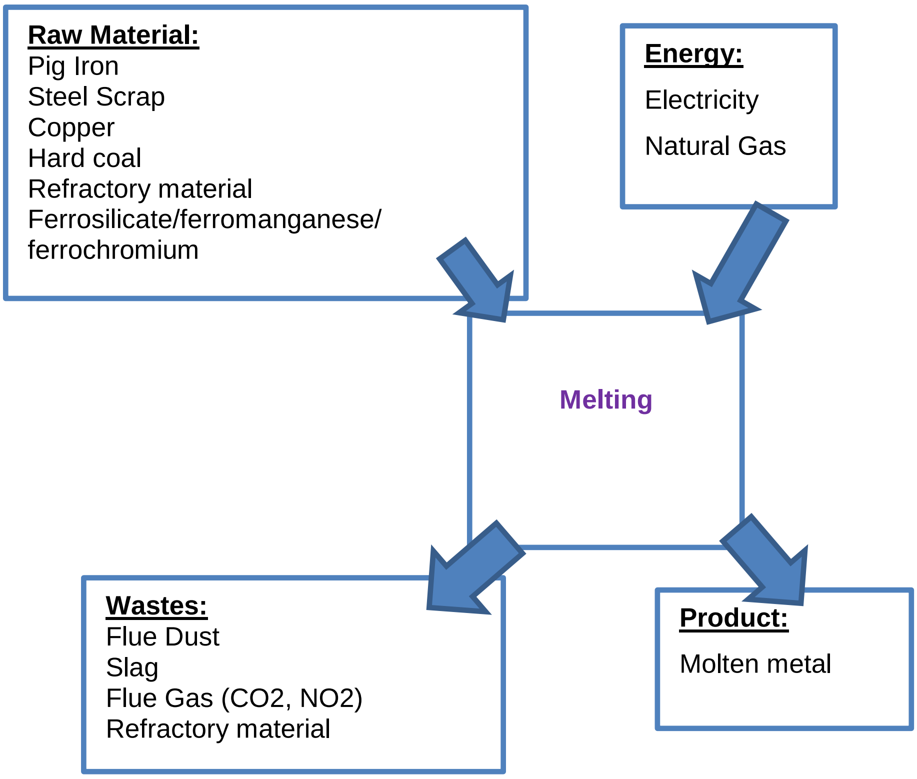


Figure 11. Inputs and outputs of metal melting

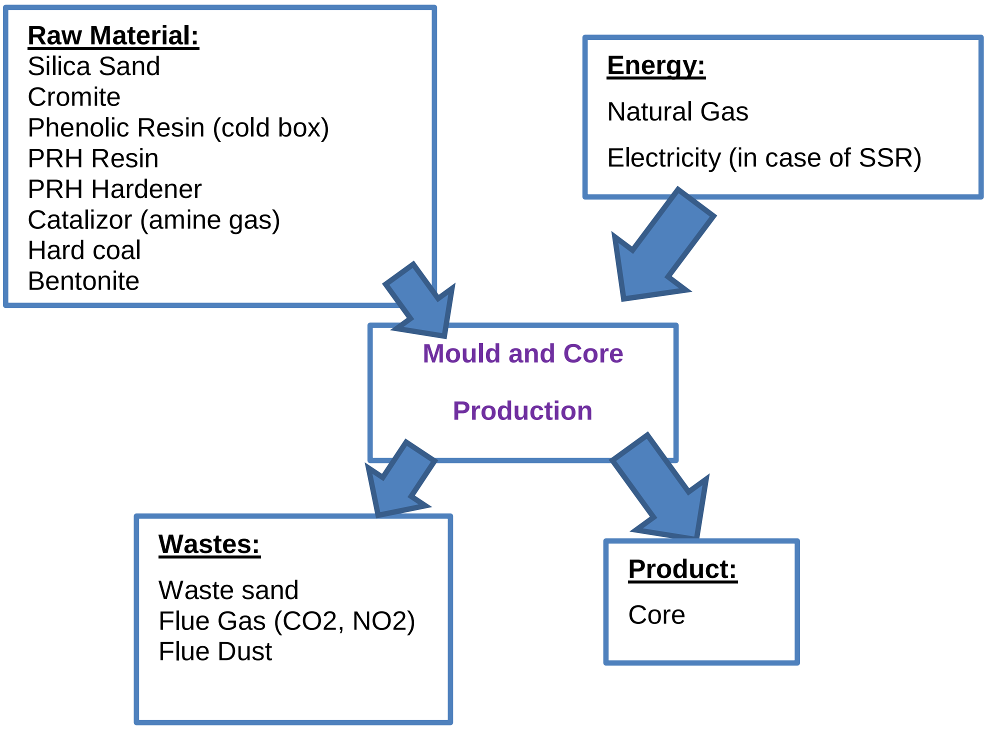


Figure 12. Inputs and outputs of core and mould production

3.2.3 Data Integration to SimaPro

Inventory analysis data need to be transmitted to the SimaPro software prior to proceeding into environmental impact assessment stage. It is very important to choose the appropriate materials from databases (Figure 7) and reorganise the data to be able to transmit it to the software for getting accurate results. Therefore, during integration, appropriate materials matching up with inputs and outputs of the foundry process were chosen from the databases.

For metal melting and casting sub-process, there was no need to reorganise the data for integration. Only, appropriate materials were chosen from the databases and amounts of every input and output items were entered according to inventory data.

However, inventory data of “core and mould production” needed to be revised and reorganised to be ready for entering the software correctly. The relevant information is provided in the following sub-section in detail.

3.2.3.1 Inventory Data Analysis for Integration to SimaPro for Core and Mould Production

For the system without SSR, amount of fresh sand and primary regenerated sand (indicated with the purple line in Figure 13) should be calculated seperately, since the amount of primary regenerated sand avoids that amount of fresh sand to be mined and processesed for using in the foundry. This application reduces environmental impacts due to fresh sand mining and processing. However, the data that was gathered from Plant 1 is the sum of fresh and primarily regenerated sand input. Output sand amount is the amount of sand that needs to be disposed after primary sand reclamation. Therefore, the difference between the input and output sand amount is the amount of sand that is primarly regenerated which is described as “avoided product” in the software. For fresh sand input, the amount of primarily regenerated sand is subtracted from the total sand amount and entered to the software as an input from technosphere. For the system with SSR plant application, similar to system without SSR practice, the amount of fresh and regenerated sand should be known seperately. For this reason, working principle of SSR plant (in Plant 2) is examined in detail. The relevant information is given in Section 2.3.4 and Section 3.1. The sand that is primarily regenerated enters to the SSR plant which consists of magnetic seperation and reclamation drum. The residue (non-magnetic) sand separated by magnetism enters directly to core production (indicated with the blue line in Figure 13) since this sand needs less binder addition. The remaining sand goes to reclamation drum, and recycled to the entrance of sand preparation plant (indicated with the red line in Figure 13). The efficiency of magnetic seperation is between 10-50% of waste sand as indicated by the Plant 2 staff. The overall efficiency of SSR plant is about 90% of waste sand which means that 10% of waste sand entering to the SSR plant can not be treated and recycled, but goes to landfill for final disposal. During the study, three scenarios were analysed for different magnetic seperation ratios; 10%, 30% and 50%. Also, taking resin burned during the casting process into consideration, amount of resin to be added to the reclaimed sand changes. In this study, it is accepted that either 50% or 70% of binders in total amount of sand is burned during the casting process based on the information gathered from the pilot plant staff. Therefore, while data is being entered to the SimaPro, the amount of total sand and binders (resins, hardener, catalyst, bentonite) are known seperately for core and mould production from the data taken from Plant 1. In this step, since non-magnetic sand and the sand recycled from reclamation drum enters to the system again, their sum is entered to the software as “avoided product”. By assuming a certain magnetic seperation efficiency (10%, 30% or 50%), the amount of recycled sand that does not need binder addition is subtracted from the total amount of sand requirement for core production, and the amount of sand that needs binder addition (according to burned ratio during the casting process) is calculated. Followingly, unit binder consumptions are calculated from the Plant 1 data for without SSR and assessed for the system with SSR (for its different scenarios). Also, waste sand going to landfill is decreased, since only 10% of waste sand is going to landfill for the system with SSR plant. Another important point that needs to be mentioned is the extra energy requirement for secondary reclamation. In BREF for Smitheries and Foundaries [2], it is stated that an additional 55 kWh is required for 1 ton waste sand reclamation. However, Plant 2 that has SSR, reported 110 kWh is required additionally for each ton of sand reclaimed. The difference in energy consumption between BREF and Plant 2 is understandable as the energy requirement depends on the size of SSR facility (number of magnetic seperation units and reclamation drum). Therefore, during LCA of the casting process with SSR plant, an unit energy requirement of 110 kWh/ton sand reclaimed is used.

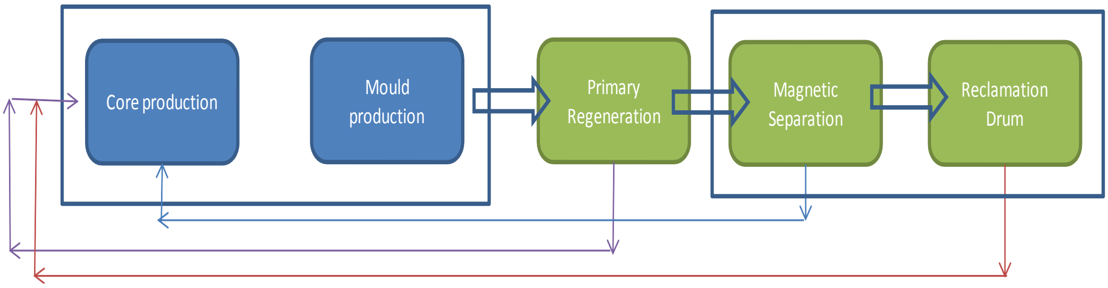


Figure 13. Casting process flow scheme with SSR

3.2.4 *Impact Assessment*

SimaPro has several methods for evaluating environmental impacts. Therefore, firstly, all the methods are examined and compared regarding to their capabilities and environmental impacts they consider. The comparison of the methods are presented in Table A 1 of APPENDIX A. Among these methods, three methods were end-point methods. Within these three end point methods, impact categories they consider were analysed and compared in order to select appropriate method for the study.

Table 4 represents the impact categories that are covered in Eco-Indicator 99, Impact 2002+ and ReCipe methods. During comparison, it was realized that the methods call the same impact category with different expressions. Also, some impact categories were divided into two sub-categories in some of the methods, eg. climate change.

Table 4. Comparison of impact categories

Impact	Eco-Indicator 99	Impact 2002+	ReCipe Endpoint	
Carcinogens	+	+	-	
Non-Carcinogens	-	+	-	
Human Toxicity	-	-	+	
Respiratory Organics	+	+	Pat. Matter Formation	+
Respiratory Inorganics	+	+		
Climate Change	+	-	Human Health	+
			Ecosystem	+
Global Warming	-	+	-	
Radiation	+	+	+	
Ozone Layer Depletion	+	+	+	
Aquatic Acidification	+	+	-	
Terrestrial Acidification		+	-	
Terrestrial Ecotoxicity	-	+	+	
Aquatic Eco-toxicity	+	+	Freshwater	+
			Marine	+
Aquatic Eutrophication	+	+	-	
Freshwater Eutrophication		-	+	
Non-renewable Energy	-	+	-	

Impact	Eco-Indicator 99	Impact 2002+	ReCipe Endpoint	
Land use	+	+	Agricultural	+
			Urban	+
Photochemical oxidation	-	+	+	
Mineral Extraction	+	+	-	
Natural Land Transformation			+	
Metal Depletion			+	
Fossil (Fuels)Depletion	+	-	+	

+ : exists in the method
-: does not exist in the method

In this study, because “Impact 2002+” covers additionally non-renewable energy with respect to other, “Impact 2002+” model is used for the assessment of environmental impacts. Non-renewable energy use is an important impact category for foundries, since they are energy intensive industries [25]. This model is damage oriented method and developed at the Swiss Federal Institute of Technology [23]. Model covers 14 mid-point categories and these mid-points are groupped into four different end-points. The relationship between mid-point and end-point impacts are illustrated in Figure 14.

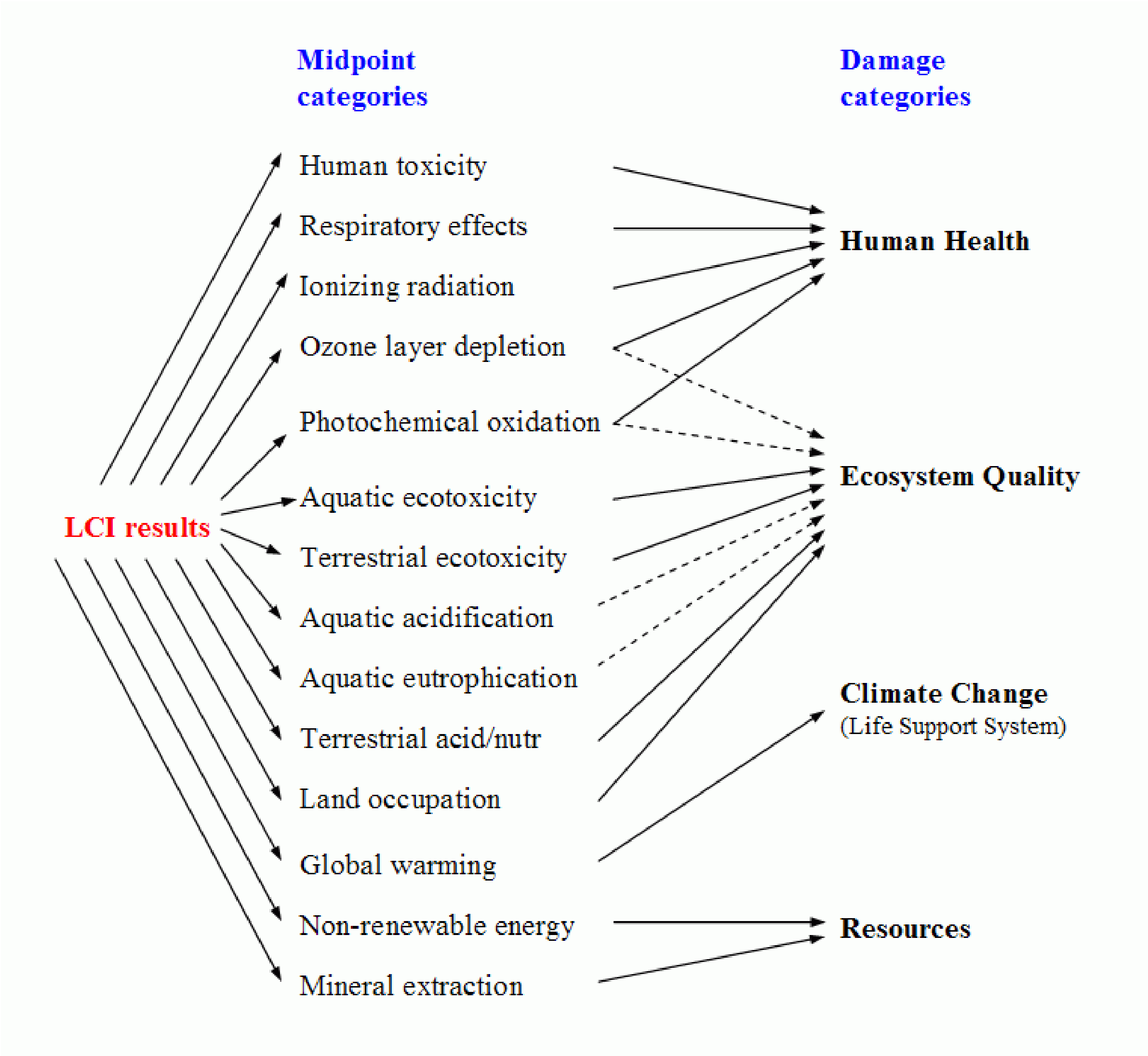


Figure 14. Linkage between mid-point categories and damage impacts in Impact 2002+ [23]

Mid-point and end-point environmental impacts covered in Impact 2002+ method are given in Table 5 and Table 6 [26].

Table 5. Mid-point impact categories and descriptions

Impact Category	**Description**
Human Toxicity	Estimates the cumulative toxicological risk and potential impacts when a chemical emitted (specified mass-kg) into the environment. Reference substance is carcinogenic effects of chloroethylene emitted into air (kg $C_2H_3Cl_{eq}$).
Respiratory Effects	Midpoints have been obtained by dividing the damage factor of the substance considered by the damage factor of the reference substance.Respiratory inorganics effect is expressed as kg $PM_{2.5\ eq}$ and respiratory organics effect is expressed as kg $C_2H_{4\ eq}$).
Global Warming	Midpoints characterization factors for global warming ($kg_{eq\text{-}CO2}$ into air/kg_{emi}) have been taken from the IPCC list (IPCC 2001). The latest Global Warming Potentials have been used with a 500 years time horizon.
Radiation	Midpoints (Bqeq Carbon-14 into air /kg_{emi}) have been obtained by dividing the damage factor of the considered substance by the damage factor of the reference substance (Carbon-14 into air).
Ozone Layer	Midpoints (kgeq CFC-11 into air /kg_{emi}) have been obtained from the US Environmental Protection Agency Ozone Depletion Potential List. Midpoint reference substance is *Trichlorofluoromethane -CFC-11*.
Aquatic Ecotoxicity	Midpoints (kgeq triethylene glycol *TEG* into water/kg_{emi}) have been obtained by dividing the damage factor of the substance considered by the damage factor of the reference substance (triethylene glycol into water).
Aquatic Acidification	Midpoints for aquatic acidification (kgeq SO_2 into air/kg_{emi}) have been taken directly from CML.
Aquatic Eutrophication	Midpoints for aquatic eutrophication (kgeq PO_4- into water/kg_{emi}) have been taken directly from CML.
Terrestrial Acidification / Nitrification	Midpoints (kg_{eq} SO2 into air/kg_{emi}) have been obtained from damage by dividing the damage factor of the substance considered by the damage factor of the reference substance (SO2 into air).
Land Occupation	Midpoints characterization factors (m^2 eq organic arable land · yr) have been obtained by dividing the damage factor of the considered flow by the damage factor of the reference flow (organic arable land·yr).
Non-renewable Energy	Midpoints (kg_{eq} crude oil (860 kg/m^3)/kgused) have been obtained by dividing the damage factor of the considered substance by the damage factor of the reference substance (crude oil (860 kg/m^3)).
Mineral Extraction	Midpoints (kg eq iron (in ore)/kg extracted) have been obtained by dividing the damage factor of the considered substance by the damage factor of the reference substance (iron (in ore)).

Table 6. End-point impact categories and descriptions

Impact Category	**Description**
Human Health	Covers carcinogens, non-carcinogens, respiratory organics, respiratory inorganics, ionizing radiation and ozone layer depletion. Unit is “disability adjusted life years-DALY” which characterizes the disease severity, accounting for both mortality (Years of Life Lost due to premature death) and morbidity.
Ecosystem Quality	Covers aquatic ecotoxicity, terrestrial ecotoxicity, terrestrial acidification/nutri, land occupation, aquatic acidification, aquatic eutrophication. Unit is the “potentially disappeared fraction- PDF* m2* yr” which means potentially disappeared fraction of plant species .
Climate Change	Covers global warming. Unit is the “kg CO2 eq”.
Resources	Covers non-renewable energy and mineral extraction. Unit is “MJ” which means MJ primary on non-renewable energy.

CHAPTER 4

RESULTS AND DISCUSSION

In this study, by using SimaPro ver. 7.2.4 software and data from pilot plants and mainly Ecoinvent database, environmental impact of conventional sand casting process was assessed from cradle to grave. Firstly, environmental impact of metal melting together with casting was calculated by selecting 1 ton of metal melted as functional unit. Secondly, environmental impact of mould and core making was assessed for 1 ton of mould production. Sum of the environmental impacts for 1 ton of cast product (mainly corresponds to 1 ton metal and 2 tons sand) of these two sub-processes constitute the environmental impact of traditional sand casting process with no SSR practice. As aforementioned, since waste from foundry processes mainly arises from mould and core making and spent sand is a major waste from the production of ferrous (also nonferrous) metal castings, the spent sand is recycled and reused multiple times in Plant 2. Eventually, however, heat and mechanical abrasion render the sand unsuitable for reuse in the casting process. At that point, the spent sand term as “foundry waste” is replaced with virgin sand and either recycled in a non-foundry application or landfilled. In this framework, environmental impact of second scenario which is traditional sand casting with the presence of SSR system was assessed. The purpose of the regeneration is to reduce the consumption of virgin sand and binder, and associated costs with providing these inputs, (extraction and transportation) and to reduce the amount of sand to be landfilled. However, this process requires additional energy consumption. In this step, three different scenarios were developed and assessed according to core (magnetic) seperation efficiency of SSR plant.

4.1 Environmental Impact of Foundry Sub-Processes without SSR

In this section, firstly environmental impact of each foundry sub-process (metal melting and core mould production) is presented for the absence of SSR.

4.1.1 Environmental Impact of Metal Melting

Pig iron, iron scrap, steel, copper are mixed to get ferrous alloy and coal is added to maintain carbon content of the alloy. Also, some additives (FeSi, FeMn) are added to the alloy to meet the ductility and durability of the metal. The alloy is then melted in induction furnaces which get their energy from electricity. Therefore, Turkey’s electricity production profile is introduced to the program and used during impact assessment which is given in Table 7. For the natural gas consumption, Europe’s profile which exist in the Ecoinvent database is used. During calculations, calorific value of natural gas is taken as 10.64 kWh as indicated by Public of Turkey Energy Market Regulatory Authority. Input output analysis of ferrous melting was entered to SimaPro. Since boundaries of this analysis is cradle to grave, while entering the inputs and outputs, all the downstream processes were included of each input and output. The details of these inputs and outputs were presented in

Table **8**.

.

Table 7. Turkey electricity supply profile [42]

Energy Type	**% (2009)**
Natural Gas	48.6
Domestic Coal	21.7
Hydraulic Energy	18.5

Imported Coal	6.6
Fuel Oil	3.4
Wind	0.76
Geothermal & Biogas	0.34

Table 8. Monthly average input and outputs from metal melting process for Plant 1

	Amount	Included process
Products		
Cast iron, at plant/RER U *	1612.50 ton/month	“RER” is the abbreviation which means data belongs to average of Europe. CY is the initials of author of the thesis, which indicates this product is prepared for this study.
Resources		
Ferrosilicate	28.93 kg/month	
Ferromanganese	6.85 kg /month	
Ferrochromium	2.00 kg/month	
Materials / Fuels		
Pig iron, at plant/ GLO U	853.66 ton/month	Blast furnace process. Emissions are abated. “GLO” means data used is the global data.
Hard coal mix, at regional storage/UCTE U	14.42 ton/month	Transport of the coal to harbours and storage. Average transport distance specific for the country has been used. Dust from transport and load/unload operations is included. Average coal losses are considered. Average emissions to water due to leaching from coal heaps at storage is estimated from the literature. “UCTE” means data used is the Europes data.
Refractory basic packed, at plant/DE U	7.97 ton/month	Includes the whole manufacturing process, internal processes (transport, etc.), packing and infrastructure. “DE” means data used is Germany data.
Steel, low alloyed, at plant/RER U	487.56 ton/month	Mix of differently produced steels and hot rolling
Copper, at regional storage/RER U	2.63 ton/month	Transport of primary metal to Europe from the countries importing to Europe is included. It is designed for the use of the metal various technical applications such as alloys and construction material. “RER” is the abbreviation which means data belongs to average of Europe.
Known inputs from technosphere (electricity/heat)		
Electricity/TR	2,645,402 kWh/month	Production of electricity according to Turkey profile.

Natural Gas, high pressure at consumer, RER S	28592.87 kWH/month	Describes the energy requirements and the emissions of the high pressure distribution network in Europe. “RER” is the abbreviation which means data belongs to average of Europe.
Emissions to air		
Carbon monoxide, fossil	0.0174 kg/month	
Particulates, >2.5μm, and <10 μm	382.50 kg/month	
Waste to treatment		
Disposal inert waste, 5% water, to inert material landfill /CH U	1.58 ton/month	No direct emissions from inert material landfill (leachate) are inventoried as deemed negligible. Module contains only exchanges to process-specific burdens (energy, land use) and infrastructure. “CH” is the Chinese data.
Disposal, slag waste, unalloyed electr. Steel, 0% water, to residual material landfill /CH U	35.68 ton/month	Waste-specific short-term emissions to water from leachate. Long-term emissions from landfill to ground water. Inventoried waste contains 100% slag from electric steel production to landfill. “CH” is the Chinese data.

* : means production of cast iron in the content of this study

Based on data entered in Table 8 and screenshots given in APPENDIX B Figure B 1 represents the normalized environmental impact of 1 ton metal melting by using Impact 2002+ method. The highest environmental impact contribution belongs to one of the inputs, namely, pig iron production; since blast furnace process which uses high amounts of energy is used for the production of pig iron. Second most contributor was investigated as steel production which also has several steps to be produced with high amounts of energy requirement. Hence, for these two inputs, respiratory inorganics, global warming and non-renewable energy categories shared the three top among other impact categories. This impact is due to coke and sinter consumption in the production of these inputs [43]. Within impact categories, non-renewable energy, respiratory inorganics, and global warming ranked top three with the values 0.1691, 0.1653 and 0.1329 mpts respectively, among environmental impacts that is covered by Impact 2002+ method. Other impacted categories by metal melting are carcinogens, non-carcinogens, non-carcinogens and terrestrial ecotoxicity.Steel and iron production are contributors of these impacts. Table C 1 in APPENDIX C present detailed impacts of metal melting according to its mid-point results. APPENDIX D, Table D 1 exhibits end-point results of this system.

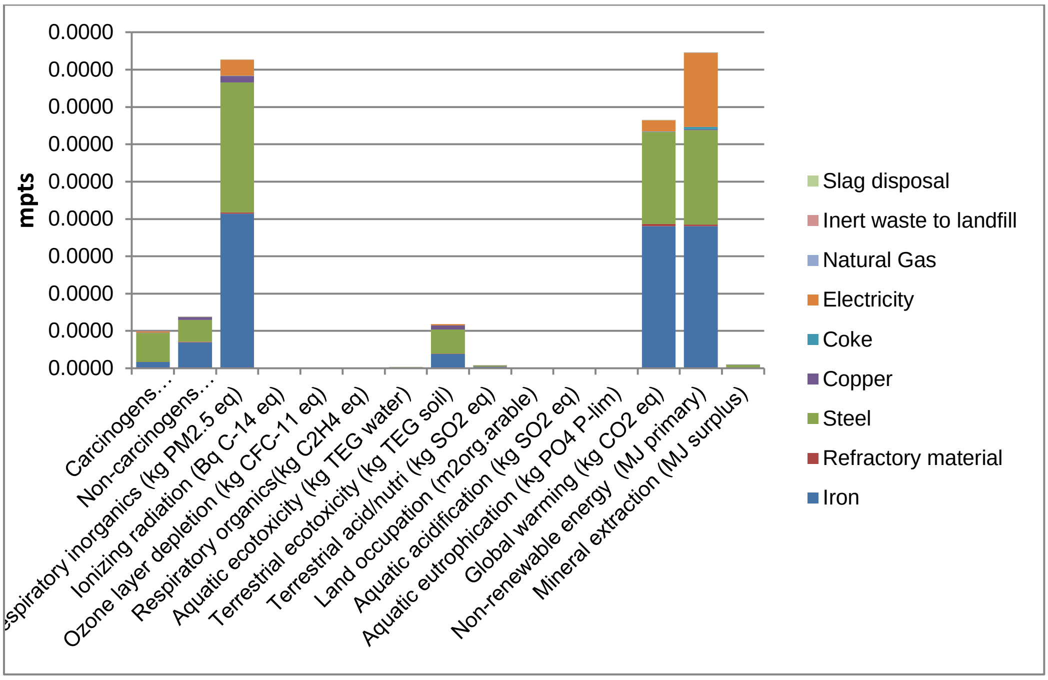


Figure 15. Environmental impact of metal melting based on inputs and outputs in milipoints (mpts)

4.1.2 Environmental Impact of Core and Mould Production without SSR

For core and mould production; silica sand which is mainly quartz, chromite sand, resins and binders are used together with catalysts and some fine tuning elements. In conventional sand casting, mostly phenolic resins are used as binders. Main catalyst used in the process is dimethyethylamine gas. Fine tuning elements are furan resin and furan hardener. Outputs of the process are spent foundry waste, particulate matter and flue gas. Energy supply of moulding is natural gas in Plant 1.

Table 9 summarizes the data entered in SimaPro for the impact assessment of core production without sand reclamation application and its screenshot is given in APENDIX B, Figure B 2. For these inputs and outputs, processes included are presented in Table 10.

Table 9. Core and mould production without sand reclamation application input/output data entered in SimaPro for Plant 1

	Amount	**Unit**
Known outputs to technosphere. Products and co-products name		
Core and mould/TR	827.62	ton/month
Known outputs to technosphere. Avoided products		
Sand at mine/CH U	110.7	ton/month
Known inputs from technosphere (materials/fuels)		
Chromite, ore concentrate, at beneficiation/GLO U	6.19	ton/month
Sand at mine/CH U	996	ton/month
Phenol-resorcinol- formaldehyde hardener, at plant, US	1.58	ton/month
Dimethylamine, at plant/RER U	693.17	kg/month
Phenol-resorcinol- formaldehyde resin, at plant,	4.83	ton/month

	Amount	**Unit**
US		
Phenolica resin, at plant/RER U	7.67	ton/month
Known inputs from technosphere (electricity/heat)		
Natural gas, high pressure, at consumer/RER U	8251	MWh/month
Emissions to air		
Carbon monoxide	0.31	kg/month
Particulates, <10 μm (mobile)	123.26	kon/month
Nitrogen dioxide	0.02	kg/month
Known outputs to technosphere. Waste and emissions to treatment		
Disposal inert waste, 5% water, to inert material landfill /CH S	996	ton/month

Table 10. Processes Included for core and mould production [23]

Input / output name	**Included process**
Sand at mine	The whole manufacturing process for digging of gravel round and sand (no crushed gravel), internal processes (transport) and infrastructure for the operation (machinery)
Chromite	Mining and a beneficiation step with the mining infrastructure and disposal of overburden tailings
Phenol-resorcinol-formaldehyde (PRF) hardener, at plant, US	Complete allocated cradle to grave LCI for PRF hardener
Phenol-resorcinol-formaldehyde (PRF) resin, at plant, US	Complete allocated cradle to grave LCI for PRF resin
Phenolic resin	Raw materials and chemicals used for production transport of materials to manufacturing plant, estimated emissions to air and water from production, estimation of energy demand, infrastructure of the plant. Solid wastes omitted.
Coal at mine	Average operational condiitons in the relevant geographical region. Quatifies directly affected area and occupation during operation of the mine. Electricity, heat and diesel requirements for minig operations are included. Pumped groundwater explosives, emissions to air and water and solid waste complete the module.
Bentonite at mine	Excavation by digger, transportation to first grindign machine, the lans use of the mine and recultivation.

A sample calculation is presented in Table 11. This sample belongs to the enviornmental impact of benzene in hard coal (used in core and mould production) on human health. In order to conduct this calculation; amount of benzene in the coal and its charactarization, damage and normalisation factors should be known. As it is stated before; these factors change depending on the calculation method. For Impact 2002+ method, these factors are presented in this Table. Human health is the end-point effect and includes carcinogens, non-carcinogens, respiratory inorganics, ionizing radiation, ozone layer depletion and respiratory organics. Therefore, impact of benzene in coal is the sum of each environmental impacts of these mid-point effects.

	Characterisation Factor	Unit	Damage Factor	unit	Normalisation Factor
Carcinogens	3,84E-05	kg C2H3Cleq/kg	2,80E-06	DALY/kg C2H3Cl q	141
Non-carcinogens	7,415	kg C2H3Cleq/kg	2,80E-06	DALY/kg C2H3Cl q	
Resp. Inorg.		kg PM 2,5 eq/kg	7,00E-04	DALY/kg PM2,5 eq	
Ionizing Radiation		Bq C-14eq/Bq	2,10E-10	DALY/Bq C-14 eq	
Ozone Layer Depletion		kg CFC-14 eq/kg	1,05E-03	DALY/kg CFC-11 eq	
Resp. Org.	0,219	kg C2H4 eq/kg	2,13E-06	DALY/kg CH4 eq	

	Calculated	**Unit**
Carcinogens	0,86x10E-9x3,84E-05 =3,29 E-14	kg C2H3Cleq
Non-carcinogens	0,86x10E-9x7,415 = 6,35 E-9	kg C2H3Cleq
Resp. Inorg.	NA	kg PM 2,5 eq
Ionizing Radiation	NA	Bq C-14eq
Ozone Layer Depletion	NA	kg CFC-14 eq
Resp. Org.	0,86x10 E-9x0,219 =1,88 E-10	kg C2h4 eq

	Calculated	**Unit**
Carcinogens	3,29 E-14x 2,80 E-06 = 9,20 E-20	DALY
Non-carcinogens	6,35 E-9x2,80E-06 = 1,78 E-14	DALY
Resp. Inorg.	NA	DALY
Ionizing Radiation	NA	DALY
Ozone Layer Depletion	NA	DALY
Resp. Org.	1,88 E-10x2,13E-06= 4 E-16	DALY

	Calculated	**Unit**
Carcinogens	9,20 E-20x141 =1,30 E-17	unitless
Non-carcinogens	1,78 E-14x141=2,50 E-12	unitless
Resp. Inorg.	NA	unitless
Ionizing Radiation	NA	unitless
Ozone Layer Depletion	NA	unitless
Resp. Org.	4 E-16x141 =5,65 E-14	unitless

TOTAL **2,56 E-12**

Table 11. Sample environmental impact calculation (for hard coal used in core and mould production on human health)

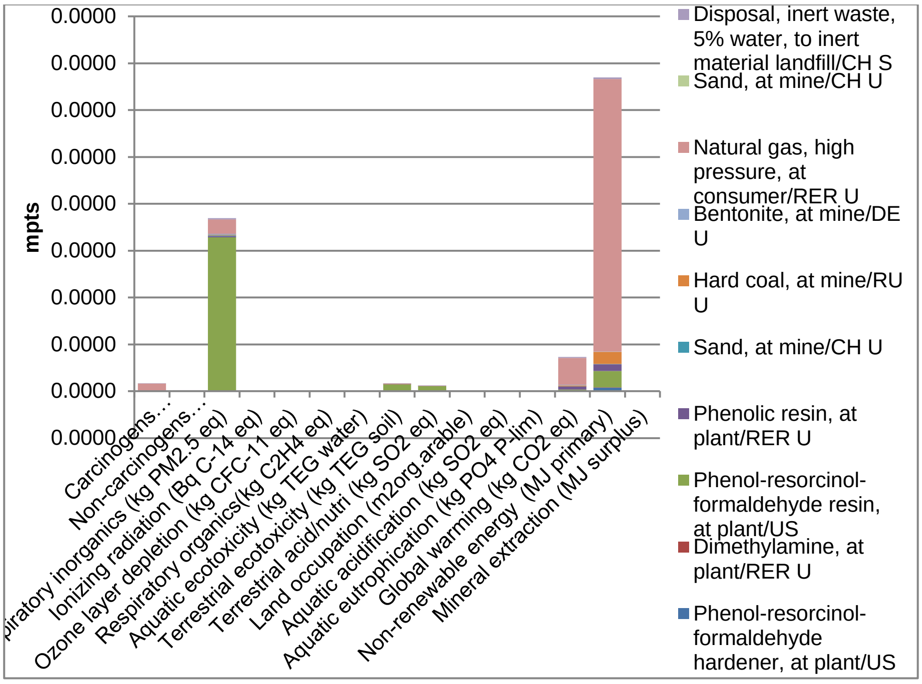


Figure 16. Environmental impact of core and mould preperation without SSR in millipoints (mpts)

Based on the results presented above, it is shown that phenol-resorcinol formaldehyde resin due to its high pollution contribution to respiratory inorganics (0.1639 mpts) and the natural gas due to its non-renewable energy property (0.2906 mpts) have the highest environmental impact. When the reason of respiratory inorganics pollution contribution of phenol-resorcinol formaldehyde resin is traced back in SimaPro, it is realized that, these inorganics came from the production of the resin. Also, global energy impact category results in considerable amount (0.0289 mpts) because of high natural gas consumption in the process. The negative value (-0.0001 mpts) in the figure belongs to the primarily regenerated sand which is entered as "avoided product" in SimaPro. The amount of primarily regenerated sand prevented the emission of respiratory inorganics. Detailed information regarding to mid-point results of this process is given in Table C 2 in APPENDIX C. End-point results are given in APPENDIX D.

4.2 Environmental Impact of Foundry Sub-Processes with SSR

In this part of the study, LCA of core and mould preparation is conducted by taking into consideration different magnetic separation ratios (10%, 30% and 50%) and different amounts of burned sand (50% and 70%) during melting. So, in this part, only core and mould production environmental impacts change. There is no change in metal melting part. The following bullets illustrates the environmental impact of these scenarios.

4.2.1 Scenario A : Environmental Impact of Mould and Core Production with 10% Magnetic Seperation Efficiency and 50% Burned Sand

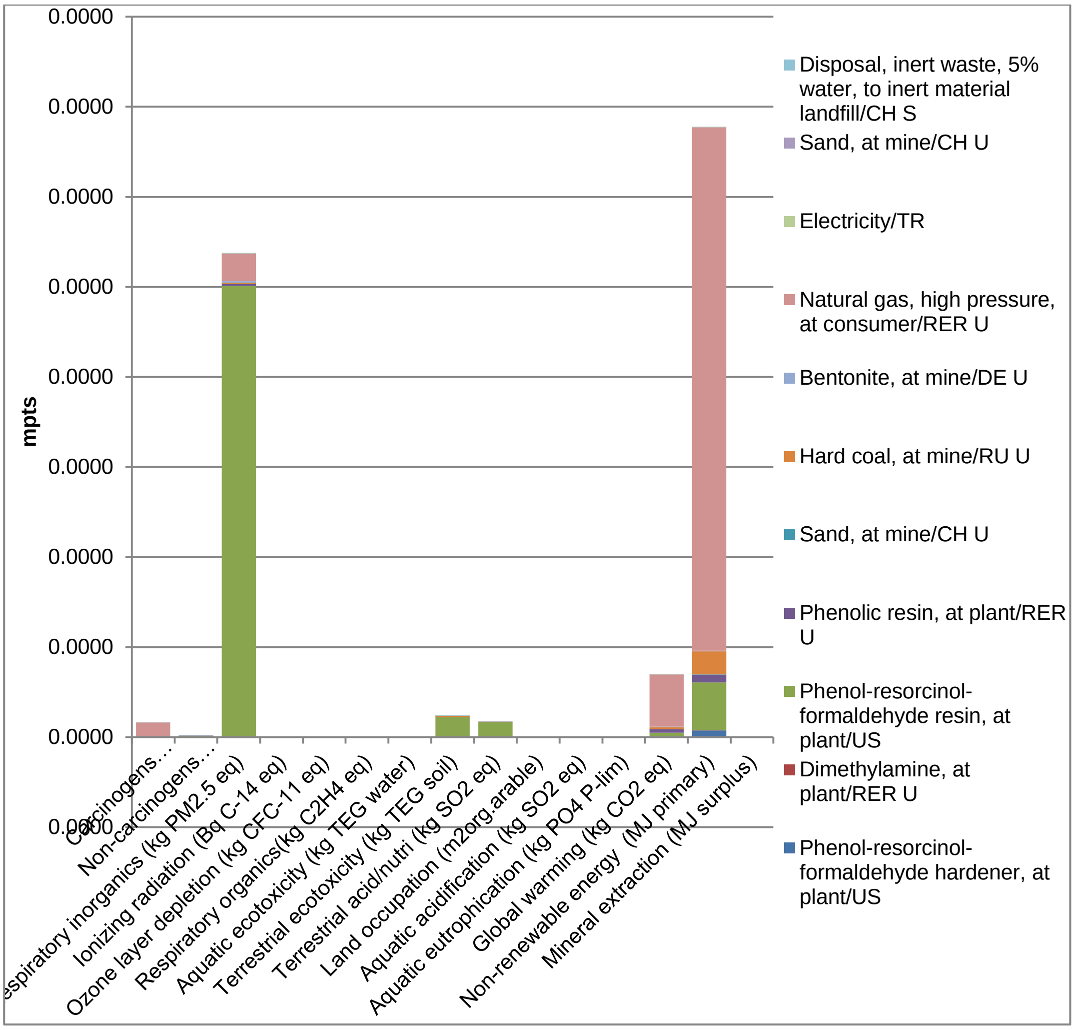


Figure 17. Environmental Impact of Mould and Core Production with 10% Magnetic Seperation Efficiency and 50% Burned Sand in millipoints (mpts)

Figure 17 presents environmental impact of mould and core production followed by SSR. In this scenario, it is accepted that 10% of spent sand which can not primarily regenerated is seperated by magnetism in SSR as core sand and its 50% is burned during metal pouring which means that 50% of the resin is burned during molten metal pouring. Therefore, amount of sand to be recycled is increased whereas amount of sand to be landfilled is decreased in case of SSR application (for the screenshots of SimaPro: APPENDIX B Figure B 3). For this reason, recycled amount of sand is avoided to be mined and processed to be ready for the casting. Therefore, this recycled amount of sand has an positive impact on environment (in SimaPro, since it does not have additional impact on environment, it is indicated by negative values). More importanly, amount of resins, hardener, chromite and dimethylamine is reduced in proportional with the magnetic seperation efficiency and burned sand amount. Because, sand which does not exhibit magnetism, is core sand and amount of burned sand needs additional resins and catalysts in order to gain its properties again. However, additional energy which is electricity is added to the system. As compared with the scenario with no SSR (Figure 16) effect on respiratory inorganics due to phenol-resorcinol formaldehyde resin (0.2503 mpts) is decreased because of less resin requirement. If total effect of these scenarios are compared, this scenario (0.6713 mpts) has more environmental effect than the scenario without SSR (0.5795 mpts). This means, reduction in environmental impact regarding to resin consumption and sand for landfilling could not compensate the increase in environmental impact in energy utilisation (natural gas and electircity). Detailed mid-point results are presented in APPENDIX C (Table C3), The end-point results are given in APPENDIX D Table D 3.

4.2.2 Scenario B: Environmental Impact of Mould and Core Production with 10% Magnetic Seperation Efficiency and 70% Burned Sand

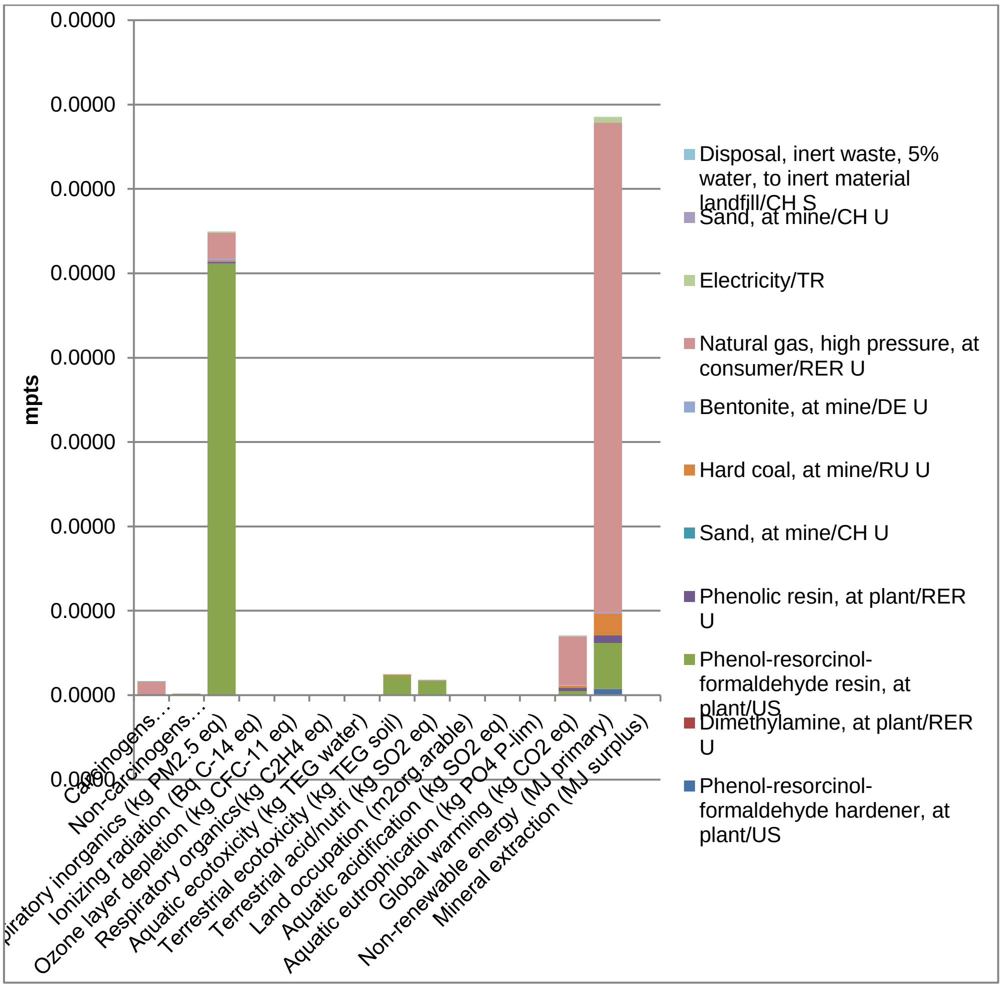


Figure 18. Environmental Impact of Mould and Core Production with 10% Magnetic Seperation Efficiency and 70% Burned Sand in millipoints (mpts)

In this scenario, it is accepted that 10% of spent sand which can be primarily regenerated is seperated by magnetism in SSR as core sand, and its 70% is burned during metal pouring. The data entered in SimaPro is given in APPENDIX B Figure B 4 as screenshots. As compared with the system with the above scenario with 50% burned sand, effect on respiratory inorganics due to phenol-resorcinol foemaldehyde resin (0.2556 mpts) is increased because of more resin requirement since 70% of resin is burned during metal pouring. Effects regarding to energy utilization stays the same. If total effect of these scenarios are compared, this scenario (0.6825 mpts) has more environmental effect than scenario A (0.6713 mpts). This is mainly due to increase in amount of resin burned during metal melting which needs more resin addition than in Scenario A. Detailed mid-point results are presented in APPENDIX C, Table C 4. End-ponit results are given in APPENDIX D, Table D 4.

4.2.3 Scenario C: Environmental Impact of Mould and Core Production with 30% Magnetic Seperation Efficiency and 50% Burned Sand

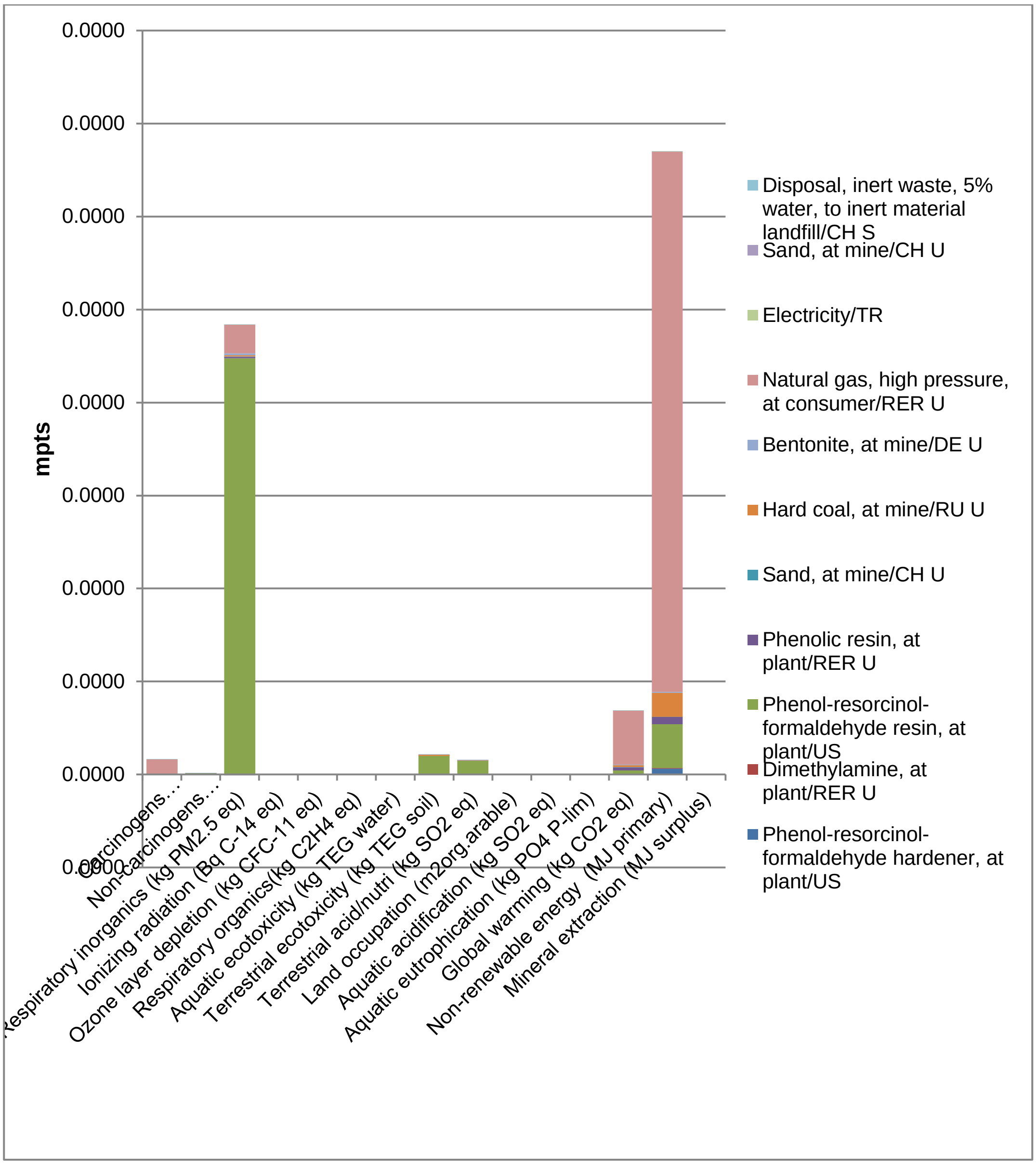


Figure 19. Environmental Impact of Mould and Core Production with 30% Magnetic Seperation Efficiency and 50% Burned Sand

In this scenario, it is accepted that 30% of spent sand which can be primarily regenerated is seperated by magnetism in SSR as core sand, and its 50% is burned during metal pouring. The data regarding to this process is given as screenshots in APPENDIX B, Figure B 5. As compared with Scenario A, effect on respiratory inorganics due to phenol-resorcinol foemaldehyde resin (0.2236 mpts) is decreased because of less resin requirement since

30% of spent sand is recycled. This effect is also less than the same effect in scenario B. This is mainly because of, more amount of sand is seperated by magnetism. Effects regarding to energy utilization stays the same. Regarding to total environmental effect, scenario C has the lower environmental impact than scenario A and B. Detailed mid-point results are presented in APPENDIX C, Table C 5. End-point results are given in APPENDIX D, Table D 5.

4.2.4 Scenario D: Environmental Impact of Mould and Core Production with 30% Magnetic Seperation Efficiency and 70% Burned Sand

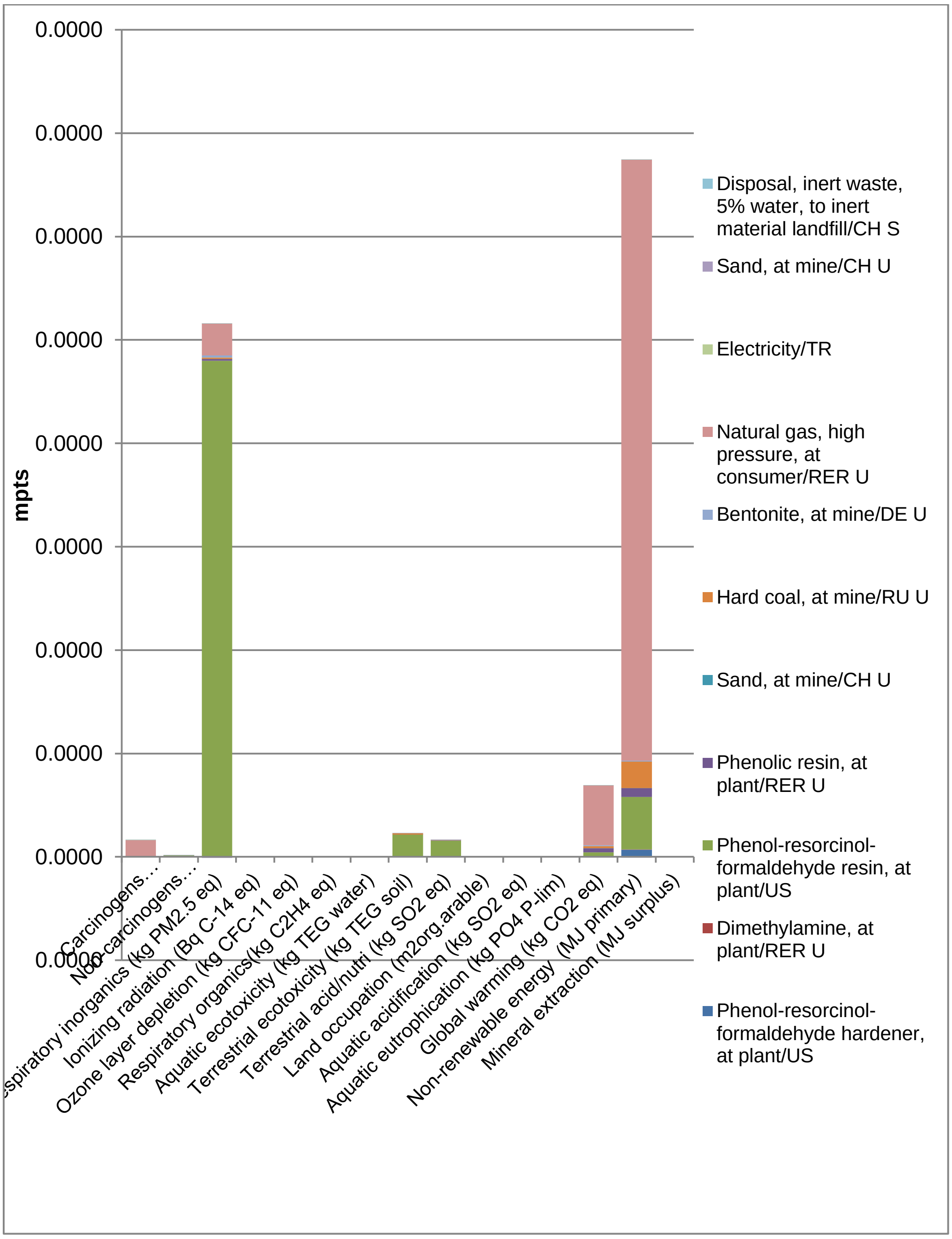


Figure 20. Environmental Impact of Mould and Core Production with 30% Magnetic Seperation Efficiency and 70% Burned Sand

In this scenario, it is accepted that 30% of spent sand which can be primarily regenerated is seperated by magnetism in SSR as core sand, and its 70% is burned during metal pouring. The data entered for this scenario is given in screenshots in APPENDIX B, Figure B 6. As compared with Scenario A, effect on respiratory inorganics due to phenol-resorcinol formaldehyde resin (0.2396 mpts) is decreased because of less resin requirement since 30% of spent sand is recycled although amount of burned sand is less. This effect is also less than the same effect in scenario B. This is mainly because of, more amount of sand is seperated by magnetism. However, since resin curement in scenario C is less than that secnario, environmental effect belonging to phenol-resorcinol formaldehyde resin is higher than scenario C. Regarding to total environmental effect, this scenario has higher impact than scenario C but lower impact than scenario A and B. Detailed mid-point results are presented in APPENDIX C. End-point results are given in APPENDIX D Table D 6.

4.2.5 *Scenario E: Environmental Impact of Mould and Core Production with 50% Magnetic Seperation Efficiency and 50% Burned Sand*

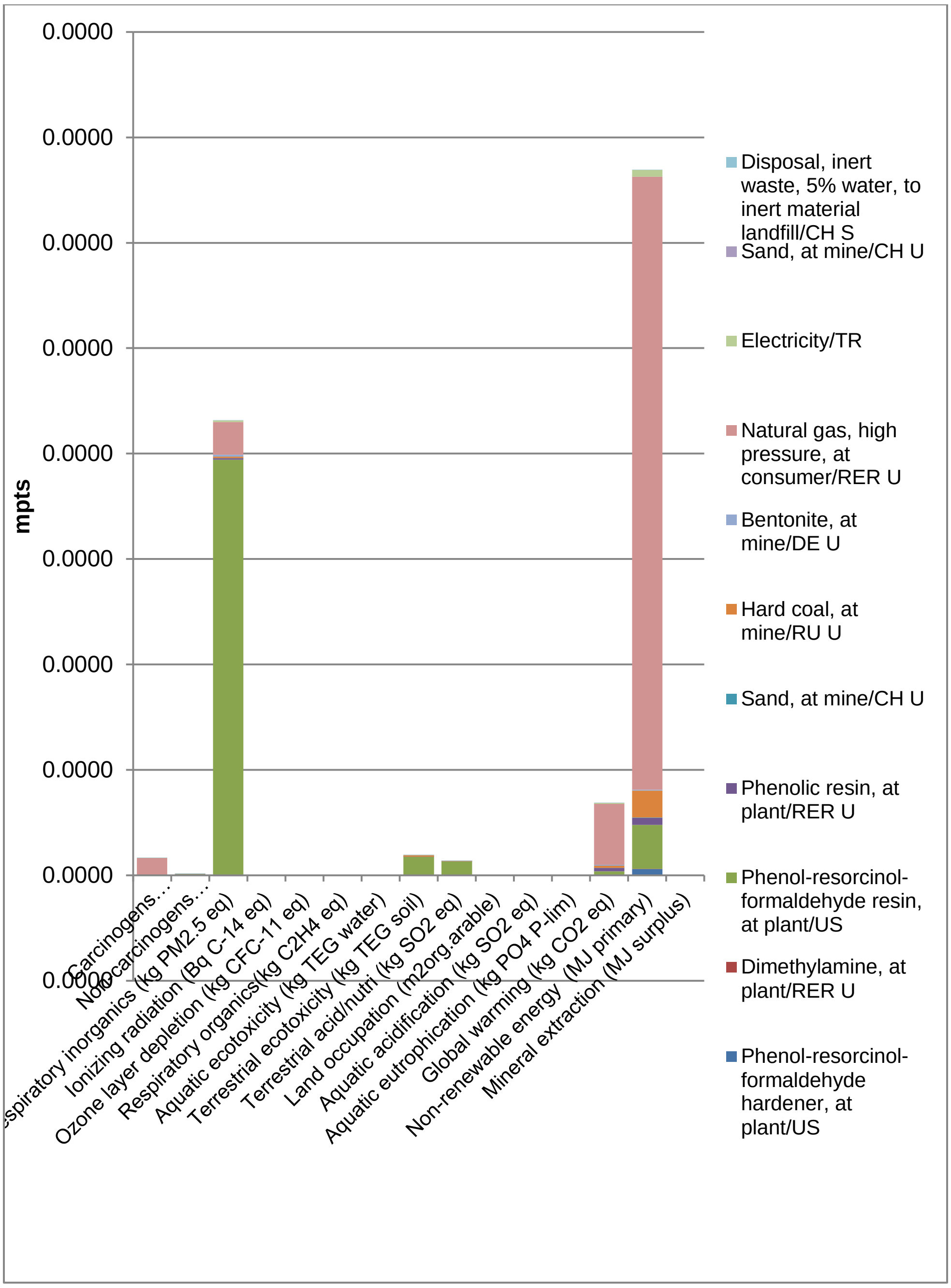


Figure 21. Environmental Impact of Mould and Core Production with 50% Magnetic Seperation Efficiency and 50% Burned Sand

In this scenario, it is accepted that 50% of spent sand which can be primarily regenerated is seperated by magnetism in SSR as core sand, and its 50% is burned during metal pouring. The data entered for this scenario is given in screenshot APPENDIX B Figure B 7. As compared with all of the scenarios, this scenario has the lowest environmental impact (0.1969 mpts) regarding to resin. This is mainly because of, more amount of sand is seperated by magnetism. Regarding to total environmental effect, this scenario has lowest environmental impact than all of the other scenarios (0.6095 mpts). However, it is still higher than the process without SSR (0.5795 mpts). Detailed mid-point results are given in APPENDIX C Table C 7. End-point results were given in APPENDIX D Table D 7.

4.2.6 Scenario F: Environmental Impact of Mould and Core Production with 50% Magnetic Seperation Efficiency and 70% Burned Sand

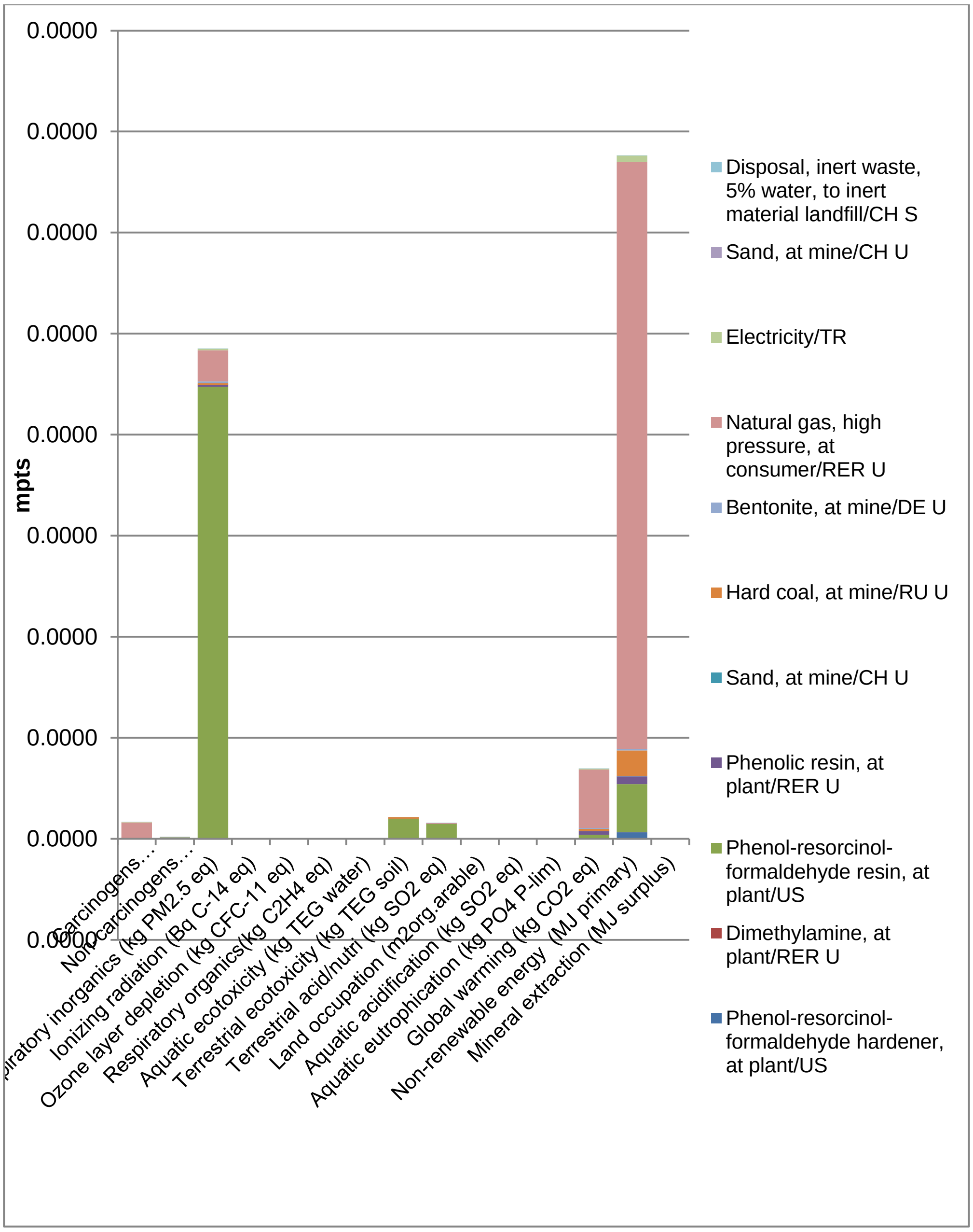


Figure 22. Environmental Impact of Mould and Core Production with 50% Magnetic Seperation Efficiency and 70% Burned Sand

In this scenario, it is accepted that 50% of spent sand which can be primarily regenerated is seperated by magnetism in SSR as core sand, and its 50% is burned during metal pouring. As compared with all of the scenarios, this scenario has the lowest environmental impact (0.1969 mpts) regarding to resin. This is mainly because of, more amount of sand is seperated by magnetism. Regarding to total environmental effect, this scenario has lowest environmental impact than all of the other scenarios (0.6246 mpts). Detailed mid-point results are given in APPENDIX C Table C 8. End-point results are given in APPENDIX D, Table D 8.

Table 12 summarizes the environmental impacts of foundary sub-processes with and without SSR. If table is analysed from top to bottom, the increse in environmental impact is due to additional resin requirement since amount of resin is increased from 50% to 70%. From left to right, environmental impact for core and mould production is decreased due to amount of sand reused again which is avoided product. As it is shown in the table, core and mould production without SSR has the lowest environmental impact whereas metal melting has the highest environmental impact.

Table 12. Comparison of the environmental impacts (mpts) of the scenarios with and without SSR

	NO SSR	**SSR**		
		10%	**30%**	**50%**
Metal melting	0.82335524	0.82335524	0.8233552	0.82335524
Core and mould preperation	0.57974693			
Core and mould preperation with 50% burned sand		0.6715859	0.6383959	0.60965173
		Scenario A	*Scenario C*	*Scenario E*
Core and mould preperation with 70% burned sand		0.68273642	0.6583117	0.64283798
		Scenario B	*Scenario D*	*Scenario F*

Environmental impact according to mid-point results for each functional unit; one ton metal melting and one ton sand preperation is given in Figure 23.

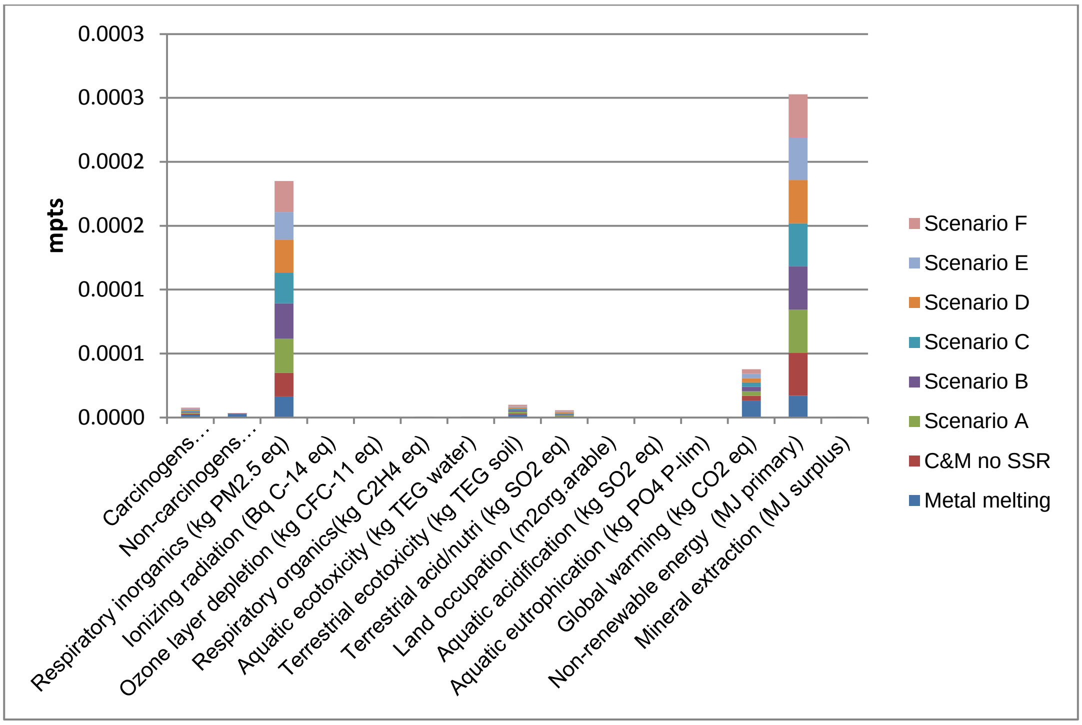


Figure 23. Environmental impact according to mid-point results for each functional unit

4.2.7 Environmental Impact of Foundry Products

Up to this part of the study, environmental impacts of foundry sub-processes and effect of SSR by considering six scenarios are analysed towards LCA goal. In this part, by using the data obtained from above analyses, environmental impact of two different foundry products are calculated. Products are selected according to their metal to sand ratios. As the first product, it is assumed that 8 tons of foundry sand is used during 1 ton of metal casting whereas in the second product it is assumed to be 16 tons of sand for 1 ton of metal casting.

Environmental impacts of each products are calculated for every scenario that is given in Section 4.2.1. Results are given in

Table 13 for functional units 1 ton of product which needs 8 tons of sand and 1 ton of product which needs 16 tons of sand during casting. According to the results presented in Table 13 product which has metal to sand ratio 1:8 with SSR magnetic seperation efficiency 50% and 50% burned sand has the lowest environmental effect (5.7005 mpts). This is because, not only less the amount of sand utilised than metal to core rarito 1:16, but also efficiency of magnetic sand seperation and and amount of burned sand since this scenario needs less binder addition.

Table 13. Environmental impacts of foundry sub-processes and products

	NO SSR	**SSR**		
		10%	**30%**	**50%**
Metal to core ratio: 1 to 8	5.46133068			
Metal to core ratio: 1 to 16	10.0993061			

	NO SSR	**SSR**		
		10%	**30%**	**50%**
Metal to core ratio: 1 to 8 (50% burned)		6.19604246	5.9305225	5.70056906
Metal to core ratio: 1 to 8 (70% burned)		6.2852466	6.089849	5.96605906
Metal to core ratio: 1 to16 (50% burned)		11.5687297	11.03769	10.5777829
Metal to core ratio: 1 to 16 (70% burned)		11.747138	11.356343	11.1087629

CHAPTER 5

CONCLUSION

This study was conducted to investigate LCA of conventional sand casting and to assess efficiency of SSR which is suggested as BAT in the literature. To this purpose, 1 ton of metal melting and 1 ton of core and mould production were selected as functional units. Data used during tha calculations is the monthly average data of Plant 1. The LCA is conducted by using SimaPro ver 7.2.4 software. The foundry processes were analyzed from cradle to grave manner. Data for the gate to gate part of the study gathered from pilot plant studies. For missing or unavailable data, Ecoinvent database was used.

Results of the study revealed that among all of the sub-processes, in a foundry with sand casting tecnology, metal melting has more environmental impact due to high energy demand during production of pig iron and steel and for melting the metal. For core and mould production process without SSR, phenol-resorcinol formaldehyde resin production has more impact on environment followed by natural gas production. Within impact categories; non-renewable energy, respiratory inorganics, and global warming ranked top three. As an alternative scenario, use of sand reclamation system was analyzed since it is suggested as one of BAT in the literature. SSR was analysed according to different scenarios depending on the efficiency of magnetic separation efficiency and amount of burned sand during molten metal pouring into moulds (Figure 24). The presence of the sand reclamation system lead to significant increase in respiratory inorganics, non-renewable energy due to its additional energy demand.

Beyond assessing environmental effects of foundry sub-processes, environmental impacts of foundry products were also analysed. Two different products were used in the calculations: first one was the product which has metal to sand ratio 1:8 and second one has metal to sand ratio 1:16. Effects of these two products were analysed for each scenario. Product which has metal to sand ratio 1:8 with Scenario E showed the lowest environmental effect. However; some uncertainty in the results are epected since monthly average data is used during calculations. These uncertainties could not performed because of the time limitation problem. However, it is evaluated that minimum and maximum values of the data is changing between 5-60%, therefore although calculations could not performed, the deviation of environmental impacts is expected as same as the difference between minimum and maximum data. Additionally, since the scope of the study is the comparison of the several scenarios, it was thought that this possible uncertanity will not effect the results to a great extent as it will affect all the scenario cases to the same extent.

To sum up, among all of the foundry sub-processes, metal melting showed the highest environmental impact, whereas sand and core preparation with SSR which has 10% magnetic sand efficiency and 70% burned sand showed the highest environmental impact. By this way, it is also proved that application of SSR which is indicated as BAT in the literature does not reduce environmental impacts in the whole life cycle of foundry processes due to its energy demand. On the other hand; since the amount of waste sand going to landfiil and fresh sand transported is reduced and amount of consumed energy is increased, economic feasibility of the SSR application should also be taken into consideration during decision. Within the scope of this study, such analysis could not be performed due to the required detailed information regarding to the plant operation (such as the number of employees, their salaries, number of shifts etc.) and transport (such as vehicle type and numbers etc), as well as the cost of fresh sand.

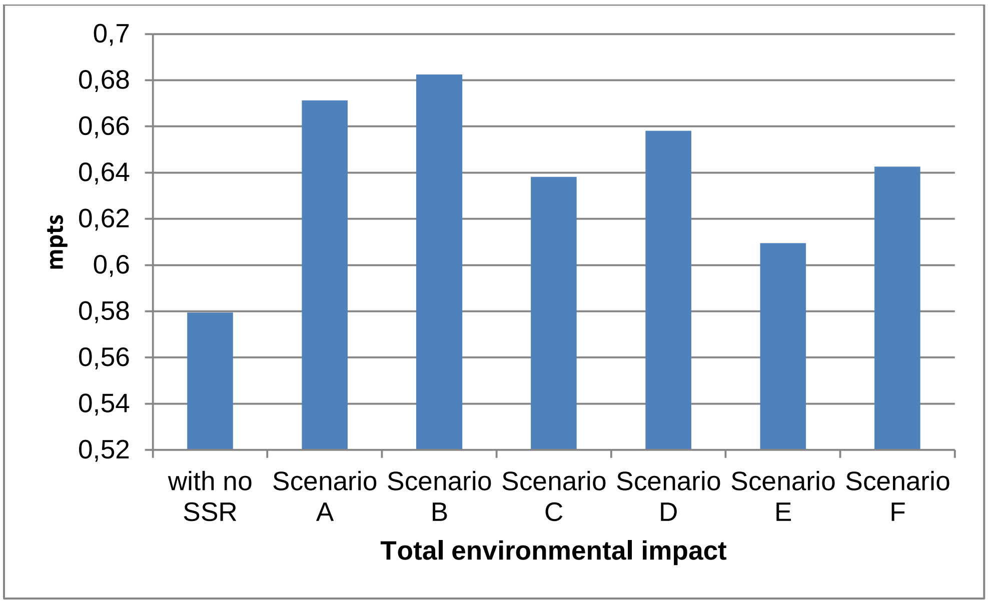


Figure 24. Comparison of scenarios with no SSR and with SSR

CHAPTER 6

RECOMMENDATIONS

This study was conducted to determine and compare environmental impacts of foundry processes and products without and with the application of SSR. Since the study is focused on the environmental impact of the industry, economic feasibility of the study couldn’t performed. It is recommended that; economic feasibility of the SSR application should be conducted to complete and support this study. Also, detailed uncertainty analysis should be performed.

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APPENDIX A - LCA CALCULATION METHODS AND IMPACT CATEGORIES

Table A 1. LCA calculation methods and their covered impact categories

CML 2 BASELINE 2000	CML 2001	
Abiotic depletion	Abiotic depletion	Terrestrial ecotoxicity infinite
Acidification	Acidification	Marine sediment ecotox. 20a
Eutrophication	Eutrophication	Marine sediment ecotox. infinite
Global warming (GWP100)	Global warming 20a	Freshwater sediment ecotox. 20a
Ozone layer depletion (ODP)	Upper limit of net global warming	Freshwater sediment ecotox. infinite
Human toxicity	Lower limit of net global warming	Average European (kg NOx eq)
Fresh water aquatic ecotox.	Ozone layer depletion 5a	Average European (kg SO2-Eq)
Marine aquatic ecotoxicity	Ozone layer depletion steady state	Land competition
Terrestrial ecotoxicity	Human toxicity 20a	Ionising radiation
Photochemical oxidation	Human toxicity infinite	Photochemical oxidation
	Freshwater aquatic ecotox. 20a	Photochemical oxidation (low NOx)
	Fresh water aquatic ecotox. infinite	Malodours air
	Marine aquatic ecotox. 20a	Equal benefit incremental reactivity
	Marine aquatic ecotoxicity infinite	Max. incremental reactivity
	Terrestrial ecotoxicity 20a	Max. ozone incremental reactivity

Table A 1. LCA calculation methods and their covered impact categories – continued

ECO-INDICATOR 99 (E-H-I)	ECOLOGICAL SCARCITY 2006	EDIP 2003
Carcinogens	Emission into air	Global warming 100a
Resp. organics	Emission into surface water	Ozone depletion
Resp. inorganics	Emission into ground water	Ozone formation (Vegetation)
Climate change	Emission into top soil	Ozone formation (Human)
Radiation	Energy resources	Acidification
Ozone layer	Natural resources	Terrestrial eutrophication
Ecotoxicity	Deposited waste	Aquatic eutrophication EP(N)
Acidification/ Eutrophication		Aquatic eutrophication EP(P)
Land use		Human toxicity air
Minerals		Human toxicity water
Fossil fuels		Human toxicity soil
		Ecotoxicity water chronic
		Ecotoxicity water acute
		Ecotoxicity soil chronic
		Hazardous waste
		Slags/ashes
		Bulk waste
		Radioactive waste
		Resources (all)

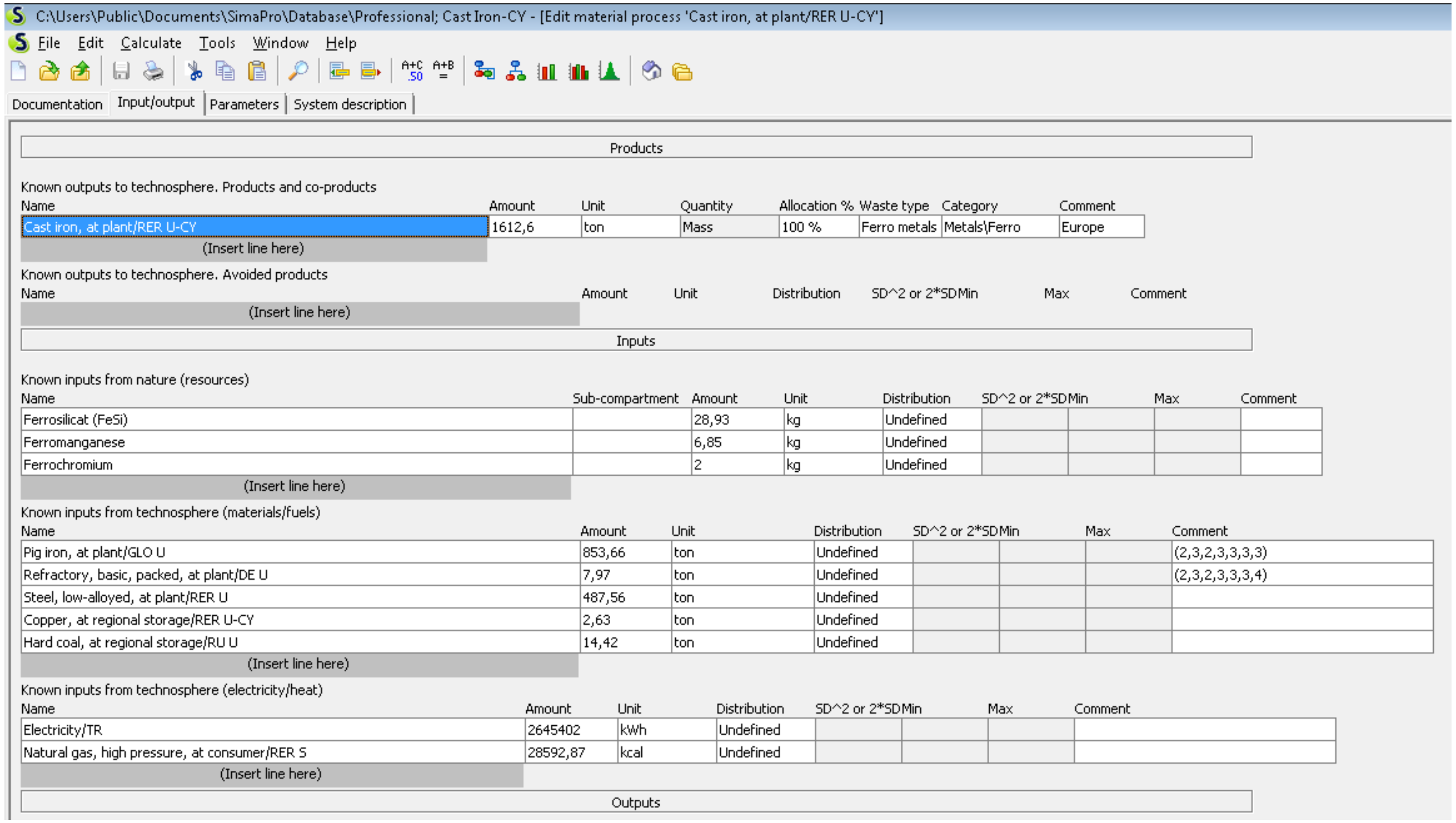
Table A 1. LCA calculation methods and their covered impact categories-continued

EPD (2008)	**EPS 2000**	**IMPACT 2002+**	**ReCiPe Endpoint (E-H-I)**
Global warming (GWP100)	Life expectancy	Carcinogens	Climate change Human Health
Ozone layer depletion (ODP)	Severe morbidity	Non-carcinogens	Ozone depletion
Photochemical oxidation	Morbidity	Respiratory inorganics	Human toxicity
Acidification	Severe nuisance	Ionizing radiation	Photochemical oxidant formation
Eutrophication	Nuisance	Ozone layer depletion	Particulate matter formation
Non renewable, fossil	Crop growth capacity	Respiratory organics	Ionising radiation
	Wood growth capacity	Aquatic ecotoxicity	Climate change Ecosystems
	Fish and meat production	Terrestrial ecotoxicity	Terrestrial acidification
	Soil acidification	Terrestrial acid/nutri	Freshwater eutrophication
	Prod. cap. irrigation Water	Land occupation	Terrestrial ecotoxicity
	Prod. cap. drinking water	Aquatic acidification	Freshwater ecotoxicity
	Depletion of reserves	Aquatic eutrophication	Marine ecotoxicity
	Species extinction	Global warming	Agricultural land occupation
		Non-renewable energy	Urban land occupation
		Mineral extraction	Natural land transformation
			Metal depletion
			Fossil depletion

Table A 1. LCA calculation methods and their covered impact categories – continued

ReCiPe Midpoint (E-H-I)	**BEES**	**TRACI 2**	**CUMULATIVE ENERGY DEMAND**
Climate change	Global warming	Global warming	Non renewable, fossil
Ozone depletion	Acidification	Acidification	Non-renewable, nuclear
Human toxicity	HH cancer	Carcinogenics	Non-renewable, biomass
Photochemical oxidant formation	HH noncancer	Non carcinogenics	Renewable, biomass
Particulate matter formation	HH criteria air pollutants	Respiratory effects	Renewable, wind, solar, geothe
Ionising radiation	Eutrophication	Eutrophication	Renewable, water
Terrestrial acidification	Ecotoxicity	Ozone depletion	
Freshwater eutrophication	Smog	Ecotoxicity	
Marine eutrophication	Natural resource depletion	Smog	
Terrestrial ecotoxicity	Indoor air quality		
Freshwater ecotoxicity	Habitat alteration		
Marine ecotoxicity	Water intake		
Agricultural land occupation	Ozone depletion		
Urban land occupation			
Natural land transformation			
Water depletion			
Metal depletion			
Fossil depletion			

APPENDIX B – SCREENSHOT OF THE PROCESSES IN SIMAPRO



Known outputs to technosphere. Products and co-products

Name	Amount	Unit	Quantity	Allocation %	Waste type	Category	Comment
Cast iron, at plant/RER U-CY	1612,6	ton	Mass	100 %	Ferro metals	Metals\Ferro	Europe

Known outputs to technosphere. Avoided products

Name	Amount	Unit	Distribution	SD^2 or 2*SDMin	Max	Comment

Known inputs from nature (resources)

Name	Sub-compartment	Amount	Unit	Distribution	SD^2 or 2*SDMin	Max	Comment
Ferrosilicat (FeSi)		28,93	kg	Undefined			
Ferromanganese		6,85	kg	Undefined			
Ferrochromium		2	kg	Undefined			

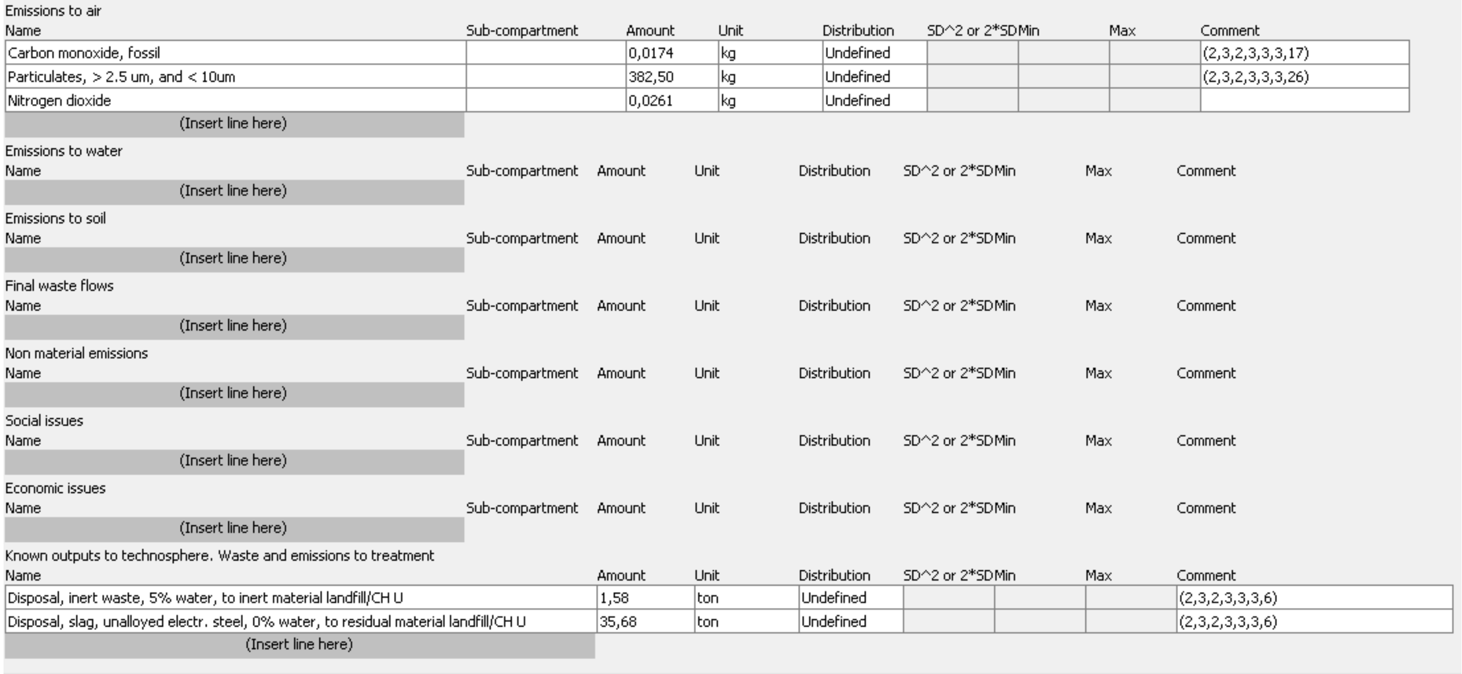
Known inputs from technosphere (materials/fuels)

Name	Amount	Unit	Distribution	SD^2 or 2*SDMin	Max	Comment
Pig iron, at plant/GLO U	853,66	ton	Undefined			(2,3,2,3,3,3,3)
Refractory, basic, packed, at plant/DE U	7,97	ton	Undefined			(2,3,2,3,3,3,4)
Steel, low-alloyed, at plant/RER U	487,56	ton	Undefined			
Copper, at regional storage/RER U-CY	2,63	ton	Undefined			
Hard coal, at regional storage/RU U	14,42	ton	Undefined			

Known inputs from technosphere (electricity/heat)

Name	Amount	Unit	Distribution	SD^2 or 2*SDMin	Max	Comment
Electricity/TR	2645402	kWh	Undefined			
Natural gas, high pressure, at consumer/RER S	28592,87	kcal	Undefined			

Figure B 1. The screenshot of the metal melting process in SimaPro



Emissions to air

Name	Sub-compartment	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
Carbon monoxide, fossil		0,0174	kg	Undefined				(2,3,2,3,3,3,17)
Particulates, > 2.5 um, and < 10um		382,50	kg	Undefined				(2,3,2,3,3,3,26)
Nitrogen dioxide		0,0261	kg	Undefined				
(Insert line here)								

Emissions to water

Name	Sub-compartment	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
(Insert line here)								

Emissions to soil

Name	Sub-compartment	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
(Insert line here)								

Final waste flows

Name	Sub-compartment	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
(Insert line here)								

Non material emissions

Name	Sub-compartment	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
(Insert line here)								

Social issues

Name	Sub-compartment	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
(Insert line here)								

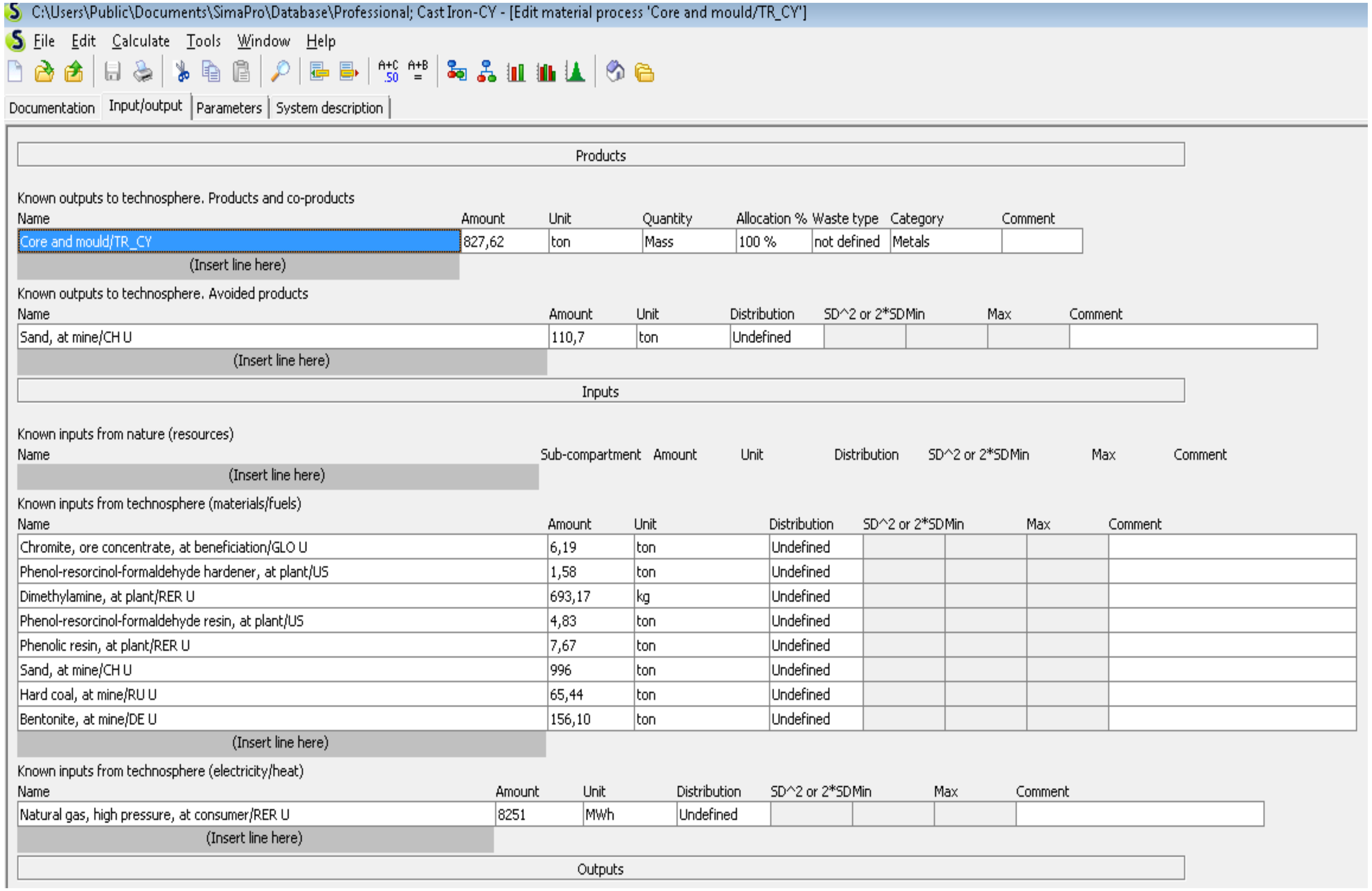
Economic issues

Name	Sub-compartment	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
(Insert line here)								

Known outputs to technosphere. Waste and emissions to treatment

Name	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
Disposal, inert waste, 5% water, to inert material landfill/CH U	1,58	ton	Undefined				(2,3,2,3,3,3,6)
Disposal, slag, unalloyed electr. steel, 0% water, to residual material landfill/CH U	35,68	ton	Undefined				(2,3,2,3,3,3,6)
(Insert line here)							

Figure B 1. The screenshot of the metal melting process in SimaPro - continued



Products

Known outputs to technosphere. Products and co-products

Name	Amount	Unit	Quantity	Allocation %	Waste type	Category	Comment
Core and mould/TR_CY	827,62	ton	Mass	100 %	not defined	Metals	
(Insert line here)							

Known outputs to technosphere. Avoided products

Name	Amount	Unit	Distribution	SD^2 or 2*SDMin	Max	Comment
Sand, at mine/CH U	110,7	ton	Undefined			
(Insert line here)						

Inputs

Known inputs from nature (resources)

Name	Sub-compartment	Amount	Unit	Distribution	SD^2 or 2*SDMin	Max	Comment
(Insert line here)							

Known inputs from technosphere (materials/fuels)

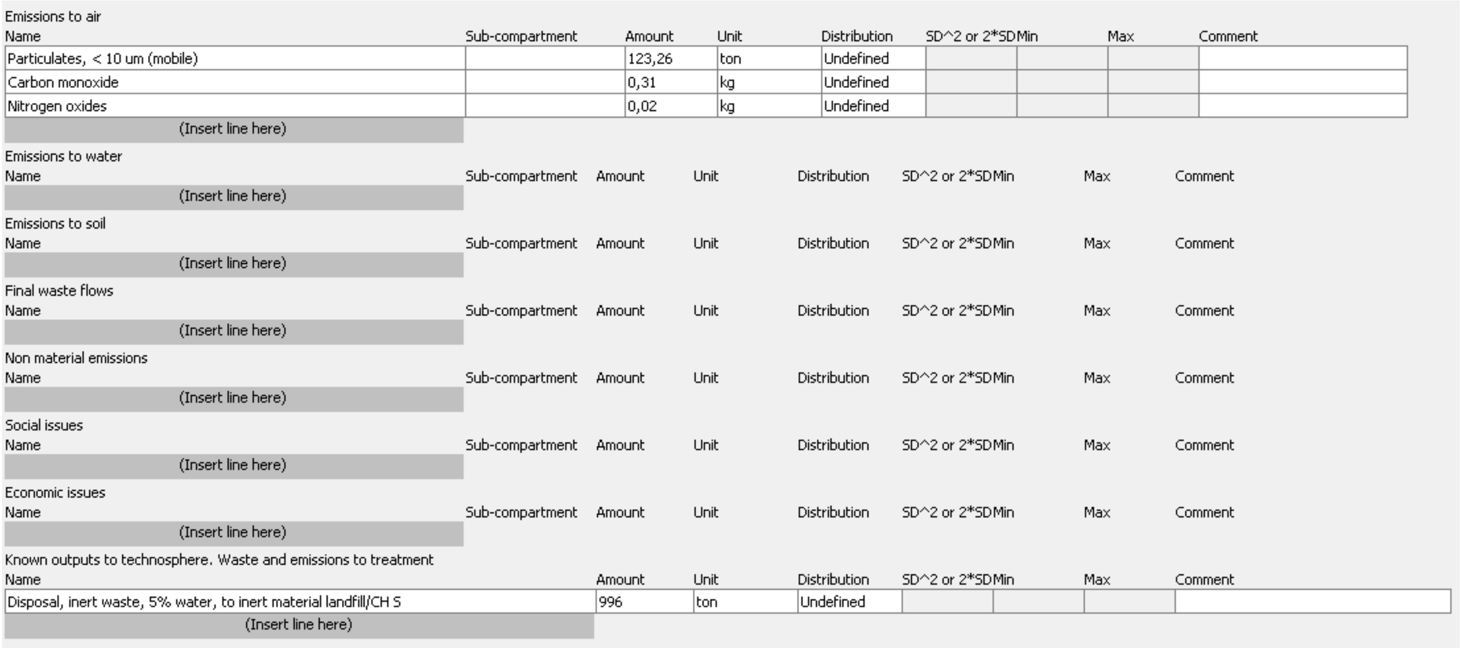
Name	Amount	Unit	Distribution	SD^2 or 2*SDMin	Max	Comment
Chromite, ore concentrate, at beneficiation/GLO U	6,19	ton	Undefined			
Phenol-resorcinol-formaldehyde hardener, at plant/US	1,58	ton	Undefined			
Dimethylamine, at plant/RER U	693,17	kg	Undefined			
Phenol-resorcinol-formaldehyde resin, at plant/US	4,83	ton	Undefined			
Phenolic resin, at plant/RER U	7,67	ton	Undefined			
Sand, at mine/CH U	996	ton	Undefined			
Hard coal, at mine/RU U	65,44	ton	Undefined			
Bentonite, at mine/DE U	156,10	ton	Undefined			
(Insert line here)						

Known inputs from technosphere (electricity/heat)

Name	Amount	Unit	Distribution	SD^2 or 2*SDMin	Max	Comment
Natural gas, high pressure, at consumer/RER U	8251	MWh	Undefined			
(Insert line here)						

Outputs

Figure B 2. The screenshot of the core and mould production process without SSR in SimaPro



Emissions to air

Name	Sub-compartment	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
Particulates, < 10 um (mobile)		123,26	ton	Undefined				
Carbon monoxide		0,31	kg	Undefined				
Nitrogen oxides		0,02	kg	Undefined				
(Insert line here)								

Emissions to water

Name	Sub-compartment	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
(Insert line here)								

Emissions to soil

Name	Sub-compartment	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
(Insert line here)								

Final waste flows

Name	Sub-compartment	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
(Insert line here)								

Non material emissions

Name	Sub-compartment	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
(Insert line here)								

Social issues

Name	Sub-compartment	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
(Insert line here)								

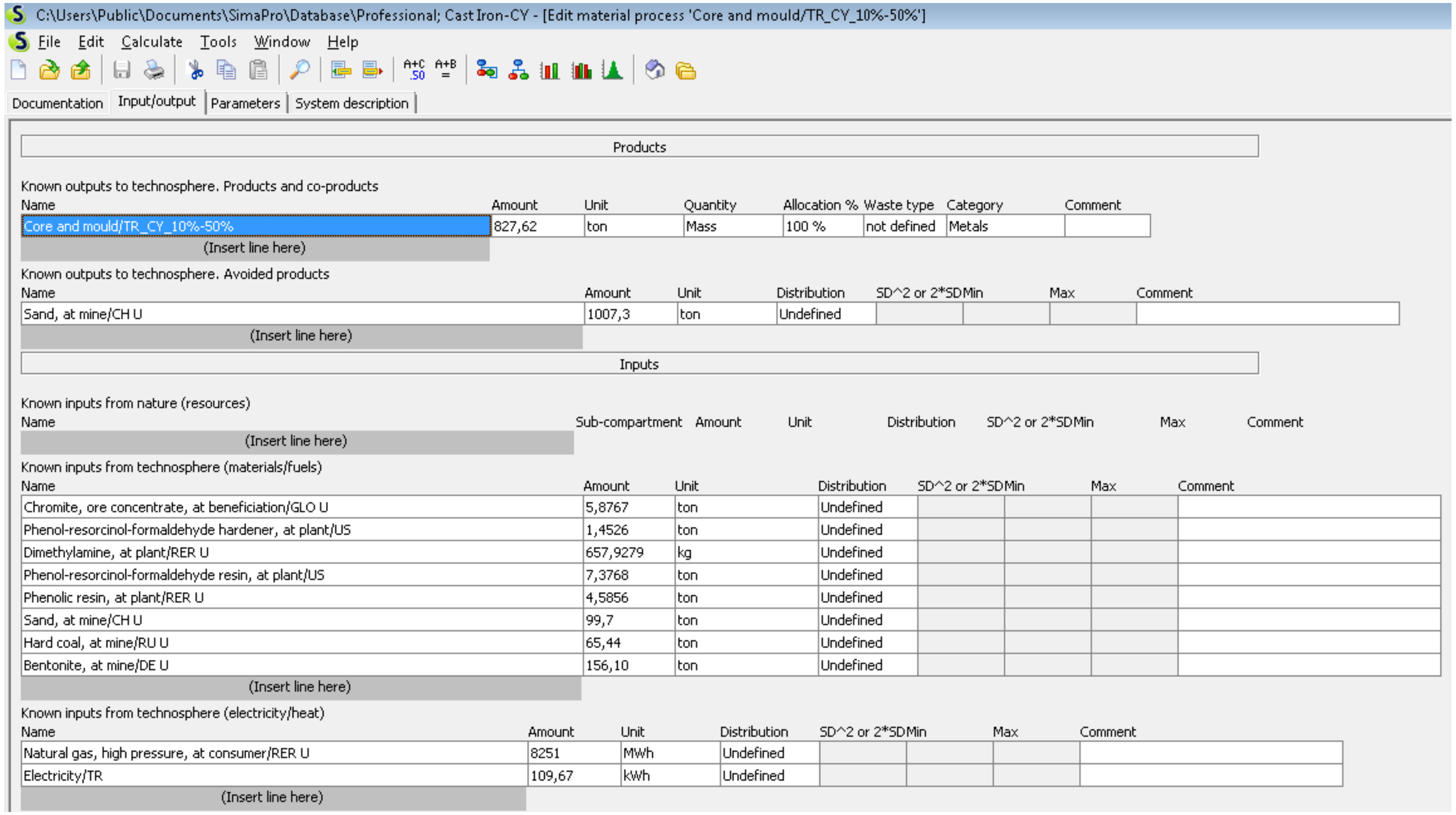
Economic issues

Name	Sub-compartment	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
(Insert line here)								

Known outputs to technosphere. Waste and emissions to treatment

Name	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
Disposal, inert waste, 5% water, to inert material landfill/CH S	996	ton	Undefined				
(Insert line here)							

Figure B 2. The screenshot of the core and mould production process without SSR in SimaPro - continued



Products

Known outputs to technosphere. Products and co-products

Name	Amount	Unit	Quantity	Allocation %	Waste type	Category	Comment
Core and mould/TR_CY_10%-50%	827,62	ton	Mass	100 %	not defined	Metals	

Known outputs to technosphere. Avoided products

Name	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
Sand, at mine/CH U	1007,3	ton	Undefined				

Inputs

Known inputs from nature (resources)

Name	Sub-compartment	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment

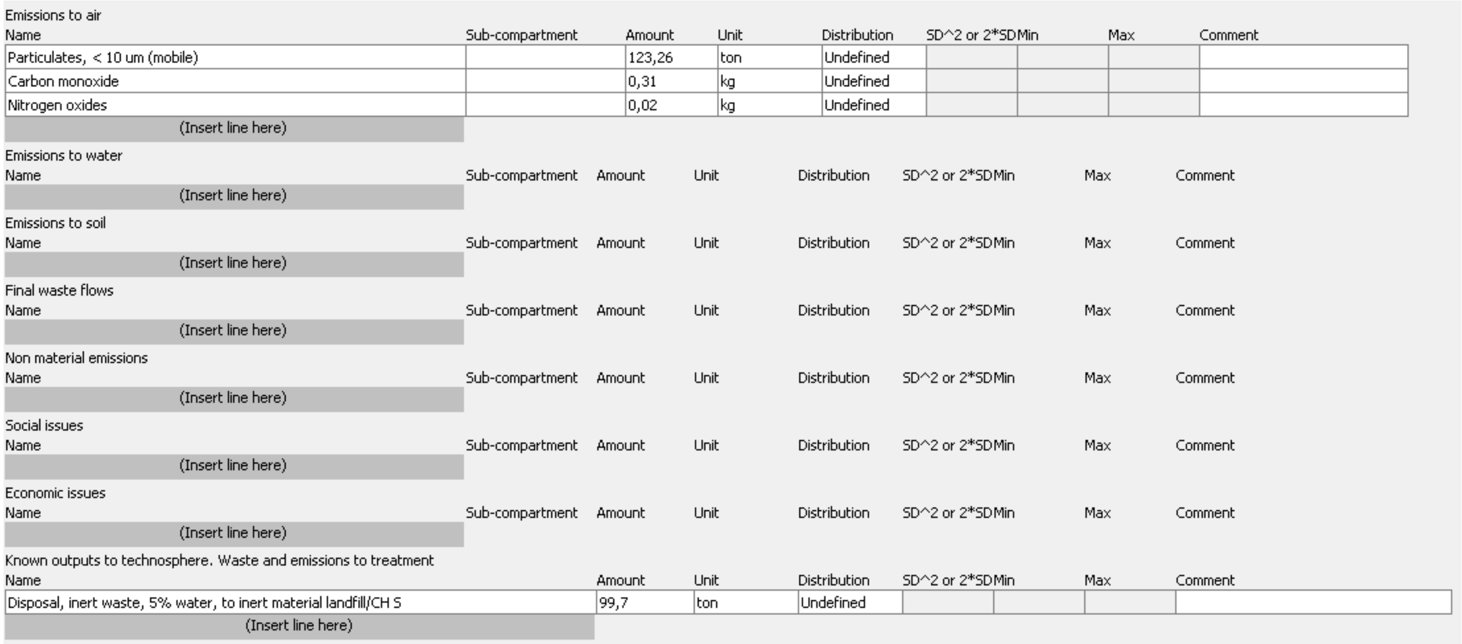
Known inputs from technosphere (materials/fuels)

Name	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
Chromite, ore concentrate, at beneficiation/GLO U	5,8767	ton	Undefined				
Phenol-resorcinol-formaldehyde hardener, at plant/US	1,4526	ton	Undefined				
Dimethylamine, at plant/RER U	657,9279	kg	Undefined				
Phenol-resorcinol-formaldehyde resin, at plant/US	7,3768	ton	Undefined				
Phenolic resin, at plant/RER U	4,5856	ton	Undefined				
Sand, at mine/CH U	99,7	ton	Undefined				
Hard coal, at mine/RU U	65,44	ton	Undefined				
Bentonite, at mine/DE U	156,10	ton	Undefined				

Known inputs from technosphere (electricity/heat)

Name	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
Natural gas, high pressure, at consumer/RER U	8251	MWh	Undefined				
Electricity/TR	109,67	kWh	Undefined				

Figure B 3. The screenshot of the core and mould production process with SSR in SimaPro (Scenario A)



Emissions to air

Name	Sub-compartment	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
Particulates, < 10 um (mobile)		123,26	ton	Undefined				
Carbon monoxide		0,31	kg	Undefined				
Nitrogen oxides		0,02	kg	Undefined				
(Insert line here)								

Emissions to water

Name	Sub-compartment	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
(Insert line here)								

Emissions to soil

Name	Sub-compartment	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
(Insert line here)								

Final waste flows

Name	Sub-compartment	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
(Insert line here)								

Non material emissions

Name	Sub-compartment	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
(Insert line here)								

Social issues

Name	Sub-compartment	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
(Insert line here)								

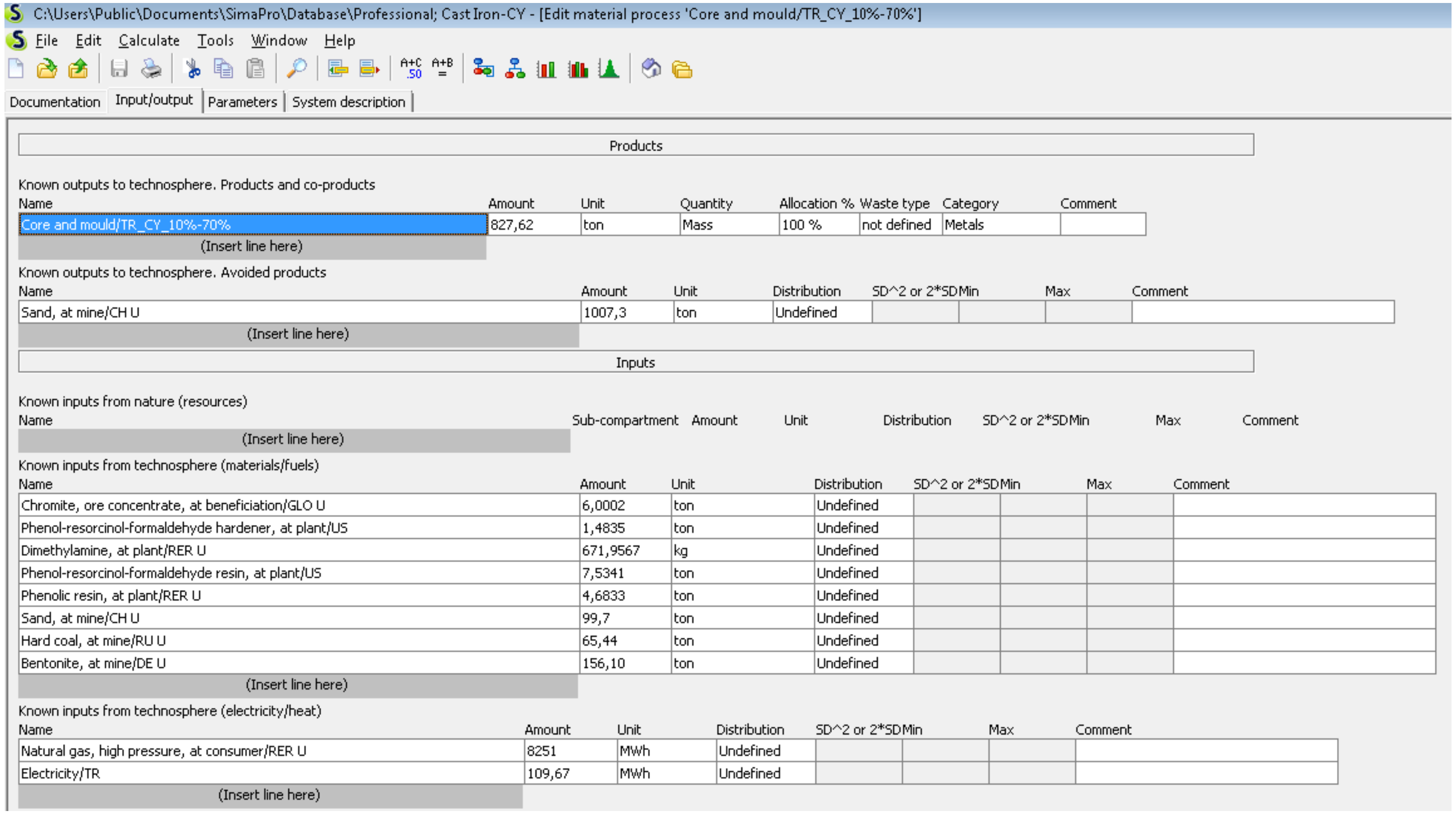
Economic issues

Name	Sub-compartment	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
(Insert line here)								

Known outputs to technosphere. Waste and emissions to treatment

Name	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
Disposal, inert waste, 5% water, to inert material landfill/CH S	99,7	ton	Undefined				
(Insert line here)							

Figure B 3. The screenshot of the core and mould production process with SSR in SimaPro (Scenario A) - continued



Known outputs to technosphere. Products and co-products

Name	Amount	Unit	Quantity	Allocation %	Waste type	Category	Comment
Core and mould/TR_CY_10%-70%	827,62	ton	Mass	100 %	not defined	Metals	

Known outputs to technosphere. Avoided products

Name	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
Sand, at mine/CH U	1007,3	ton	Undefined				

Known inputs from nature (resources)

Name	Sub-compartment	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment

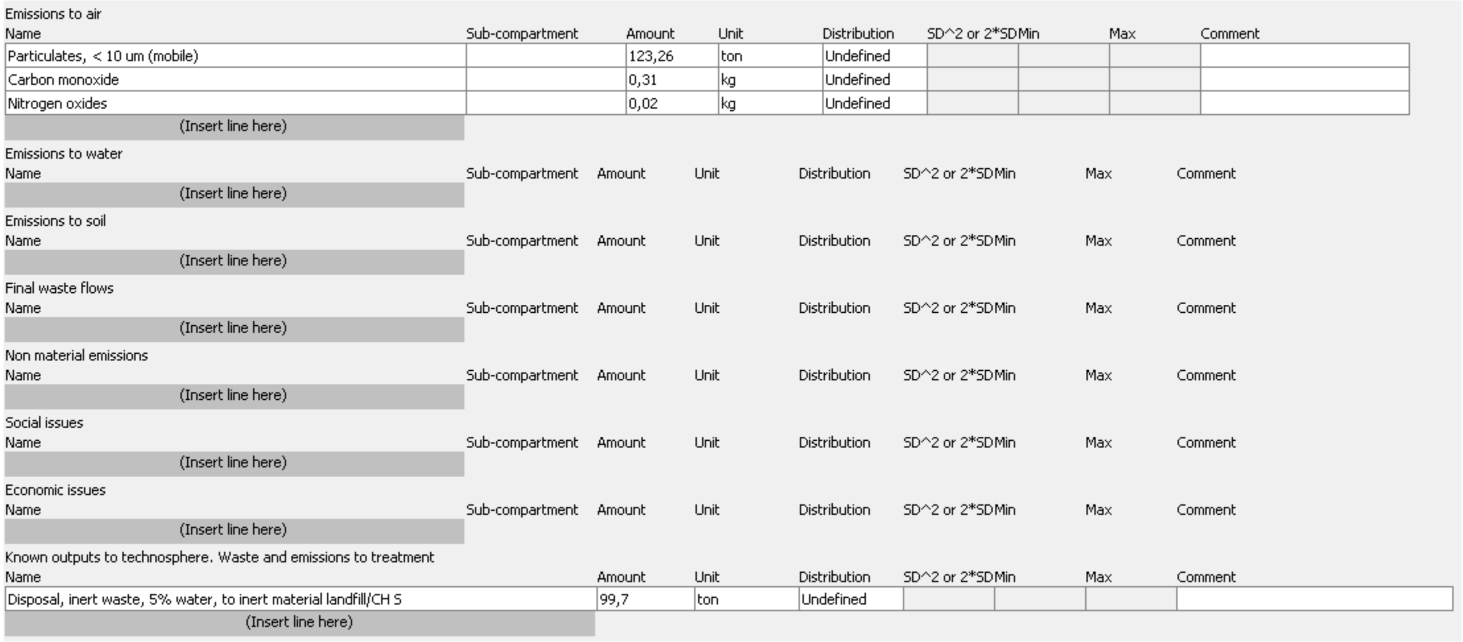
Known inputs from technosphere (materials/fuels)

Name	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
Chromite, ore concentrate, at beneficiation/GLO U	6,0002	ton	Undefined				
Phenol-resorcinol-formaldehyde hardener, at plant/US	1,4835	ton	Undefined				
Dimethylamine, at plant/RER U	671,9567	kg	Undefined				
Phenol-resorcinol-formaldehyde resin, at plant/US	7,5341	ton	Undefined				
Phenolic resin, at plant/RER U	4,6833	ton	Undefined				
Sand, at mine/CH U	99,7	ton	Undefined				
Hard coal, at mine/RU U	65,44	ton	Undefined				
Bentonite, at mine/DE U	156,10	ton	Undefined				

Known inputs from technosphere (electricity/heat)

Name	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
Natural gas, high pressure, at consumer/RER U	8251	MWh	Undefined				
Electricity/TR	109,67	MWh	Undefined				

Figure B 4. The screenshot of the core and mould production process with SSR in SimaPro (Scenario B)



Emissions to air

Name	Sub-compartment	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
Particulates, < 10 um (mobile)		123,26	ton	Undefined				
Carbon monoxide		0,31	kg	Undefined				
Nitrogen oxides		0,02	kg	Undefined				
(Insert line here)								

Emissions to water

Name	Sub-compartment	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
(Insert line here)								

Emissions to soil

Name	Sub-compartment	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
(Insert line here)								

Final waste flows

Name	Sub-compartment	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
(Insert line here)								

Non material emissions

Name	Sub-compartment	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
(Insert line here)								

Social issues

Name	Sub-compartment	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
(Insert line here)								

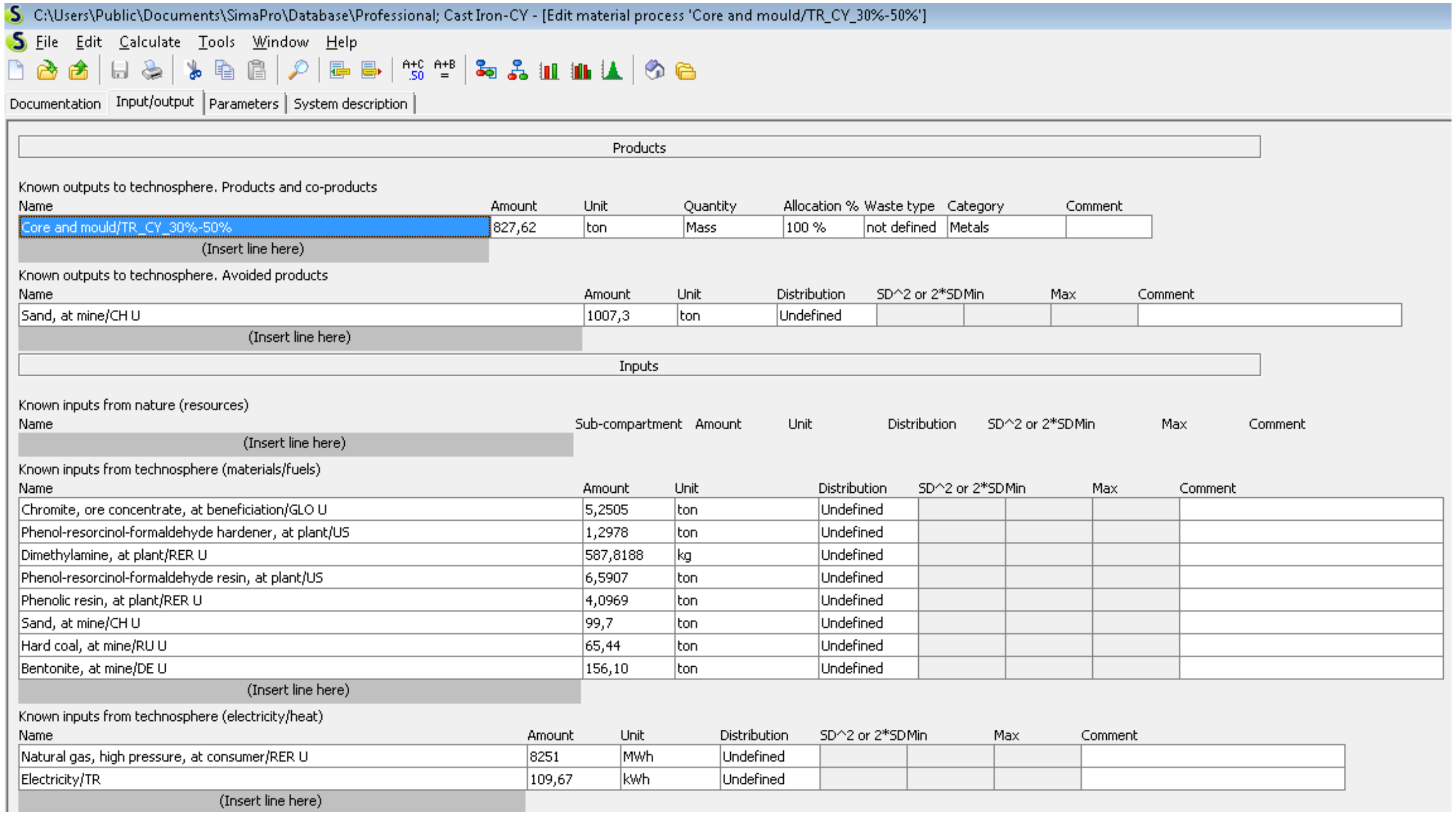
Economic issues

Name	Sub-compartment	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
(Insert line here)								

Known outputs to technosphere. Waste and emissions to treatment

Name	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
Disposal, inert waste, 5% water, to inert material landfill/CH S	99,7	ton	Undefined				
(Insert line here)							

Figure B 4. The screenshot of the core and mould production process witht SSR in SimaPro (Scenario B) - continued



Products

Known outputs to technosphere. Products and co-products

Name	Amount	Unit	Quantity	Allocation %	Waste type	Category	Comment
Core and mould/TR_CY_30%-50%	827,62	ton	Mass	100 %	not defined	Metals	
(Insert line here)							

Known outputs to technosphere. Avoided products

Name	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
Sand, at mine/CH U	1007,3	ton	Undefined				
(Insert line here)							

Inputs

Known inputs from nature (resources)

Name	Sub-compartment	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
(Insert line here)								

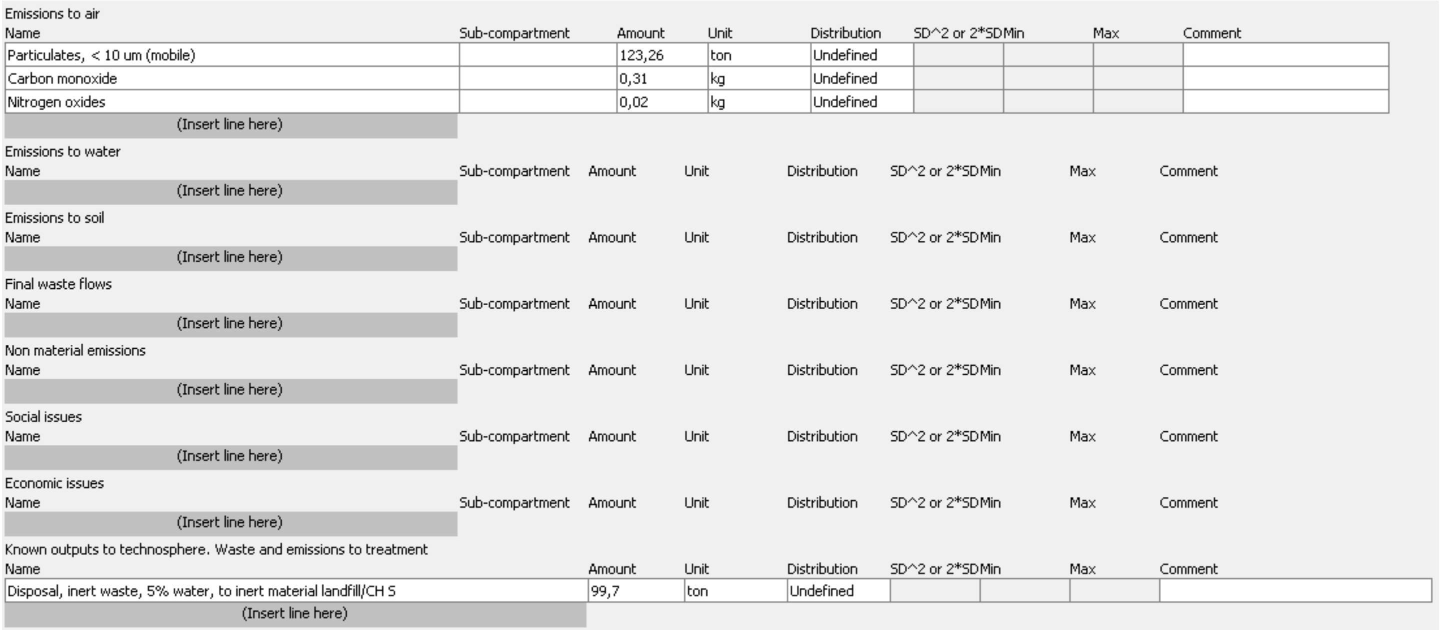
Known inputs from technosphere (materials/fuels)

Name	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
Chromite, ore concentrate, at beneficiation/GLO U	5,2505	ton	Undefined				
Phenol-resorcinol-formaldehyde hardener, at plant/US	1,2978	ton	Undefined				
Dimethylamine, at plant/RER U	587,8188	kg	Undefined				
Phenol-resorcinol-formaldehyde resin, at plant/US	6,5907	ton	Undefined				
Phenolic resin, at plant/RER U	4,0969	ton	Undefined				
Sand, at mine/CH U	99,7	ton	Undefined				
Hard coal, at mine/RU U	65,44	ton	Undefined				
Bentonite, at mine/DE U	156,10	ton	Undefined				
(Insert line here)							

Known inputs from technosphere (electricity/heat)

Name	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
Natural gas, high pressure, at consumer/RER U	8251	MWh	Undefined				
Electricity/TR	109,67	kWh	Undefined				
(Insert line here)							

Figure B 5. The screenshot of the core and mould production process witht SSR in SimaPro (Scenario C)



Emissions to air

Name	Sub-compartment	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
Particulates, < 10 um (mobile)		123,26	ton	Undefined				
Carbon monoxide		0,31	kg	Undefined				
Nitrogen oxides		0,02	kg	Undefined				
(Insert line here)								

Emissions to water

Name	Sub-compartment	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
(Insert line here)								

Emissions to soil

Name	Sub-compartment	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
(Insert line here)								

Final waste flows

Name	Sub-compartment	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
(Insert line here)								

Non material emissions

Name	Sub-compartment	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
(Insert line here)								

Social issues

Name	Sub-compartment	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
(Insert line here)								

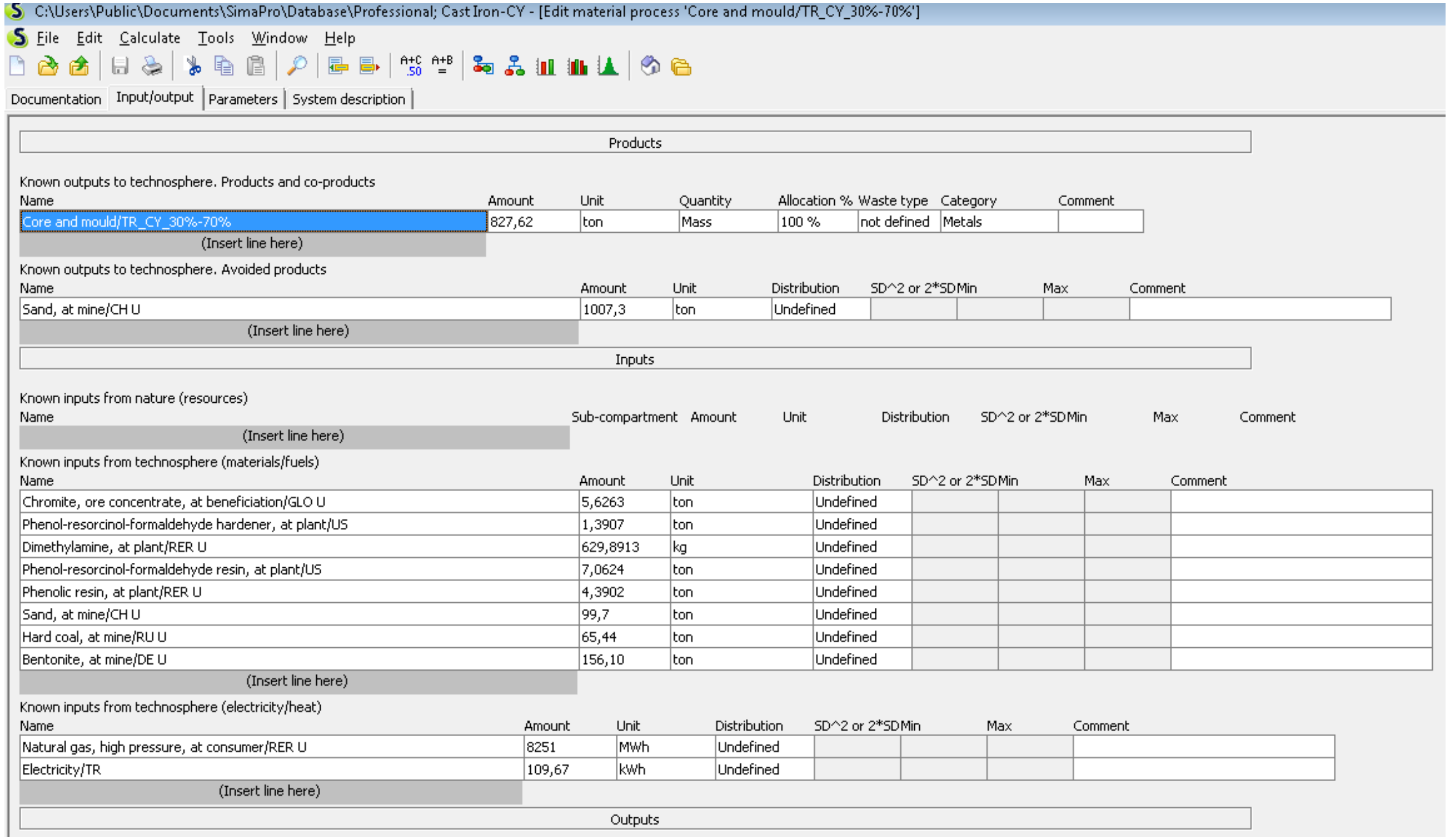
Economic issues

Name	Sub-compartment	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
(Insert line here)								

Known outputs to technosphere. Waste and emissions to treatment

Name	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
Disposal, inert waste, 5% water, to inert material landfill/CH S	99,7	ton	Undefined				
(Insert line here)							

Figure B 5. The screenshot of the core and mould production process with SSR in SimaPro (Scenario C) - continued



Products

Known outputs to technosphere. Products and co-products

Name	Amount	Unit	Quantity	Allocation %	Waste type	Category	Comment
Core and mould/TR_CY_30%-70%	827,62	ton	Mass	100 %	not defined	Metals	
(Insert line here)							

Known outputs to technosphere. Avoided products

Name	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
Sand, at mine/CH U	1007,3	ton	Undefined				
(Insert line here)							

Inputs

Known inputs from nature (resources)

Name	Sub-compartment	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
(Insert line here)								

Known inputs from technosphere (materials/fuels)

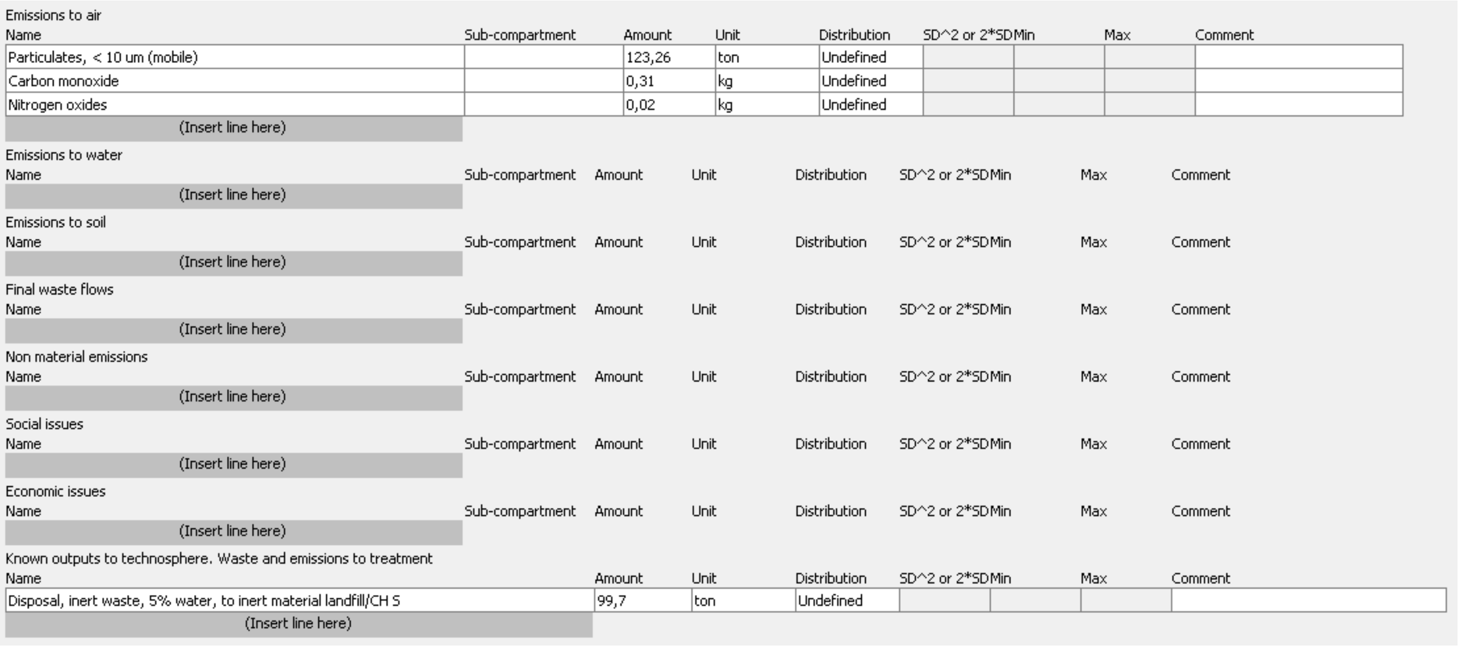
Name	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
Chromite, ore concentrate, at beneficiation/GLO U	5,6263	ton	Undefined				
Phenol-resorcinol-formaldehyde hardener, at plant/US	1,3907	ton	Undefined				
Dimethylamine, at plant/RER U	629,8913	kg	Undefined				
Phenol-resorcinol-formaldehyde resin, at plant/US	7,0624	ton	Undefined				
Phenolic resin, at plant/RER U	4,3902	ton	Undefined				
Sand, at mine/CH U	99,7	ton	Undefined				
Hard coal, at mine/RU U	65,44	ton	Undefined				
Bentonite, at mine/DE U	156,10	ton	Undefined				
(Insert line here)							

Known inputs from technosphere (electricity/heat)

Name	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
Natural gas, high pressure, at consumer/RER U	8251	MWh	Undefined				
Electricity/TR	109,67	kWh	Undefined				
(Insert line here)							

Outputs

Figure B 6. The screenshot of the core and mould production process with SSR in SimaPro (Scenario D)



Emissions to air

Name	Sub-compartment	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
Particulates, < 10 um (mobile)		123,26	ton	Undefined				
Carbon monoxide		0,31	kg	Undefined				
Nitrogen oxides		0,02	kg	Undefined				
(Insert line here)								

Emissions to water

Name	Sub-compartment	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
(Insert line here)								

Emissions to soil

Name	Sub-compartment	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
(Insert line here)								

Final waste flows

Name	Sub-compartment	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
(Insert line here)								

Non material emissions

Name	Sub-compartment	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
(Insert line here)								

Social issues

Name	Sub-compartment	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
(Insert line here)								

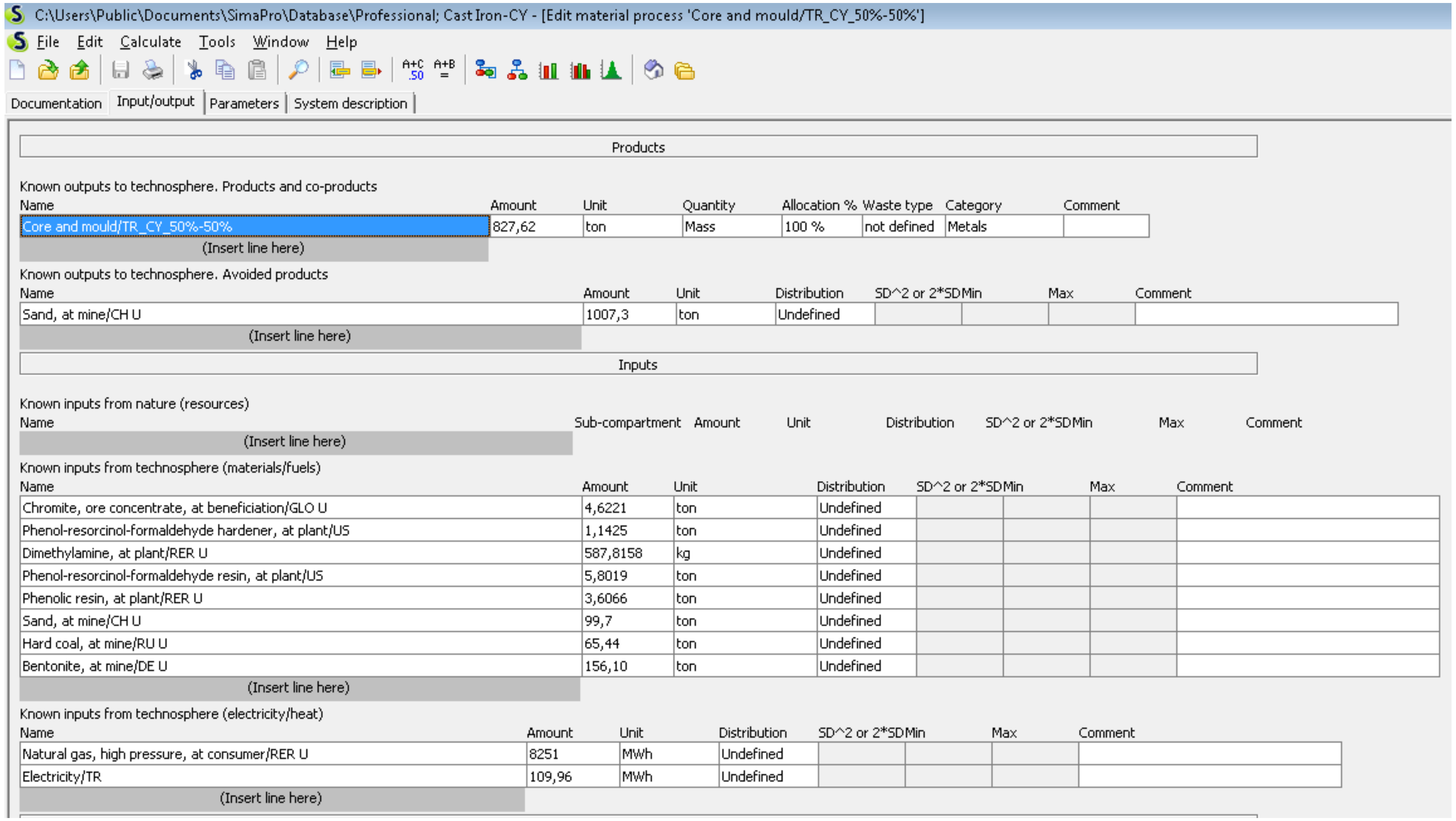
Economic issues

Name	Sub-compartment	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
(Insert line here)								

Known outputs to technosphere. Waste and emissions to treatment

Name	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
Disposal, inert waste, 5% water, to inert material landfill/CH S	99,7	ton	Undefined				
(Insert line here)							

Figure B 6. The screenshot of the core and mould production process witht SSR in SimaPro (Scenario D) - continued



Products

Known outputs to technosphere. Products and co-products

Name	Amount	Unit	Quantity	Allocation %	Waste type	Category	Comment
Core and mould/TR_CY_50%-50%	827,62	ton	Mass	100 %	not defined	Metals	
(Insert line here)							

Known outputs to technosphere. Avoided products

Name	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
Sand, at mine/CH U	1007,3	ton	Undefined				
(Insert line here)							

Inputs

Known inputs from nature (resources)

Name	Sub-compartment	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
(Insert line here)								

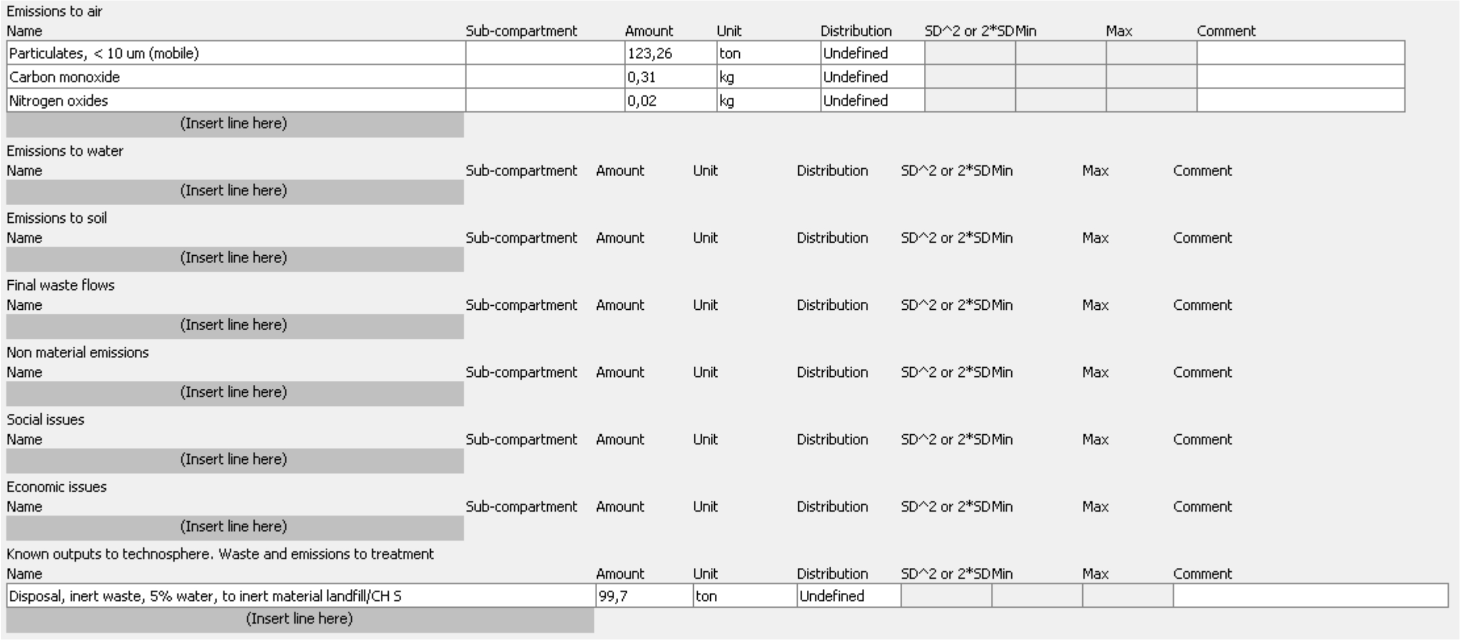
Known inputs from technosphere (materials/fuels)

Name	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
Chromite, ore concentrate, at beneficiation/GLO U	4,6221	ton	Undefined				
Phenol-resorcinol-formaldehyde hardener, at plant/US	1,1425	ton	Undefined				
Dimethylamine, at plant/RER U	587,8158	kg	Undefined				
Phenol-resorcinol-formaldehyde resin, at plant/US	5,8019	ton	Undefined				
Phenolic resin, at plant/RER U	3,6066	ton	Undefined				
Sand, at mine/CH U	99,7	ton	Undefined				
Hard coal, at mine/RU U	65,44	ton	Undefined				
Bentonite, at mine/DE U	156,10	ton	Undefined				
(Insert line here)							

Known inputs from technosphere (electricity/heat)

Name	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
Natural gas, high pressure, at consumer/RER U	8251	MWh	Undefined				
Electricity/TR	109,96	MWh	Undefined				
(Insert line here)							

Figure B 7. The screenshot of the core and mould production process with SSR in SimaPro (Scenario E)



Emissions to air

Name	Sub-compartment	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
Particulates, < 10 um (mobile)		123,26	ton	Undefined				
Carbon monoxide		0,31	kg	Undefined				
Nitrogen oxides		0,02	kg	Undefined				
(Insert line here)								

Emissions to water

Name	Sub-compartment	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
(Insert line here)								

Emissions to soil

Name	Sub-compartment	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
(Insert line here)								

Final waste flows

Name	Sub-compartment	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
(Insert line here)								

Non material emissions

Name	Sub-compartment	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
(Insert line here)								

Social issues

Name	Sub-compartment	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
(Insert line here)								

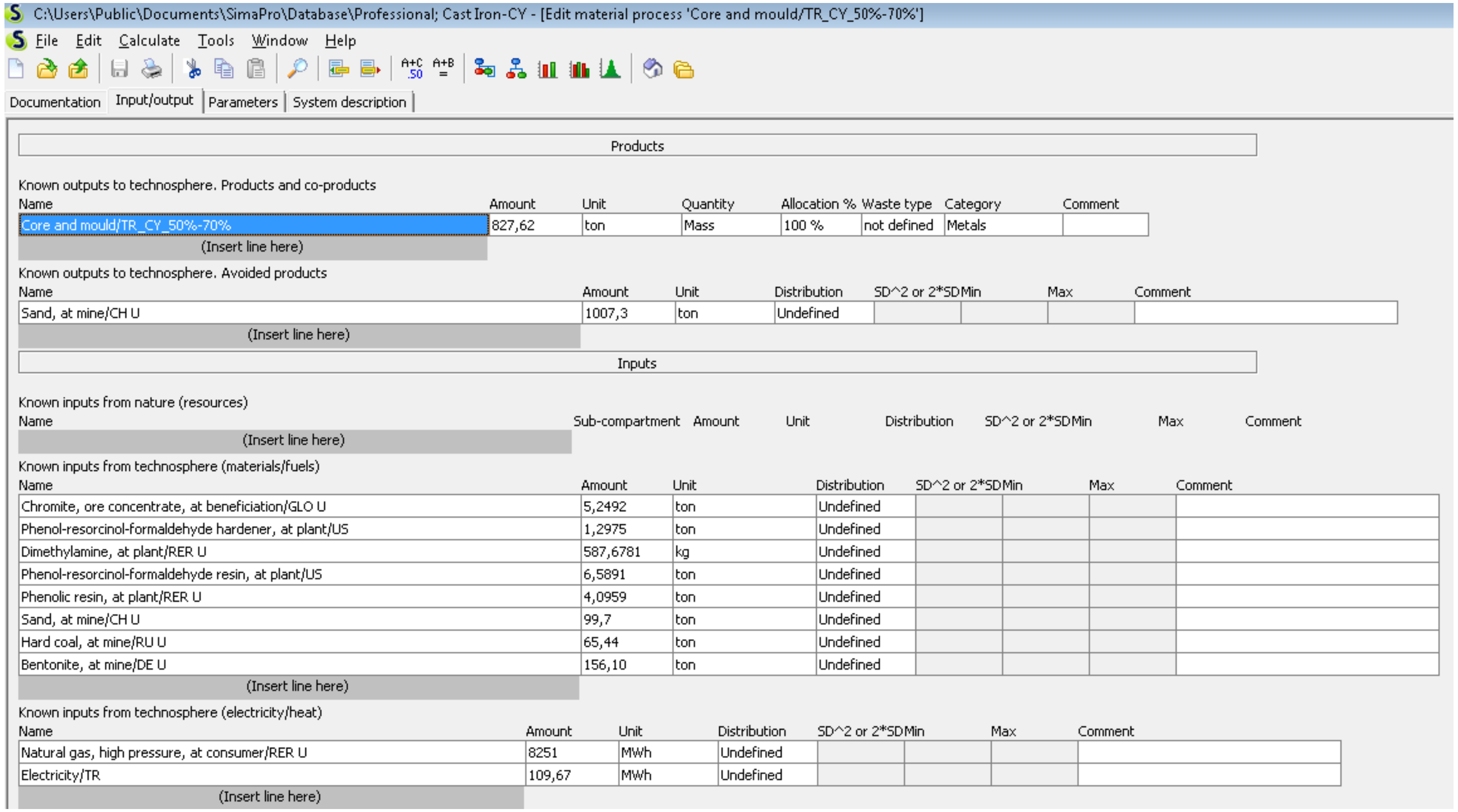
Economic issues

Name	Sub-compartment	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
(Insert line here)								

Known outputs to technosphere. Waste and emissions to treatment

Name	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
Disposal, inert waste, 5% water, to inert material landfill/CH S	99,7	ton	Undefined				
(Insert line here)							

Figure B 7. The screenshot of the core and mould production process witht SSR in SimaPro (Scenario E) - continued



Products

Known outputs to technosphere. Products and co-products

Name	Amount	Unit	Quantity	Allocation %	Waste type	Category	Comment
Core and mould/TR_CY_50%-70%	827,62	ton	Mass	100 %	not defined	Metals	
(Insert line here)							

Known outputs to technosphere. Avoided products

Name	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
Sand, at mine/CH U	1007,3	ton	Undefined				
(Insert line here)							

Inputs

Known inputs from nature (resources)

Name	Sub-compartment	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
(Insert line here)								

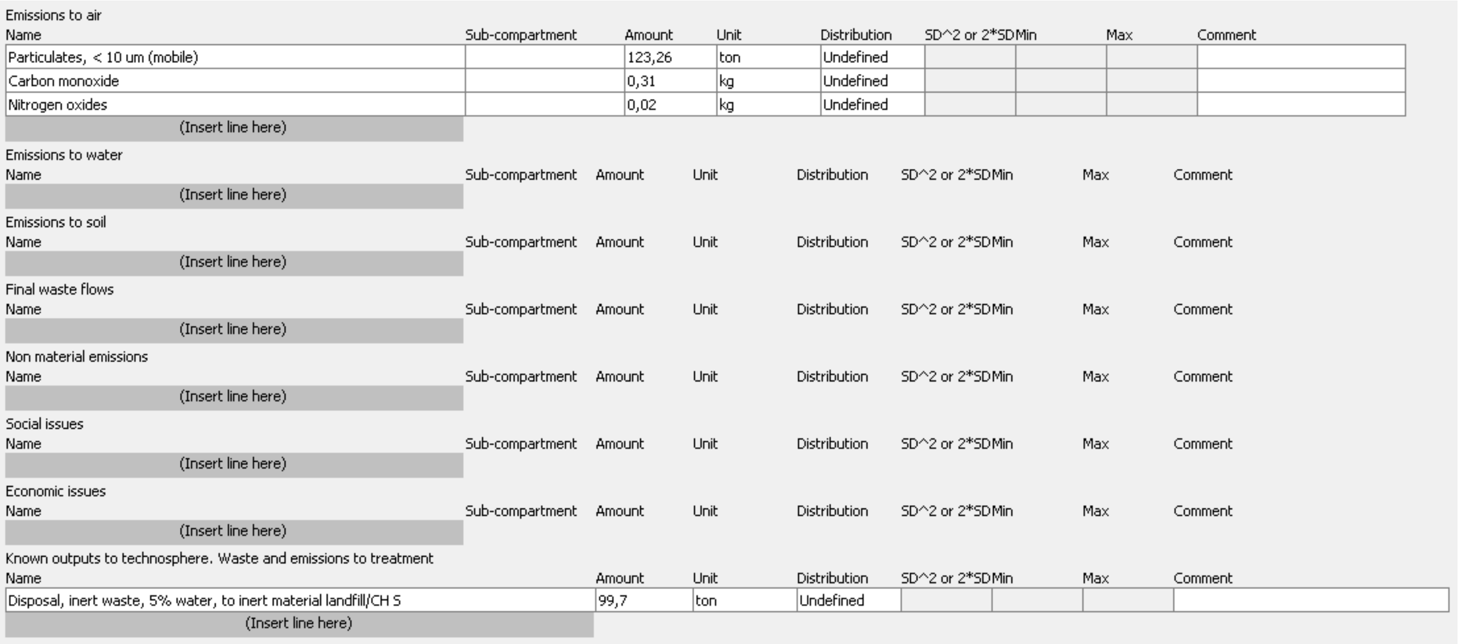
Known inputs from technosphere (materials/fuels)

Name	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
Chromite, ore concentrate, at beneficiation/GLO U	5,2492	ton	Undefined				
Phenol-resorcinol-formaldehyde hardener, at plant/US	1,2975	ton	Undefined				
Dimethylamine, at plant/RER U	587,6781	kg	Undefined				
Phenol-resorcinol-formaldehyde resin, at plant/US	6,5891	ton	Undefined				
Phenolic resin, at plant/RER U	4,0959	ton	Undefined				
Sand, at mine/CH U	99,7	ton	Undefined				
Hard coal, at mine/RU U	65,44	ton	Undefined				
Bentonite, at mine/DE U	156,10	ton	Undefined				
(Insert line here)							

Known inputs from technosphere (electricity/heat)

Name	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
Natural gas, high pressure, at consumer/RER U	8251	MWh	Undefined				
Electricity/TR	109,67	MWh	Undefined				
(Insert line here)							

Figure B 8. The screenshot of the core and mould production process witht SSR in SimaPro (Scenario F)



Emissions to air

Name	Sub-compartment	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
Particulates, < 10 um (mobile)		123,26	ton	Undefined				
Carbon monoxide		0,31	kg	Undefined				
Nitrogen oxides		0,02	kg	Undefined				
(Insert line here)								

Emissions to water

Name	Sub-compartment	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
(Insert line here)								

Emissions to soil

Name	Sub-compartment	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
(Insert line here)								

Final waste flows

Name	Sub-compartment	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
(Insert line here)								

Non material emissions

Name	Sub-compartment	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
(Insert line here)								

Social issues

Name	Sub-compartment	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
(Insert line here)								

Economic issues

Name	Sub-compartment	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
(Insert line here)								

Known outputs to technosphere. Waste and emissions to treatment

Name	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
Disposal, inert waste, 5% water, to inert material landfill/CH S	99,7	ton	Undefined				
(Insert line here)							

Figure B 8. The screenshot of the core and mould production process with SSR in SimaPro (Scenario F) - continued

APPENDIX C – ENVIRONMENTAL IMPACT OF FOUNDRY SUB-PROSESSES ACCORDING TO MID-POINT RESULTS

Table C 1. Environmental impact of metal melting - mid-point results

Label	**Carcinogens (kg C2H3Cl eq)**		**Non-carcinogens (kg C2H3Cl eq)**		**Respiratory inorganics (kg PM2.5 eq)**		**Ionizing radiation (Bq C-14 eq)**		**Ozone layer depletion (kg CFC-11 eq)**	
	Amount	**%**	**Amount**	**%**	**Amount**	**%**	**Amount**	**%**	**Amount**	**%**
Iron	0.0034	17.2043	0.0139	50.5922	0.0829	50.1457	0.0000	0.0002	0.0000	19.1418
Refractory material	0.0001	0.2700	0.0004	1.4137	0.0006	0.3787	0.0000	0.8472	0.0000	1.3231
Steel	0.0155	78.1268	0.0116	42.0775	0.0697	42.1433	0.0001	93.1869	0.0000	32.0249
Copper	0.0002	0.8312	0.0015	5.5033	0.0034	2.0607	0.0000	0.8872	0.0000	0.2943
Coke	0.0000	0.0045	0.0000	0.0074	0.0001	0.0612	0.0000	0.5214	0.0000	0.0572
Electricity	0.0007	3.5626	0.0001	0.1845	0.0086	5.2081	0.0000	4.6324	0.0000	47.1444
Natural Gas	0.0000	0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0011
Inert waste to landfill	0.0000	0.0000	0.0000	0.0000	0.0000	0.0004	0.0000	0.0000	0.0000	0.0005
Slag disposal	0.0000	0.0005	0.0000	0.0549	0.0000	0.0088	0.0000	0.0024	0.0000	0.0127

Table C 1. Environmental impact of metal melting - mid-point results-continued

Label	**Respiratory organics** (kg C2H4 eq)		**Aquatic ecotoxicity** (kg TEG water)		**Terrestrial ecotoxicity** (kg TEG soil)		**Terrestrial acid/nutri** (kg SO2 eq)		**Land occupation** (m2org.arable)	
	Amount	**%**	**Amount**	**%**	**Amount**	**%**	**Amount**	**%**	**Amount**	**%**
Iron	0.0000	37.5019	0.0002	40.9065	0.0078	33.0669	0.0008	54.0348	0.0001	57.2740
Refractory material	0.0000	0.6292	0.0000	9.0219	0.0000	0.1754	0.0000	0.6613	0.0000	0.3193
Steel	0.0000	46.8221	0.0002	34.8556	0.0129	54.7890	0.0005	35.2156	0.0000	29.2858
Copper	0.0000	0.9993	0.0000	6.4283	0.0021	9.0520	0.0000	2.0052	0.0000	0.4046
Coke	0.0000	0.1143	0.0000	0.3944	0.0001	0.3293	0.0000	0.1589	0.0000	0.5982
Electricity	0.0000	13.9142	0.0000	3.0237	0.0006	2.5873	0.0001	7.9056	0.0000	12.0522
Natural Gas	0.0000	0.0002	0.0000	0.0000	0.0000	0.0000	0.0000	0.0001	0.0000	0.0001
Inert waste to landfill	0.0000	0.0008	0.0000	0.0000	0.0000	0.0000	0.0000	0.0008	0.0000	0.0000
Slag disposal	0.0000	0.0180	0.0000	5.3696	0.0000	0.0002	0.0000	0.0178	0.0000	0.0001

Table C 1. Environmental impact of metal melting - mid-point results- continued

Label	**Aquatic acidification (kg SO2 eq)**	**Aquatic eutrophication (kg PO4 P-lim)**	**Global warming (kg CO2 eq)**		**Non-renewable energy (MJ primary)**		**Mineral extraction (MJ surplus)**		**TOTAL**
			Amount	**%**	**Amount**	**%**	**Amount**	**%**	
Iron	0.	0.	0.0762	57.337	0.0762	45.077	0.0002	11.4121	0.2619
Refractory material	0.	0.	0.0011	0.8324	0.0008	0.4773	0.	0.0574	0.0031
Steel	0.	0.	0.0492	37.0573	0.0506	29.9233	0.0018	87.5477	0.2121
Copper	0.	0.	0.0003	0.1897	0.0003	0.1561	0.	1.0875	0.0078
Coke	0.	0.	0.0001	0.0971	0.0015	0.8694	0.	0.0004	0.0018
Electricity	0.	0.	0.006	4.4832	0.0398	23.5103	0.	0.0025	0.0559
Natural Gas	0.	0.	0.	0.	0.	0.0004	0.	0.	0.
Inert waste to landfill	0.	0.	0.	0.0002	0.	0.0001	0.	0.	0.
Slag disposal	0.	0.	0.	0.0047	0.	0.0037	0.	0.	0.0001
TOTAL	0.	0.	0.1329	100.	0.1691	100.	0.002	100.	0.5426

Table C 2. Environmental impact of core and mould production without SSR – mid-point results

Label	**Carcinogens (kg C2H3Cl eq)**		**Non-carcinogens (kg C2H3Cl eq)**		**Respiratory inorganics (kg PM2.5 eq)**		**Ionizing radiation (Bq C-14 eq)**	**Ozone layer depletion (kg CFC-11 eq)**	
	Amount	**%**	**Amount**	**%**	**Amount**	**%**	**Amount**	**Amount**	**%**
Phenol-resorcinol-formaldehyde hardener, at plant/US	0.0001	0.6325	0.0000	0.3237	0.0003	0.1434	0.0000	0.0000	0.0000
Dimethylamine, at plant/RER U	0.0000	0.0432	0.0000	0.1503	0.0000	0.0252	0.0000	0.0000	0.0000
Phenol-resorcinol-formaldehyde resin, at plant/US	0.0000	0.0000	0.0005	73.7130	0.1639	88.6702	0.0000	0.0000	0.0000
Phenolic resin, at plant/RER U	0.0005	5.3616	0.0001	16.0761	0.0015	0.8366	0.0000	0.0000	0.0000
Sand, at mine/CH U	0.0000	0.0580	0.0000	0.5253	0.0005	0.2534	0.0000	0.0000	0.0000
Hard coal, at mine/RU U	0.0000	0.0777	0.0000	2.6235	0.0007	0.4029	0.0000	0.0000	0.0000
Bentonite, at mine/DE U	0.0000	0.3257	0.0000	0.8965	0.0009	0.4876	0.0000	0.0000	0.0000
Natural gas, high pressure, at consumer/RER U	0.0078	93.0672	0.0000	2.2237	0.0155	8.3743	0.0000	0.0000	0.0001
Sand, at mine/CH U	0.0000	-0.0064	0.0000	-0.0584	-0.0001	-0.0282	0.0000	0.0000	0.0000
Disposal, inert waste, 5% water, to inert material landfill/CH S	0.0000	0.4406	0.0000	3.5262	0.0015	0.8345	0.0000	0.0000	0.0000

Table C 2. Environmental impact of core and mould production without SSR – mid-point results – continued

Label	**Respiratory organics (kg C2H4 eq)**		**Aquatic ecotoxicity (kg TEG water)**	**Terrestrial ecotoxicity (kg TEG soil)**		**Terrestrial acid/nutri (kg SO2 eq)**		**Land occupation (m2org.arable)**	
	Amount	**%**	**Amount**	**Amount**	**%**	**Amount**	**%**	**Amount**	**%**
Phenol-resorcinol-formaldehyde hardener, at plant/US	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.1174	0.0000	0.0000
Dimethylamine, at plant/RER U	0.0000	0.0000	0.0000	0.0000	0.0254	0.0000	0.0237	0.0000	0.0000
Phenol-resorcinol-formaldehyde resin, at plant/US	0.0000	0.0000	0.0000	0.0073	89.0900	0.0054	92.1232	0.0000	0.0000
Phenolic resin, at plant/RER U	0.0000	0.0000	0.0000	0.0001	0.6343	0.0000	0.4717	0.0000	0.0000
Sand, at mine/CH U	0.0000	0.0000	0.0000	0.0000	0.0727	0.0000	0.1468	0.0000	0.0000
Hard coal, at mine/RU U	0.0000	0.0000	0.0000	0.0007	8.4113	0.0000	0.3171	0.0000	0.0000
Bentonite, at mine/DE U	0.0000	0.0000	0.0000	0.0000	0.1715	0.0000	0.2940	0.0000	0.0000
Natural gas, high pressure, at consumer/RER U	0.0001	100.0000	0.0000	0.0000	0.3078	0.0004	5.9831	0.0000	0.0000
Sand, at mine/CH U	0.0000	0.0000	0.0000	0.0000	-0.0081	0.0000	-0.0163	0.0000	0.0000
Disposal, inert waste, 5% water, to inert material landfill/CH S	0.0000	0.0000	0.0000	0.0001	1.2950	0.0000	0.5393	0.0000	0.0000

Table C 2. Environmental impact of core and mould production without SSR – mid-point results – continued

Label	**Aquatic acidification (kg SO2 eq)**	**Aquatic eutrophication (kg PO4 P-lim)**	**Global warming (kg CO2 eq)**		**Non-renewable energy (MJ primary)**		**Mineral extraction (MJ surplus)**	**TOTAL**
			Amount	**%**	**Amount**	**%**	**Amount**	
Phenol-resorcinol-formaldehyde hardener, at plant/US	0.0000	0.0000	0.0003	0.9432	0.0039	1.1746	0.0000	0.0046
Dimethylamine, at plant/RER U	0.0000	0.0000	0.0001	0.2593	0.0002	0.0672	0.0000	0.0004
Phenol-resorcinol-formaldehyde resin, at plant/US	0.0000	0.0000	0.0013	3.4852	0.0173	5.1727	0.0000	0.1957
Phenolic resin, at plant/RER U	0.0000	0.0000	0.0034	9.1867	0.0074	2.2120	0.0000	0.0130
Sand, at mine/CH U	0.0000	0.0000	0.0002	0.6207	0.0004	0.1097	0.0000	0.0011
Hard coal, at mine/RU U	0.0000	0.0000	0.0010	2.7395	0.0128	3.8301	0.0000	0.0153
Bentonite, at mine/DE U	0.0000	0.0000	0.0005	1.3025	0.0005	0.1396	0.0000	0.0019
Natural gas, high pressure, at consumer/RER U	0.0000	0.0000	0.0289	79.2758	0.2906	86.8383	0.0000	0.3435
Sand, at mine/CH U	0.0000	0.0000	0.0000	-0.0690	0.0000	-0.0122	0.0000	-0.0001
Disposal, inert waste, 5% water, to inert material landfill/CH S	0.0000	0.0000	0.0008	2.2560	0.0016	0.4680	0.0000	0.0042
TOTAL	0.0000	0.0000	0.0365	100.0000	0.3347	100.0000	0.0000	0.5795

Table C 3. Environmental impact of core and mould production with SSR (Scenario A) – mid-point results

Label	**Carcinogens (kg C2H3Cl eq)**		**Non-carcinogens (kg C2H3Cl eq)**		**Respiratory inorganics (kg PM2.5 eq)**		**Ionizing radiation (Bq C-14 eq)**	**Ozone layer depletion (kg CFC-11 eq)**	
	Amount	**%**	**Amount**	**%**	**Amount**	**%**	**Amount**	**Amount**	**%**
Phenol-resorcinol-formaldehyde hardener, at plant/US	0.0000	0.5977	0.0000	0.2321	0.0002	0.0908	0.0000	0.0000	0.0000
Dimethylamine, at plant/RER U	0.0000	0.0421	0.0000	0.1113	0.0000	0.0165	0.0000	0.0000	0.0000
Phenol-resorcinol-formaldehyde resin, at plant/US	0.0000	0.0000	0.0007	87.7816	0.2503	93.2687	0.0000	0.0000	0.0000
Phenolic resin, at plant/RER U	0.0003	3.2948	0.0001	7.4941	0.0009	0.3445	0.0000	0.0000	0.0000
Sand, at mine/CH U	0.0000	0.0060	0.0000	0.0410	0.0000	0.0175	0.0000	0.0000	0.0000
Hard coal, at mine/RU U	0.0000	0.0799	0.0000	2.0456	0.0007	0.2774	0.0000	0.0000	0.0000
Bentonite, at mine/DE U	0.0000	0.3347	0.0000	0.6990	0.0009	0.3358	0.0000	0.0000	0.0000
Natural gas, high pressure, at consumer/RER U	0.0078	95.6591	0.0000	1.7339	0.0155	5.7675	0.0000	0.0001	100.0000
Electricity/TR	0.0000	0.0007	0.0000	0.0005	0.0000	0.0003	0.0000	0.0000	0.0000
Sand, at mine/CH U	0.0000	-0.0603	0.0000	-0.4142	-0.0005	-0.1765	0.0000	0.0000	0.0000
Disposal, inert waste, 5% water, to inert material landfill/CH S	0.0000	0.0453	0.0000	0.2752	0.0002	0.0575	0.0000	0.0000	0.0000

Table C 3. Environmental impact of core and mould production with SSR (Scenario A) – mid-point results – continued

Label	**Respiratory organics (kg C2H4 eq)**		**Aquatic ecotoxicity (kg TEG water)**	**Terrestrial ecotoxicity (kg TEG soil)**		**Terrestrial acid/nutri (kg SO2 eq)**		**Land occupation (m2org.arable)**
	Amount	%	Amount	Amount	%	Amount	%	Amount
Phenol-resorcinol-formaldehyde hardener, at plant/US	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0731	0.0000
Dimethylamine, at plant/RER U	0.0000	0.0000	0.0000	0.0000	0.0166	0.0000	0.0153	0.0000
Phenol-resorcinol-formaldehyde resin, at plant/US	0.0000	0.0000	0.0000	0.0111	93.5650	0.0083	95.3077	0.0000
Phenolic resin, at plant/RER U	0.0000	0.0000	0.0000	0.0000	0.2608	0.0000	0.1911	0.0000
Sand, at mine/CH U	0.0000	0.0000	0.0000	0.0000	0.0050	0.0000	0.0100	0.0000
Hard coal, at mine/RU U	0.0000	0.0000	0.0000	0.0007	5.7839	0.0000	0.2148	0.0000
Bentonite, at mine/DE U	0.0000	0.0000	0.0000	0.0000	0.1180	0.0000	0.1991	0.0000
Natural gas, high pressure, at consumer/RER U	0.0001	100.0000	0.0000	0.0000	0.2117	0.0004	4.0529	0.0000
Electricity/TR	0.0000	0.0000	0.0000	0.0000	0.0004	0.0000	0.0001	0.0000
Sand, at mine/CH U	0.0000	0.0000	0.0000	0.0000	-0.0505	0.0000	-0.1006	0.0000
Disposal, inert waste, 5% water, to inert material landfill/CH S	0.0000	0.0000	0.0000	0.0000	0.0891	0.0000	0.0366	0.0000

Table C 3. Environmental impact of core and mould production with SSR (Scenario A) – mid-point results – continued

Label	**Aquatic acidification (kg SO2 eq)**	**Aquatic eutrophication (kg PO4 P-lim)**	**Global warming (kg CO2 eq)**		**Non-renewable energy (MJ primary)**		**Mineral extraction (MJ surplus)**	**TOTAL**
			Amount	**%**	**Amount**	**%**	**Amount**	
Phenol-resorcinol-formaldehyde hardener, at plant/US	0.0000	0.0000	0.0003	0.9136	0.0036	1.0679	0.0000	0.0042
Dimethylamine, at plant/RER U	0.0000	0.0000	0.0001	0.2593	0.0002	0.0631	0.0000	0.0004
Phenol-resorcinol-formaldehyde resin, at plant/US	0.0000	0.0000	0.0019	5.6086	0.0264	7.8125	0.0000	0.2989
Phenolic resin, at plant/RER U	0.0000	0.0000	0.0020	5.7871	0.0044	1.3078	0.0000	0.0078
Sand, at mine/CH U	0.0000	0.0000	0.0000	0.0655	0.0000	0.0109	0.0000	0.0001
Hard coal, at mine/RU U	0.0000	0.0000	0.0010	2.8865	0.0128	3.7876	0.0000	0.0153
Bentonite, at mine/DE U	0.0000	0.0000	0.0005	1.3724	0.0005	0.1381	0.0000	0.0019
Natural gas, high pressure, at consumer/RER U	0.0000	0.0000	0.0289	83.5291	0.2906	85.8746	0.0000	0.3435
Electricity/TR	0.0000	0.0000	0.0000	0.0014	0.0000	0.0009	0.0000	0.0000
Sand, at mine/CH U	0.0000	0.0000	-0.0002	-0.6614	-0.0004	-0.1097	0.0000	-0.0011
Disposal, inert waste, 5% water, to inert material landfill/CH S	0.0000	0.0000	0.0001	0.2379	0.0002	0.0463	0.0000	0.0004
TOTAL	0.0000	0.0000	0.0346	100.0000	0.3385	100.0000	0.0000	0.6713

Table C 4. Environmental impact of core and mould production with SSR (Scenario B) – mid-point results

Label	**Carcinogens (kg C2H3Cl eq)**		**Non-carcinogens (kg C2H3Cl eq)**		**Respiratory inorganics (kg PM2.5 eq)**		**Ionizing radiation (Bq C-14 eq)**	**Ozone layer depletion (kg CFC-11 eq)**	
	Amount	**%**	**Amount**	**%**	**Amount**	**%**	**Amount**	**Amount**	**%**
Phenol-resorcinol-formaldehyde hardener, at plant/US	0.0001	0.6057	0.0000	0.2311	0.0002	0.0907	0.0000	0.0000	0.0000
Dimethylamine, at plant/RER U	0.0000	0.0427	0.0000	0.1108	0.0000	0.0164	0.0000	0.0000	0.0000
Phenol-resorcinol-formaldehyde resin, at plant/US	0.0000	0.0000	0.0007	87.4270	0.2556	93.1546	0.0000	0.0000	0.0000
Phenolic resin, at plant/RER U	0.0003	3.3390	0.0001	7.4637	0.0009	0.3441	0.0000	0.0000	0.0000
Sand, at mine/CH U	0.0000	0.0059	0.0000	0.0400	0.0000	0.0171	0.0000	0.0000	0.0000
Hard coal, at mine/RU U	0.0000	0.0792	0.0000	1.9948	0.0007	0.2713	0.0000	0.0000	0.0000
Bentonite, at mine/DE U	0.0000	0.3321	0.0000	0.6817	0.0009	0.3284	0.0000	0.0000	0.0000
Natural gas, high pressure, at consumer/RER U	0.0078	94.9213	0.0000	1.6908	0.0155	5.6402	0.0000	0.0001	100.0000
Electricity/TR	0.0001	0.6888	0.0000	0.4957	0.0007	0.2536	0.0000	0.0000	0.0000
Sand, at mine/CH U	0.0000	-0.0598	0.0000	-0.4039	-0.0005	-0.1726	0.0000	0.0000	0.0000
Disposal, inert waste, 5% water, to inert material landfill/CH S	0.0000	0.0450	0.0000	0.2684	0.0002	0.0563	0.0000	0.0000	0.0000

Table C 4. Environmental impact of core and mould production with SSR (Scenario B) – mid-point results – continued

Label	**Respiratory organics (kg C2H4 eq)**		**Aquatic ecotoxicity (kg TEG water)**	**Terrestrial ecotoxicity (kg TEG soil)**		**Terrestrial acid/nutri (kg SO2 eq)**		**Land occupation (m2org.arable)**
	Amount	**%**	**Amount**	**Amount**	**%**	**Amount**	**%**	**Amount**
Phenol-resorcinol-formaldehyde hardener, at plant/US	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0731	0.0000
Dimethylamine, at plant/RER U	0.0000	0.0000	0.0000	0.0000	0.0165	0.0000	0.0153	0.0000
Phenol-resorcinol-formaldehyde resin, at plant/US	0.0000	0.0000	0.0000	0.0114	93.3037	0.0085	95.2891	0.0000
Phenolic resin, at plant/RER U	0.0000	0.0000	0.0000	0.0000	0.2601	0.0000	0.1910	0.0000
Sand, at mine/CH U	0.0000	0.0000	0.0000	0.0000	0.0049	0.0000	0.0097	0.0000
Hard coal, at mine/RU U	0.0000	0.0000	0.0000	0.0007	5.6474	0.0000	0.2103	0.0000
Bentonite, at mine/DE U	0.0000	0.0000	0.0000	0.0000	0.1152	0.0000	0.1949	0.0000
Natural gas, high pressure, at consumer/RER U	0.0001	100.0000	0.0000	0.0000	0.2067	0.0004	3.9675	0.0000
Electricity/TR	0.0000	0.0000	0.0000	0.0000	0.4079	0.0000	0.1117	0.0000
Sand, at mine/CH U	0.0000	0.0000	0.0000	0.0000	-0.0493	0.0000	-0.0985	0.0000
Disposal, inert waste, 5% water, to inert material landfill/CH S	0.0000	0.0000	0.0000	0.0000	0.0870	0.0000	0.0358	0.0000

Table C 4. Environmental impact of core and mould production with SSR (Scenario B) – mid-point results – continued

Label	**Aquatic acidification (kg SO2 eq)**	**Aquatic eutrophication (kg PO4 P-lim)**	**Global warming (kg CO2 eq)**		**Non-renewable energy (MJ primary)**		**Mineral extraction (MJ surplus)**	**TOTAL**
			Amount	**%**	**Amount**	**%**	**Amount**	
Phenol-resorcinol-formaldehyde hardener, at plant/US	0.0000	0.0000	0.0003	0.9179	0.0037	1.0781	0.0000	0.0043
Dimethylamine, at plant/RER U	0.0000	0.0000	0.0001	0.2606	0.0002	0.0637	0.0000	0.0004
Phenol-resorcinol-formaldehyde resin, at plant/US	0.0000	0.0000	0.0020	5.6349	0.0270	7.8871	0.0000	0.3052
Phenolic resin, at plant/RER U	0.0000	0.0000	0.0020	5.8141	0.0045	1.3202	0.0000	0.0079
Sand, at mine/CH U	0.0000	0.0000	0.0000	0.0644	0.0000	0.0107	0.0000	0.0001
Hard coal, at mine/RU U	0.0000	0.0000	0.0010	2.8395	0.0128	3.7440	0.0000	0.0153
Bentonite, at mine/DE U	0.0000	0.0000	0.0005	1.3500	0.0005	0.1365	0.0000	0.0019
Natural gas, high pressure, at consumer/RER U	0.0000	0.0000	0.0289	82.1684	0.2906	84.8845	0.0000	0.3435
Electricity/TR	0.0000	0.0000	0.0005	1.3669	0.0032	0.9379	0.0000	0.0045
Sand, at mine/CH U	0.0000	0.0000	-0.0002	-0.6507	-0.0004	-0.1084	0.0000	-0.0011
Disposal, inert waste, 5% water, to inert material landfill/CH S	0.0000	0.0000	0.0001	0.2341	0.0002	0.0458	0.0000	0.0004
TOTAL	0.0000	0.0000	0.0352	100.0000	0.3424	100.0000	0.0000	0.6825

Table C 5. Environmental impact of core and mould production with SSR (Scenario C) – mid-point results

Label	**Carcinogens (kg C2H3Cl eq)**		**Non-carcinogens (kg C2H3Cl eq)**		**Respiratory inorganics (kg PM2.5 eq)**		**Ionizing radiation (Bq C-14 eq)**	**Ozone layer depletion (kg CFC-11 eq)**	
	Amount	**%**	**Amount**	**%**	**Amount**	**%**	**Amount**	**Amount**	**%**
Phenol-resorcinol-formaldehyde hardener, at plant/US	0.0000	0.5362	0.0000	0.2308	0.0002	0.0901	0.0000	0.0000	0.0000
Dimethylamine, at plant/RER U	0.0000	0.0378	0.0000	0.1107	0.0000	0.0163	0.0000	0.0000	0.0000
Phenol-resorcinol-formaldehyde resin, at plant/US	0.0000	0.0000	0.0007	87.3253	0.2236	92.5754	0.0000	0.0000	0.0000
Phenolic resin, at plant/RER U	0.0002	2.9560	0.0001	7.4551	0.0008	0.3419	0.0000	0.0000	0.0000
Sand, at mine/CH U	0.0000	0.0060	0.0000	0.0457	0.0000	0.0194	0.0000	0.0000	0.0000
Hard coal, at mine/RU U	0.0000	0.0802	0.0000	2.2777	0.0007	0.3082	0.0000	0.0000	0.0000
Bentonite, at mine/DE U	0.0000	0.3361	0.0000	0.7784	0.0009	0.3730	0.0000	0.0000	0.0000
Natural gas, high pressure, at consumer/RER U	0.0078	96.0619	0.0000	1.9306	0.0155	6.4074	0.0000	0.0001	100.0000
Electricity/TR	0.0000	0.0007	0.0000	0.0006	0.0000	0.0003	0.0000	0.0000	0.0000
Sand, at mine/CH U	0.0000	-0.0605	0.0000	-0.4612	-0.0005	-0.1961	0.0000	0.0000	0.0000
Disposal, inert waste, 5% water, to inert material landfill/CH S	0.0000	0.0455	0.0000	0.3064	0.0002	0.0639	0.0000	0.0000	0.0000

Table C 5. Environmental impact of core and mould production with SSR (Scenario C) – mid-point results – continued

Label	**Respiratory organics (kg C2H4 eq)**		**Aquatic ecotoxicity (kg TEG water)**	**Terrestrial ecotoxicity (kg TEG soil)**		**Terrestrial acid/nutri (kg SO2 eq)**		**Land occupation (m2org.arable)**
	Amount	**%**	**Amount**	**Amount**	**%**	**Amount**	**%**	**Amount**
Phenol-resorcinol-formaldehyde hardener, at plant/US	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0727	0.0000
Dimethylamine, at plant/RER U	0.0000	0.0000	0.0000	0.0000	0.0165	0.0000	0.0152	0.0000
Phenol-resorcinol-formaldehyde resin, at plant/US	0.0000	0.0000	0.0000	0.0100	92.8828	0.0074	94.8087	0.0000
Phenolic resin, at plant/RER U	0.0000	0.0000	0.0000	0.0000	0.2589	0.0000	0.1900	0.0000
Sand, at mine/CH U	0.0000	0.0000	0.0000	0.0000	0.0056	0.0000	0.0111	0.0000
Hard coal, at mine/RU U	0.0000	0.0000	0.0000	0.0007	6.4266	0.0000	0.2392	0.0000
Bentonite, at mine/DE U	0.0000	0.0000	0.0000	0.0000	0.1311	0.0000	0.2217	0.0000
Natural gas, high pressure, at consumer/RER U	0.0001	100.0000	0.0000	0.0000	0.2352	0.0004	4.5126	0.0000
Electricity/TR	0.0000	0.0000	0.0000	0.0000	0.0005	0.0000	0.0001	0.0000
Sand, at mine/CH U	0.0000	0.0000	0.0000	0.0000	-0.0561	0.0000	-0.1120	0.0000
Disposal, inert waste, 5% water, to inert material landfill/CH S	0.0000	0.0000	0.0000	0.0000	0.0990	0.0000	0.0407	0.0000

Table C 5. Environmental impact of core and mould production with SSR (Scenario C) – mid-point results – continued

Label	**Aquatic acidification (kg SO2 eq)**	**Aquatic eutrophication (kg PO4 P-lim)**	**Global warming (kg CO2 eq)**		**Non-renewable energy (MJ primary)**		**Mineral extraction (MJ surplus)**	**TOTAL**
			Amount	**%**	**Amount**	**%**	**Amount**	
Phenol-resorcinol-formaldehyde hardener, at plant/US	0.0000	0.0000	0.0003	0.8274	0.0032	0.9646	0.0000	0.0038
Dimethylamine, at plant/RER U	0.0000	0.0000	0.0001	0.2349	0.0002	0.0570	0.0000	0.0003
Phenol-resorcinol-formaldehyde resin, at plant/US	0.0000	0.0000	0.0017	5.0789	0.0236	7.0571	0.0000	0.2670
Phenolic resin, at plant/RER U	0.0000	0.0000	0.0018	5.2405	0.0040	1.1813	0.0000	0.0069
Sand, at mine/CH U	0.0000	0.0000	0.0000	0.0664	0.0000	0.0110	0.0000	0.0001
Hard coal, at mine/RU U	0.0000	0.0000	0.0010	2.9257	0.0128	3.8295	0.0000	0.0153
Bentonite, at mine/DE U	0.0000	0.0000	0.0005	1.3910	0.0005	0.1396	0.0000	0.0019
Natural gas, high pressure, at consumer/RER U	0.0000	0.0000	0.0289	84.6631	0.2906	86.8231	0.0000	0.3435
Electricity/TR	0.0000	0.0000	0.0000	0.0014	0.0000	0.0010	0.0000	0.0000
Sand, at mine/CH U	0.0000	0.0000	-0.0002	-0.6704	-0.0004	-0.1109	0.0000	-0.0011
Disposal, inert waste, 5% water, to inert material landfill/CH S	0.0000	0.0000	0.0001	0.2412	0.0002	0.0468	0.0000	0.0004
TOTAL	0.0000	0.0000	0.0342	100.0000	0.3348	100.0000	0.0000	0.6382

Table C 6. Environmental impact of core and mould production with SSR (Scenario D) – mid-point results

Label	**Carcinogens (kg C2H3Cl eq)**		**Non-carcinogens (kg C2H3Cl eq)**		**Respiratory inorganics (kg PM2.5 eq)**		**Ionizing radiation (Bq C-14 eq)**		**Ozone layer depletion (kg CFC-11 eq)**	
	Amount	**%**	**Amount**	**%**	**Amount**	**%**	**Amount**	**%**	**Amount**	**%**
Phenol-resorcinol-formaldehyde hardener, at plant/US	0.0000	0.5732	0.0000	0.2316	0.0002	0.0906	0.0000	0.0000	0.0000	0.0000
Dimethylamine, at plant/RER U	0.0000	0.0404	0.0000	0.1110	0.0000	0.0164	0.0000	2.2805	0.0000	0.0411
Phenol-resorcinol-formaldehyde resin, at plant/US	0.0000	0.0000	0.0007	87.6106	0.2396	93.0087	0.0000	0.0000	0.0000	0.0000
Phenolic resin, at plant/RER U	0.0003	3.1597	0.0001	7.4796	0.0009	0.3435	0.0000	46.7126	0.0000	0.1821
Sand, at mine/CH U	0.0000	0.0060	0.0000	0.0427	0.0000	0.0182	0.0000	3.2751	0.0000	0.0086
Hard coal, at mine/RU U	0.0000	0.0800	0.0000	2.1325	0.0007	0.2890	0.0000	43.8202	0.0000	0.0672
Bentonite, at mine/DE U	0.0000	0.3353	0.0000	0.7287	0.0009	0.3498	0.0000	1.6958	0.0000	0.1802
Natural gas, high pressure, at consumer/RER U	0.0078	95.8197	0.0000	1.8075	0.0155	6.0075	0.0000	34.1873	0.0001	99.5337
Electricity/TR	0.0000	0.0007	0.0000	0.0005	0.0000	0.0003	0.0000	0.0047	0.0000	0.0007
Sand, at mine/CH U	0.0000	-0.0604	0.0000	-0.4318	-0.0005	-0.1839	0.0000	-33.0890	0.0000	-0.0867
Disposal, inert waste, 5% water, to inert	0.0000	0.0454	0.0000	0.2869	0.0002	0.0599	0.0000	1.1128	0.0000	0.0732

Table C 6. Environmental impact of core and mould production with SSR (Scenario D) – mid-point results – continued

Label	**Respiratory organics (kg C2H4 eq)**		**Aquatic ecotoxicity (kg TEG water)**	**Terrestrial ecotoxicity (kg TEG soil)**		**Terrestrial acid/nutri (kg SO2 eq)**		**Land occupation (m2org.arable)**
	Amount	**%**	**Amount**	**Amount**	**%**	**Amount**	**%**	**Amount**
Phenol-resorcinol-formaldehyde hardener, at plant/US	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0730	0.0000
Dimethylamine, at plant/RER U	0.0000	0.0000	0.0000	0.0000	0.0165	0.0000	0.0152	0.0000
Phenol-resorcinol-formaldehyde resin, at plant/US	0.0000	0.0000	0.0000	0.0107	93.3092	0.0079	95.1208	0.0000
Phenolic resin, at plant/RER U	0.0000	0.0000	0.0000	0.0000	0.2601	0.0000	0.1907	0.0000
Sand, at mine/CH U	0.0000	0.0000	0.0000	0.0000	0.0052	0.0000	0.0104	0.0000
Hard coal, at mine/RU U	0.0000	0.0000	0.0000	0.0007	6.0249	0.0000	0.2239	0.0000
Bentonite, at mine/DE U	0.0000	0.0000	0.0000	0.0000	0.1229	0.0000	0.2076	0.0000
Natural gas, high pressure, at consumer/RER U	0.0001	100.0000	0.0000	0.0000	0.2205	0.0004	4.2250	0.0000
Electricity/TR	0.0000	0.0000	0.0000	0.0000	0.0004	0.0000	0.0001	0.0000
Sand, at mine/CH U	0.0000	0.0000	0.0000	0.0000	-0.0526	0.0000	-0.1049	0.0000
Disposal, inert waste, 5% water, to inert	0.0000	0.0000	0.0000	0.0000	0.0929	0.0000	0.0381	0.0000

Table C 6. Environmental impact of core and mould production with SSR (Scenario D) – mid-point results – continued

Label	**Aquatic acidification (kg SO2 eq)**	**Aquatic eutrophication (kg PO4 P-lim)**	**Global warming (kg CO2 eq)**		**Non-renewable energy (MJ primary)**		**Mineral extraction (MJ surplus)**	**TOTAL**
			Amount	**%**	**Amount**	**%**	**Amount**	
Phenol-resorcinol-formaldehyde hardener, at plant/US	0.0000	0.0000	0.0003	0.8794	0.0035	1.0269	0.0000	0.0041
Dimethylamine, at plant/RER U	0.0000	0.0000	0.0001	0.2496	0.0002	0.0607	0.0000	0.0003
Phenol-resorcinol-formaldehyde resin, at plant/US	0.0000	0.0000	0.0019	5.3984	0.0253	7.5124	0.0000	0.2861
Phenolic resin, at plant/RER U	0.0000	0.0000	0.0019	5.5703	0.0042	1.2575	0.0000	0.0074
Sand, at mine/CH U	0.0000	0.0000	0.0000	0.0658	0.0000	0.0109	0.0000	0.0001
Hard coal, at mine/RU U	0.0000	0.0000	0.0010	2.9021	0.0128	3.8043	0.0000	0.0153
Bentonite, at mine/DE U	0.0000	0.0000	0.0005	1.3798	0.0005	0.1387	0.0000	0.0019
Natural gas, high pressure, at consumer/RER U	0.0000	0.0000	0.0289	83.9789	0.2906	86.2514	0.0000	0.3435
Electricity/TR	0.0000	0.0000	0.0000	0.0014	0.0000	0.0010	0.0000	0.0000
Sand, at mine/CH U	0.0000	0.0000	-0.0002	-0.6650	-0.0004	-0.1102	0.0000	-0.0011
Disposal, inert waste, 5% water, to inert material	0.0000	0.0000	0.0001	0.2392	0.0002	0.0465	0.0000	0.0004
TOTAL	0.0000	0.0000	0.0345	100.0000	0.3370	100.0000	0.0000	0.6581

Table C 7. Environmental impact of core and mould production with SSR (Scenario E) – mid-point results

Label	**Carcinogens (kg C2H3Cl eq)**		**Non-carcinogens (kg C2H3Cl eq)**		**Respiratory inorganics (kg PM2.5 eq)**		**Ionizing radiation (Bq C-14 eq)**		**Ozone layer depletion (kg CFC-11 eq)**	
	Amount	**%**	**Amount**	**%**	**Amount**	**%**	**Amount**	**%**	**Amount**	**%**
Phenol-resorcinol-formaldehyde hardener, at plant/US	0.0000	0.4707	0.0000	0.2278	0.0002	0.0890	0.0000	0.0000	0.0000	0.0000
Dimethylamine, at plant/RER U	0.0000	0.0377	0.0000	0.1241	0.0000	0.0183	0.0000	2.2114	0.0000	0.0381
Phenol-resorcinol-formaldehyde resin, at plant/US	0.0000	0.0000	0.0006	86.1857	0.1969	91.4068	0.0000	0.0000	0.0000	0.0000
Phenolic resin, at plant/RER U	0.0002	2.5950	0.0000	7.3579	0.0007	0.3376	0.0000	39.8748	0.0000	0.1486
Sand, at mine/CH U	0.0000	0.0060	0.0000	0.0512	0.0000	0.0218	0.0000	3.4031	0.0000	0.0085
Hard coal, at mine/RU U	0.0000	0.0800	0.0000	2.5536	0.0007	0.3457	0.0000	45.5329	0.0000	0.0667
Bentonite, at mine/DE U	0.0000	0.3352	0.0000	0.8726	0.0009	0.4184	0.0000	1.7620	0.0000	0.1790
Natural gas, high pressure, at consumer/RER U	0.0078	95.7934	0.0000	2.1644	0.0155	7.1867	0.0000	35.5235	0.0001	98.8658
Electricity/TR	0.0001	0.6969	0.0000	0.6362	0.0007	0.3239	0.0000	4.9182	0.0000	0.7068
Sand, at mine/CH U	0.0000	-0.0604	0.0000	-0.5171	-0.0005	-0.2200	0.0000	-34.3823	0.0000	-0.0861
Disposal, inert waste, 5% water, to inert material landfill/CH S	0.0000	0.0454	0.0000	0.3436	0.0002	0.0717	0.0000	1.1563	0.0000	0.0727

Table C 7. Environmental impact of core and mould production with SSR (Scenario E) – mid-point results – continued

Label	**Respiratory organics** (kg C2H4 eq)		**Aquatic ecotoxicity (kg TEG water)**	**Terrestrial ecotoxicity** (kg TEG soil)		**Terrestrial acid/nutri** (kg SO2 eq)		**Land occupation (m2org.arable)**	
	Amount	**%**	**Amount**	**Amount**	**%**	**Amount**	**%**	**Amount**	**%**
Phenol-resorcinol-formaldehyde hardener, at plant/US	0.0000	1.8239	0.0000	0.0000	0.0000	0.0000	0.0722	0.0000	0.0000
Dimethylamine, at plant/RER U	0.0000	0.0890	0.0000	0.0000	0.0184	0.0000	0.0171	0.0000	0.0000
Phenol-resorcinol-formaldehyde resin, at plant/US	0.0000	0.1577	0.0000	0.0088	91.5457	0.0065	94.0426	0.0000	0.0000
Phenolic resin, at plant/RER U	0.0000	5.1364	0.0000	0.0000	0.2552	0.0000	0.1885	0.0000	0.0000
Sand, at mine/CH U	0.0000	0.0446	0.0000	0.0000	0.0062	0.0000	0.0125	0.0000	0.0000
Hard coal, at mine/RU U	0.0000	0.6972	0.0000	0.0007	7.1953	0.0000	0.2695	0.0000	0.0000
Bentonite, at mine/DE U	0.0000	1.1856	0.0000	0.0000	0.1467	0.0000	0.2498	0.0000	0.0000
Natural gas, high pressure, at consumer/RER U	0.0001	90.1536	0.0000	0.0000	0.2633	0.0004	5.0846	0.0000	0.0000
Electricity/TR	0.0000	0.8970	0.0000	0.0000	0.5211	0.0000	0.1436	0.0000	0.0000
Sand, at mine/CH U	0.0000	-0.4501	0.0000	0.0000	-0.0629	0.0000	-0.1262	0.0000	0.0000
Disposal, inert waste, 5% water, to inert material landfill/CH S	0.0000	0.2652	0.0000	0.0000	0.1109	0.0000	0.0459	0.0000	0.0000

Table C 7. Environmental impact of core and mould production with SSR (Scenario E) – mid-point results – continued

Label	**Aquatic acidification (kg SO2 eq)**	**Aquatic eutrophication (kg PO4 P-lim)**	**Global warming (kg CO2 eq)**		**Non-renewable energy (MJ primary)**		**Mineral extraction (MJ surplus)**	**TOTAL**
			Amount	**%**	**Amount**	**%**	**Amount**	
Phenol-resorcinol-formaldehyde hardener, at plant/US	0.0000	0.0000	0.0002	0.7278	0.0028	0.8504	0.0000	0.0033
Dimethylamine, at plant/RER U	0.0000	0.0000	0.0001	0.2347	0.0002	0.0571	0.0000	0.0003
Phenol-resorcinol-formaldehyde resin, at plant/US	0.0000	0.0000	0.0015	4.4676	0.0208	6.2212	0.0000	0.2351
Phenolic resin, at plant/RER U	0.0000	0.0000	0.0016	4.6098	0.0035	1.0414	0.0000	0.0061
Sand, at mine/CH U	0.0000	0.0000	0.0000	0.0663	0.0000	0.0110	0.0000	0.0001
Hard coal, at mine/RU U	0.0000	0.0000	0.0010	2.9235	0.0128	3.8349	0.0000	0.0153
Bentonite, at mine/DE U	0.0000	0.0000	0.0005	1.3899	0.0005	0.1398	0.0000	0.0019
Natural gas, high pressure, at consumer/RER U	0.0000	0.0000	0.0289	84.5982	0.2906	86.9452	0.0000	0.3435
Electricity/TR	0.0000	0.0000	0.0005	1.4111	0.0032	0.9632	0.0000	0.0045
Sand, at mine/CH U	0.0000	0.0000	-0.0002	-0.6699	-0.0004	-0.1111	0.0000	-0.0011
Disposal, inert waste, 5% water, to inert material landfill/CH S	0.0000	0.0000	0.0001	0.2410	0.0002	0.0469	0.0000	0.0004
TOTAL	0.0000	0.0000	0.0342	100.0000	0.3343	100.0000	0.0000	0.6095

Table C 8. Environmental impact of core and mould production with SSR (Scenario F) – mid-point results

Label	**Carcinogens (kg C2H3Cl eq)**		**Non-carcinogens (kg C2H3Cl eq)**		**Respiratory inorganics (kg PM2.5 eq)**		**Ionizing radiation (Bq C-14 eq)**		**Ozone layer depletion (kg CFC-11 eq)**	
	Amount	**%**	**Amount**	**%**	**Amount**	**%**	**Amount**	**%**	**Amount**	**%**
Phenol-resorcinol-formaldehyde hardener, at plant/US	0.0000	0.5324	0.0000	0.2296	0.0002	0.0899	0.0000	0.0000	0.0000	0.0000
Dimethylamine, at plant/RER U	0.0000	0.0375	0.0000	0.1101	0.0000	0.0163	0.0000	2.0976	0.0000	0.0381
Phenol-resorcinol-formaldehyde resin, at plant/US	0.0000	0.0000	0.0007	86.8332	0.2236	92.3081	0.0000	0.0000	0.0000	0.0000
Phenolic resin, at plant/RER U	0.0002	2.9349	0.0001	7.4131	0.0008	0.3409	0.0000	42.9660	0.0000	0.1687
Sand, at mine/CH U	0.0000	0.0059	0.0000	0.0454	0.0000	0.0194	0.0000	3.2288	0.0000	0.0085
Hard coal, at mine/RU U	0.0000	0.0796	0.0000	2.2654	0.0007	0.3074	0.0000	43.2016	0.0000	0.0667
Bentonite, at mine/DE U	0.0000	0.3338	0.0000	0.7742	0.0009	0.3721	0.0000	1.6718	0.0000	0.1789
Natural gas, high pressure, at consumer/RER U	0.0078	95.3984	0.0000	1.9202	0.0155	6.3905	0.0000	33.7047	0.0001	98.8477
Electricity/TR	0.0001	0.6922	0.0000	0.5629	0.0007	0.2873	0.0000	4.6541	0.0000	0.7048
Sand, at mine/CH U	0.0000	-0.0601	0.0000	-0.4587	-0.0005	-0.1956	0.0000	-32.6219	0.0000	-0.0861
Disposal, inert waste, 5% water, to inert material landfill/CH S	0.0000	0.0452	0.0000	0.3048	0.0002	0.0637	0.0000	1.0971	0.0000	0.0727

Table C 8. Environmental impact of core and mould production with SSR (Scenario F) – mid-point results – continued 1

Label	**Respiratory organics (kg C2H4 eq)**		**Aquatic ecotoxicity (kg TEG water)**	**Terrestrial ecotoxicity (kg TEG soil)**		**Terrestrial acid/nutri (kg SO2 eq)**		**Land occupation (m2org.arable)**
	Amount	**%**	**Amount**	**Amount**	**%**	**Amount**	**%**	**Amount**
Phenol-resorcinol-formaldehyde hardener, at plant/US	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0726	0.0000
Dimethylamine, at plant/RER U	0.0000	0.0000	0.0000	0.0000	0.0164	0.0000	0.0152	0.0000
Phenol-resorcinol-formaldehyde resin, at plant/US	0.0000	0.0000	0.0000	0.0100	92.4525	0.0074	94.6873	0.0000
Phenolic resin, at plant/RER U	0.0000	0.0000	0.0000	0.0000	0.2577	0.0000	0.1898	0.0000
Sand, at mine/CH U	0.0000	0.0000	0.0000	0.0000	0.0055	0.0000	0.0111	0.0000
Hard coal, at mine/RU U	0.0000	0.0000	0.0000	0.0007	6.3984	0.0000	0.2389	0.0000
Bentonite, at mine/DE U	0.0000	0.0000	0.0000	0.0000	0.1305	0.0000	0.2215	0.0000
Natural gas, high pressure, at consumer/RER U	0.0001	100.0000	0.0000	0.0000	0.2342	0.0004	4.5079	0.0000
Electricity/TR	0.0000	0.0000	0.0000	0.0000	0.4622	0.0000	0.1269	0.0000
Sand, at mine/CH U	0.0000	0.0000	0.0000	0.0000	-0.0559	0.0000	-0.1119	0.0000
Disposal, inert waste, 5% water, to inert material landfill/CH S	0.0000	0.0000	0.0000	0.0000	0.0986	0.0000	0.0407	0.0000

Table C 8. Environmental impact of core and mould production with SSR (Scenario F) – mid-point results – continued 2

Label	**Aquatic acidification (kg SO2 eq)**	**Aquatic eutrophication (kg PO4 P-lim)**	**Global warming (kg CO2 eq)**		**Non-renewable energy (MJ primary)**		**Mineral extraction (MJ surplus)**	**TOTAL**
			Amount	**%**	**Amount**	**%**	**Amount**	
Phenol-resorcinol-formaldehyde hardener, at plant/US	0.0000	0.0000	0.0003	0.8157	0.0032	0.9553	0.0000	0.0038
Dimethylamine, at plant/RER U	0.0000	0.0000	0.0001	0.2315	0.0002	0.0564	0.0000	0.0003
Phenol-resorcinol-formaldehyde resin, at plant/US	0.0000	0.0000	0.0017	5.0074	0.0236	6.9885	0.0000	0.2669
Phenolic resin, at plant/RER U	0.0000	0.0000	0.0018	5.1667	0.0040	1.1698	0.0000	0.0069
Sand, at mine/CH U	0.0000	0.0000	0.0000	0.0654	0.0000	0.0109	0.0000	0.0001
Hard coal, at mine/RU U	0.0000	0.0000	0.0010	2.8852	0.0128	3.7932	0.0000	0.0153
Bentonite, at mine/DE U	0.0000	0.0000	0.0005	1.3718	0.0005	0.1383	0.0000	0.0019
Natural gas, high pressure, at consumer/RER U	0.0000	0.0000	0.0289	83.4907	0.2906	86.0008	0.0000	0.3435
Electricity/TR	0.0000	0.0000	0.0005	1.3889	0.0032	0.9502	0.0000	0.0045
Sand, at mine/CH U	0.0000	0.0000	-0.0002	-0.6611	-0.0004	-0.1099	0.0000	-0.0011
Disposal, inert waste, 5% water, to inert material landfill/CH S	0.0000	0.0000	0.0001	0.2378	0.0002	0.0464	0.0000	0.0004
TOTAL	0.0000	0.0000	0.0347	100.0000	0.3380	100.0000	0.0000	0.6426

APPENDIX D - ENVIRONMENTAL IMPACT OF FOUNDRY SUB-PROSESSES ACCORDING TO END-POINT RESULTS

Table D 1. Environmental impact of metal melting-end-point results

Label	**HUMAN HEALTH**		**ECOSYSTEM QUALITY**		**CLIMATE CHANGE**		**RESOURCES**	
	Amount	**%**	**Amount**	**%**	**Amount**	**%**	**Amount**	**%**
Iron	0,1003	47,1278	0,0089	34,5822	0,0762	57,3370	0,0765	44,6752
Refractory material	0,0011	0,5027	0,0001	0,3823	0,0011	0,8324	0,0008	0,4723
Steel	0,0968	45,5043	0,0137	53,1108	0,0492	37,0573	0,0524	30,5912
Copper	0,0051	2,3901	0,0022	8,5410	0,0003	0,1897	0,0003	0,1669
Coke	0,0001	0,0492	0,0001	0,3214	0,0001	0,0971	0,0015	0,8591
Electricity	0,0094	4,4115	0,0008	2,9535	0,0060	4,4832	0,0398	23,2312
Natural Gas	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0004
Inert waste to landfill	0,0000	0,0003	0,0000	0,0001	0,0000	0,0002	0,0000	0,0001
Slag disposal	0,0000	0,0140	0,0000	0,1087	0,0000	0,0047	0,0000	0,0037
TOTAL	**0,2128**	**100,0000**	**0,0258**	**100,0000**	**0,1329**	**100,0000**	**0,1711**	100,0000

Table D 2. Environmental impact of core and mould production without SSR – end-point results

Label	**HUMAN HEALTH**		**ECOSYSTEM QUALITY**		**CLIMATE CHANGE**		**RESOURCES**	
	Amount	**%**	**Amount**	**%**	**Amount**	**%**	**Amount**	**%**
Phenol-resorcinol-formaldehyde hardener. at plant/US	0.0003	0.1667	0.0000	0.0512	0.0003	0.9432	0.0039	1.1746
Dimethylamine. at plant/RER U	0.0001	0.0267	0.0000	0.0251	0.0001	0.2593	0.0002	0.0672
Phenol-resorcinol-formaldehyde resin. at plant/US	0.1644	84.6625	0.0127	89.9835	0.0013	3.4852	0.0173	5.1727
Phenolic resin. at plant/RER U	0.0021	1.0995	0.0001	0.5785	0.0034	9.1867	0.0074	2.2120
Sand. at mine/CH U	0.0005	0.2495	0.0000	0.1071	0.0002	0.6207	0.0004	0.1097
Hard coal. at mine/RU U	0.0008	0.4011	0.0007	5.1291	0.0010	2.7395	0.0128	3.8301
Bentonite. at mine/DE U	0.0009	0.4823	0.0000	0.2232	0.0005	1.3025	0.0005	0.1396
Natural gas. high pressure. at consumer/RER U	0.0235	12.1108	0.0004	2.6785	0.0289	79.2758	0.2906	86.8381
Sand. at mine/CH U	-0.0001	-0.0277	0.0000	-0.0119	0.0000	-0.0690	0.0000	-0.0122
Disposal. inert waste. 5% water. to inert material landfill/CH S	0.0016	0.8286	0.0002	1.2357	0.0008	2.2560	**0.0016**	0.4681

Table D 3. Environmental impact of core and mould production with SSR (Scenario A) – end-point results

Label	**HUMAN HEALTH**		**ECOSYSTEM QUALITY**		**CLIMATE CHANGE**		**RESOURCES**	
	Amount	**%**	**Amount**	**%**	**Amount**	**%**	**Amount**	**%**
Phenol-resorcinol-formaldehyde hardener. at plant/US	0.0003	0.1072	0.0000	0.0323	0.0003	0.9136	0.0036	1.0679
Dimethylamine. at plant/RER U	0.0000	0.0177	0.0000	0.0163	0.0001	0.2593	0.0002	0.0631
Phenol-resorcinol-formaldehyde resin. at plant/US	0.2510	90.4286	0.0194	94.1921	0.0019	5.6086	0.0264	7.8125
Phenolic resin. at plant/RER U	0.0013	0.4597	0.0000	0.2370	0.0020	5.7871	0.0044	1.3078
Sand. at mine/CH U	0.0000	0.0175	0.0000	0.0073	0.0000	0.0655	0.0000	0.0109
Hard coal. at mine/RU U	0.0008	0.2805	0.0007	3.5153	0.0010	2.8865	0.0128	3.7877
Bentonite. at mine/DE U	0.0009	0.3373	0.0000	0.1530	0.0005	1.3724	0.0005	0.1381
Natural gas. high pressure. at consumer/RER U	0.0235	8.4697	0.0004	1.8358	0.0289	83.5291	0.2906	85.8746
Electricity/TR	0.0000	0.0003	0.0000	0.0003	0.0000	0.0014	0.0000	0.0009
Sand. at mine/CH U	-0.0005	-0.1765	0.0000	-0.0743	-0.0002	-0.6614	-0.0004	-0.1097
Disposal. inert waste. 5% water. to inert material landfill/CH S	0.0002	0.0006	0.0000	0.0848	0.0001	0.2379	0.0002	0.0463
TOTAL	**0.2776**	**100.0000**	**0.0206**	**100.0000**	**0.0346**	**100.0000**	**0.3385**	**100.0000**

Table D 4. Environmental impact of core and mould production with SSR (Scenario B) – end-point results

Label	**HUMAN HEALTH**		**ECOSYSTEM QUALITY**		**CLIMATE CHANGE**		**RESOURCES**	
	Amount	**%**	**Amount**	**%**	**Amount**	**%**	**Amount**	**%**
Phenol-resorcinol-formaldehyde hardener. at plant/US	0.0003	0.1071	0.0000	0.0322	0.0003	0.9179	0.0037	1.0781
Dimethylamine. at plant/RER U	0.0001	0.0177	0.0000	0.0163	0.0001	0.2606	0.0002	0.0637
Phenol-resorcinol-formaldehyde resin. at plant/US	0.2564	90.3563	0.0199	94.0247	0.0020	5.6349	0.0270	7.8871
Phenolic resin. at plant/RER U	0.0013	0.4593	0.0000	0.2366	0.0020	5.8141	0.0045	1.3202
Sand. at mine/CH U	0.0000	0.0171	0.0000	0.0072	0.0000	0.0644	0.0000	0.0107
Hard coal. at mine/RU U	0.0008	0.2744	0.0007	3.4358	0.0010	2.8395	0.0128	3.7440
Bentonite. at mine/DE U	0.0009	0.3300	0.0000	0.1495	0.0005	1.3500	0.0005	0.1365
Natural gas. high pressure. at consumer/RER U	0.0235	8.2862	0.0004	1.7942	0.0289	82.1684	0.2906	84.8845
Electricity/TR	0.0008	0.2677	0.0001	0.2931	0.0005	1.3669	0.0032	0.9379
Sand. at mine/CH U	-0.0005	-0.1727	0.0000	-0.0726	-0.0002	-0.6507	-0.0004	-0.1085
Disposal. inert waste. 5% water. to inert material landfill/CH S	0.0002	0.0006	0.0000	0.0829	0.0001	0.2341	0.0002	0.0458
TOTAL	**0.2837**	**100.0000**	**0.0211**	**100.0000**	**0.0352**	**100.0000**	**0.3424**	**100.0000**

Table D 5. Environmental impact of core and mould production with SSR (Scenario C) – end-point results

Label	**HUMAN HEALTH**		**ECOSYSTEM QUALITY**		**CLIMATE CHANGE**		**RESOURCES**	
	Amount	**%**	**Amount**	**%**	**Amount**	**%**	**Amount**	**%**
Phenol-resorcinol-formaldehyde hardener. at plant/US	0.0003	0.1061	0.0000	0.0321	0.0003	0.8274	0.0032	0.9646
Dimethylamine. at plant/RER U	0.0000	0.0176	0.0000	0.0162	0.0001	0.2349	0.0002	0.0570
Phenol-resorcinol-formaldehyde resin. at plant/US	0.2243	89.4696	0.0174	93.5757	0.0017	5.0789	0.0236	7.0571
Phenolic resin. at plant/RER U	0.0011	0.4548	0.0000	0.2355	0.0018	5.2405	0.0040	1.1813
Sand. at mine/CH U	0.0000	0.0193	0.0000	0.0082	0.0000	0.0664	0.0000	0.0110
Hard coal. at mine/RU U	0.0008	0.3106	0.0007	3.9089	0.0010	2.9257	0.0128	3.8295
Bentonite. at mine/DE U	0.0009	0.3735	0.0000	0.1701	0.0005	1.3910	0.0005	0.1396
Natural gas. high pressure. at consumer/RER U	0.0235	9.3793	0.0004	2.0413	0.0289	84.6631	0.2906	86.8230
Electricity/TR	0.0000	0.0003	0.0000	0.0003	0.0000	0.0014	0.0000	0.0010
Sand. at mine/CH U	-0.0005	-0.1954	0.0000	-0.0826	-0.0002	-0.6704	-0.0004	-0.1110
Disposal. inert waste. 5% water. to inert material landfill/CH S	0.0002	0.0006	0.0000	0.0943	0.0001	0.2412	0.0002	0.0469
TOTAL	**0.2507**	**100.0000**	**0.0186**	**100.0000**	**0.0342**	**100.0000**	**0.3348**	**100.0000**

Table D 6. Environmental impact of core and mould production with SSR (Scenario D) – end-point results

Label	**HUMAN HEALTH**		**ECOSYSTEM QUALITY**		**CLIMATE CHANGE**		**RESOURCES**	
	Amount	**%**	**Amount**	**%**	**Amount**	**%**	**Amount**	**%**
Phenol-resorcinol-formaldehyde hardener. at plant/US	0.0003	0.1068	0.0000	0.0322	0.0003	0.8794	0.0035	1.0269
Dimethylamine. at plant/RER U	0.0000	0.0177	0.0000	0.0163	0.0001	0.2496	0.0002	0.0607
Phenol-resorcinol-formaldehyde resin. at plant/US	0.2403	90.0683	0.0186	93.9611	0.0019	5.3984	0.0253	7.5124
Phenolic resin. at plant/RER U	0.0012	0.4579	0.0000	0.2365	0.0019	5.5703	0.0042	1.2575
Sand. at mine/CH U	0.0000	0.0182	0.0000	0.0077	0.0000	0.0658	0.0000	0.0109
Hard coal. at mine/RU U	0.0008	0.2918	0.0007	3.6628	0.0010	2.9021	0.0128	3.8043
Bentonite. at mine/DE U	0.0009	0.3509	0.0000	0.1594	0.0005	1.3798	0.0005	0.1387
Natural gas. high pressure. at consumer/RER U	0.0235	8.8115	0.0004	1.9128	0.0289	83.9789	0.2906	86.2514
Electricity/TR	0.0000	0.0003	0.0000	0.0003	0.0000	0.0014	0.0000	0.0010
Sand. at mine/CH U	-0.0005	-0.1836	0.0000	-0.0774	-0.0002	-0.6650	-0.0004	-0.1102
Disposal. inert waste. 5% water. to inert material landfill/CH S	0.0002	0.0006	0.0000	0.0883	0.0001	0.2392	0.0002	0.0465
TOTAL	**0.2668**	**100.0000**	**0.0198**	**100.0000**	**0.0345**	**100.0000**	**0.3370**	**100.0000**

Table D 7. Environmental impact of core and mould production with SSR (Scenario E) – end-point results

Label	**HUMAN HEALTH**		**ECOSYSTEM QUALITY**		**CLIMATE CHANGE**		**RESOURCES**	
	Amount	**%**	**Amount**	**%**	**Amount**	**%**	**Amount**	**%**
Phenol-resorcinol-formaldehyde hardener. at plant/US	0.0002	0.1043	0.0000	0.0317	0.0002	0.7278	0.0028	0.8504
Dimethylamine. at plant/RER U	0.0000	0.0196	0.0000	0.0182	0.0001	0.2347	0.0002	0.0571
Phenol-resorcinol-formaldehyde resin. at plant/US	0.1974	87.9739	0.0153	92.4511	0.0015	4.4676	0.0208	6.2212
Phenolic resin. at plant/RER U	0.0010	0.4472	0.0000	0.2327	0.0016	4.6098	0.0035	1.0414
Sand. at mine/CH U	0.0000	0.0216	0.0000	0.0092	0.0000	0.0663	0.0000	0.0110
Hard coal. at mine/RU U	0.0008	0.3470	0.0007	4.3870	0.0010	2.9235	0.0128	3.8349
Bentonite. at mine/DE U	0.0009	0.4172	0.0000	0.1909	0.0005	1.3899	0.0005	0.1398
Natural gas. high pressure. at consumer/RER U	0.0235	10.4764	0.0004	2.2909	0.0289	84.5982	0.2906	86.9452
Electricity/TR	0.0008	0.3393	0.0001	0.3753	0.0005	1.4111	0.0032	0.9632
Sand. at mine/CH U	-0.0005	-0.2183	0.0000	-0.0927	-0.0002	-0.6699	-0.0004	-0.1111
Disposal. inert waste. 5% water. to inert material landfill/CH S	0.0002	0.0007	0.0000	0.1058	0.0001	0.2410	0.0002	0.0469
TOTAL	**0.2244**	**100.0000**	**0.0165**	**100.0000**	**0.0342**	**100.0000**	**0.3343**	**100.0000**

Table D 8. Environmental impact of core and mould production with SSR (Scenario F) – end-point results

Label	**HUMAN HEALTH**		**ECOSYSTEM QUALITY**		**CLIMATE CHANGE**		**RESOURCES**	
	Amount	**%**	**Amount**	**%**	**Amount**	**%**	**Amount**	**%**
Phenol-resorcinol-formaldehyde hardener. at plant/US	0.0003	0.1058	0.0000	0.0320	0.0003	0.8157	0.0032	0.9553
Dimethylamine. at plant/RER U	0.0000	0.0175	0.0000	0.0162	0.0001	0.2315	0.0002	0.0564
Phenol-resorcinol-formaldehyde resin. at plant/US	0.2242	89.1974	0.0174	93.2636	0.0017	5.0074	0.0236	6.9886
Phenolic resin. at plant/RER U	0.0011	0.4535	0.0000	0.2347	0.0018	5.1667	0.0040	1.1698
Sand. at mine/CH U	0.0000	0.0193	0.0000	0.0081	0.0000	0.0654	0.0000	0.0109
Hard coal. at mine/RU U	0.0008	0.3098	0.0007	3.8968	0.0010	2.8852	0.0128	3.7932
Bentonite. at mine/DE U	0.0009	0.3725	0.0000	0.1696	0.0005	1.3718	0.0005	0.1383
Natural gas. high pressure. at consumer/RER U	0.0235	9.3531	0.0004	2.0350	0.0289	83.4907	0.2906	86.0008
Electricity/TR	0.0008	0.3021	0.0001	0.3324	0.0005	1.3889	0.0032	0.9502
Sand. at mine/CH U	-0.0005	-0.1949	0.0000	-0.0823	-0.0002	-0.6611	-0.0004	-0.1099
Disposal. inert waste. 5% water. to inert material landfill/CH S	0.0002	0.0006	0.0000	0.0940	0.0001	0.2378	0.0002	0.0464
TOTAL	**0.2514**	**100.0000**	**0.0186**	**100.0000**	**0.0347**	**100.0000**	**0.3380**	**100.0000**