Chapter 2
Aluminium Die Casting and Its Environmental Aspects

Against the scope and objectives of the planned research work, this chapter provides the necessary theoretical background about hierarchically organized industrial value chains, the aluminium die casting process, the connected chain of upstream and downstream processes and the resulting challenges for energy as well as resource intensity of die casted products. Therefore this chapter serves as a basis for the later derivation of further research demand in order to increase the energy and resource efficiency of the aluminium die casting value chain.

2.1 Industrial Value Chains and Aluminium Die Casting

The present section introduces the aluminium die casting technology from a technical perspective. As this technology can be viewed as a hierarchically organised production system, corresponding system levels from the process level to the value chain level are introduced before.

2.1.1 Industrial Process, Process- and Value Chains

2.1.1.1 Manufacturing Process

A process is defined as a transformation of inputs of a system to outputs of the same system (Denkena and Tönshoff 2011). This implies that a process can relate to manifold entities at different levels of size and complexity. A manufacturing process therefore is a process within a production system (Dyckhoff and Spengler 2007). This specific process uses and transforms inputs like operating resources, human labour, physical materials, etc. into valuable outputs (wanted products) and non-valuable outputs (not wanted products, emissions and waste) (see Fig. 2.1; Schenk et al. 2014).

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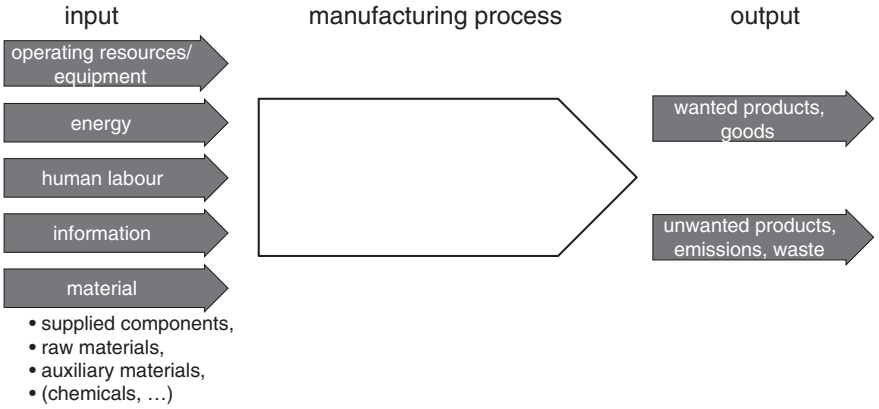

Fig. 2.1 The manufacturing process as a transformation process (according to Schenk et al. 2014)

2.1.1.2 Process Chains

The term process chain can be found in literature in manifold contexts e.g. in business administration, natural sciences as well as engineering sciences like production engineering. Even within these disciplines this term can have different meanings. In production engineering the term process chains is used to describe the following subjects (Schäfer 2003):

- interlinked product life cycle phases
- combination of logistical handling, transportation and storage processes
- linkage of design phases in the product creation process
- integrated usage of harmonised data formats and data sets for information and data processing in product design, manufacturing, production planning and quality assurance
- sequence of manufacturing processes in manufacturing engineering

The further discussion will be based on the last mentioned interpretation of the term process chain, whereas the energy and resource consumption of interlinked sequences of manufacturing processes will be especially considered. To enrich this perspective, also some aspects from a logistical perspective on process chains will be incorporated as well as supporting peripheral activities, which provide defined conditions for the considered manufacturing processes.

Therefore, the process chain in production engineering describes a sequence of value adding manufacturing processes as well as auxiliary processes (e.g., handling and transportation) and peripheral processes, which are coupled through a common material flow. The sequence of value adding processes transforms the condition of input materials from an initial state to a predefined final state (Eichgrün 2003; Reinhardt 2013; see Fig. 2.2).

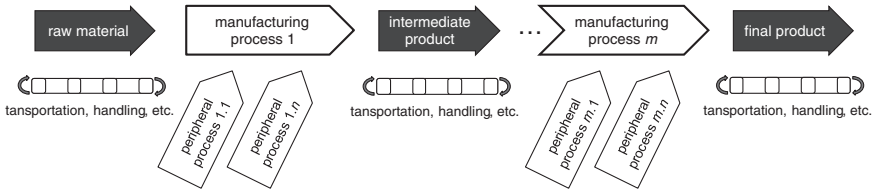

Fig. 2.2 Simplified manufacturing process chain with auxiliary and peripheral processes

2.1.1.3 Industrial Value Chains

Production is a value adding process (see Fig. 2.3). Value gets created in every process chain that transforms simple or complex parts or materials into more valuable goods (Günther and Tempelmeier 2012).

In our modern and globalized world not all of the necessary processes are performed at one single place and within one single enterprise. Rather an increasing (international) division of labour in order to generate value can be observed. The single (globally) distributed entities, which include and control an own internal manufacturing process chain, collaborate to produce final products and generate value. They constitute a value chain (Günther and Tempelmeier 2012; Westkämper and Warnecke 2010). Therefore, from a production engineering perspective an industrial value chain can be perceived as a cross company network, which integrates several intra-company process chains (see Fig. 2.4).

The understanding of industrial value chains shall provide the perspective, from which the aluminium die casting value chain will be observed in the following section. Nevertheless, it has to be stated that there are several other perspectives and definitions for value chains, especially in business sciences and micro economics. Here a value chain usually describes also business processes in combination with production processes, which are needed to satisfy a customer's need—starting from the expression of the customer's need along the whole internal order fulfilment process until the delivery of the service or good to the customer and the booking of the incoming money transfer from the customer. These processes can be distinguished into primary and supporting processes (Porter 2010).

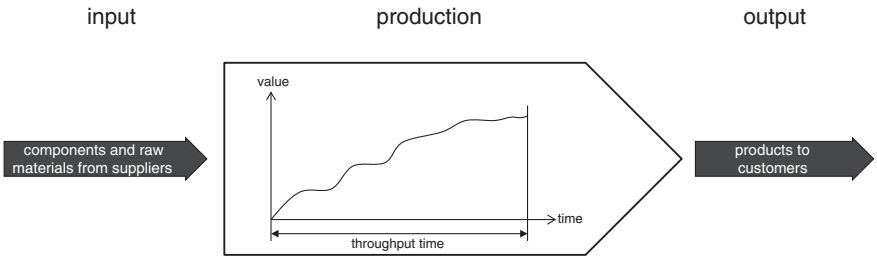

Fig. 2.3 Production as value adding process (Westkämper and Warnecke 2010)

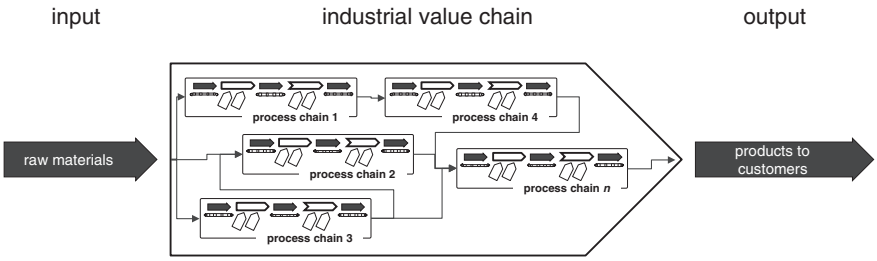

Fig. 2.4 Industrial cross-company value chain from a production engineering perspective

However, the basic principle of this perspective focuses on the sequential steps within the transformation process, which a product or service passes through—from the input material to the final product (Finkeißen 1999; Porter 2010). Therefore, this basic principle harmonizes both, the production engineering perspective as well as the microeconomic perspective on value chains.

2.1.1.4 Vertical and Horizontal Hierarchies Within Industrial Value Chains

As denoted above, industrial value chains describe networks or systems with manifold internal sub-systems. These systems can be in a vertical or hierarchical correlation to each other, which will be exemplarily described in the following section.

Vertical Hierarchies

There are manifold levels in industrial value chains which can be in a vertical hierarchical relationship to each other. This means that every system element within an industrial value chain can be part of a super-system and can contain sub-systems itself (Herrmann 2010).

Figure 2.5 exemplarily shows two attempts to classify possible hierarchical levels in industrial value chains. Herrmann et al. visualise the supply chains, factory buildings and machines as hierarchically arranged subsystems with detailed internal interrelationships, focussing on the energy related input and output flows on each hierarchical level (see Fig. 2.5a; Herrmann et al. 2010a). In contrast to this detailed system understanding Wiendahl focuses on a hierarchical order of the elements of a network introducing a common terminology for each level (see Fig. 2.5b; Wiendahl 2009).

Denkena and Tönshoff link the phrases process, process chain element and process chain into an own hierarchical order. Thereby they increase the granularity of hierarchical levels in manufacturing at a very detailed and intra-company level of the value chain. According to the presented model a process is the smallest and inseparable unit of a manufacturing system, which transforms inputs into outputs. A process chain element is a sequence of such processes and cannot contain parallel processes.

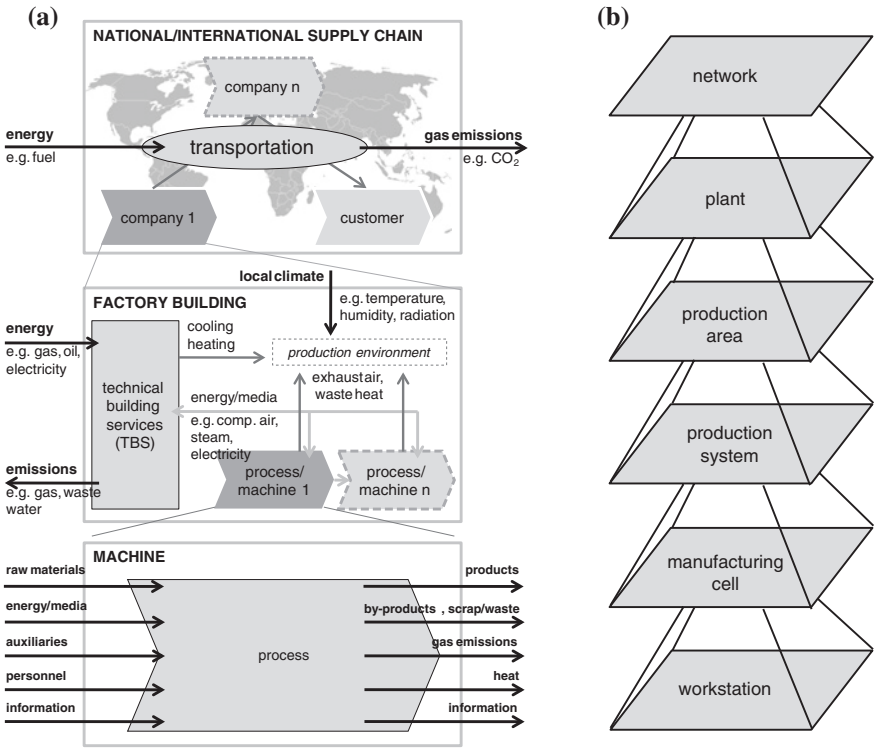

Fig. 2.5 Different (*vertical*) hierarchical levels of industrial value chains (Herrmann et al. 2010a; Wiendahl 2009; see also Heinemann et al. 2014)

The phrase process chain element can be used synonymously to the phrase process element, which describes, e.g., the processing of a work piece inside a machine tool. According to Denkena and Tönshoff the linkage of several process chain elements describes a process chain, which can contain sequential as well as parallel formations of process chain elements (see Fig. 2.6; Denkena and Tönshoff 2011).

Duflou et al. as well as Reich-Weiser et al. respect both presented perspectives (hierarchical order as well as system interdependencies) and state that the following granularity of system levels as well as the complex and individual energy and resource flows of every level need to be considered to evaluate the energy and resource efficiency as well as environmental impacts of manufacturing systems such as industrial value chains (Duflou et al. 2012; Reich-Weiser et al. 2010):

- device/unit process
- line/cell/multi-machine system
- facility
- multi-factory system
- enterprise/global supply chain

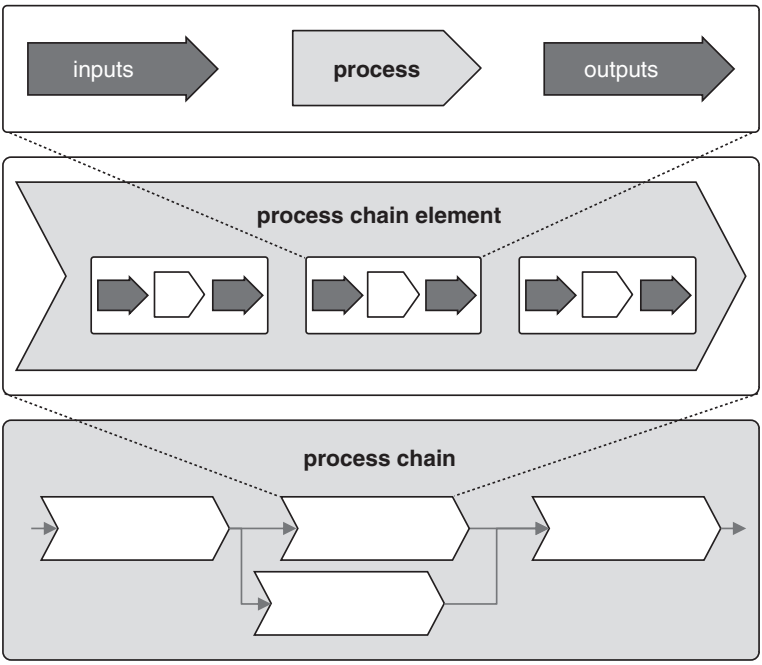

Fig. 2.6 Hierarchical order of processes, process chain elements and process chains (Denkena and Tönshoff 2011)

A similar perspective is taken by Verl et al. The authors consider multiple levels of a value chain as a conglomeration of various control loops that need to be managed to reduce the energy consumption of a manufacturing facility. Thus, every entity of a hierarchical level of a value chain depends on plans and constraints from a superior system element. These plans and constraints, which are determined by a system element, should consider energy cause models of the inferior system elements (see Fig. 2.7; Verl et al. 2011).

According to the introduced choices of the granularity of vertical manufacturing system levels, the specific aluminium die casting value chain will be introduced at the levels of the die casting process, the process chain (within the facilities of a foundry and an alloy supplier) and the cross-company die casting value chain—starting at Sect. 2.1.2.

Horizontal Hierarchies

Besides the vertical hierarchies in industrial value chains, there can be horizontal hierarchies between the single entities on a common hierarchical system level. These horizontal hierarchies can be expressed in a peripheral order of system elements (Müller 2009; Schenk et al. 2914).

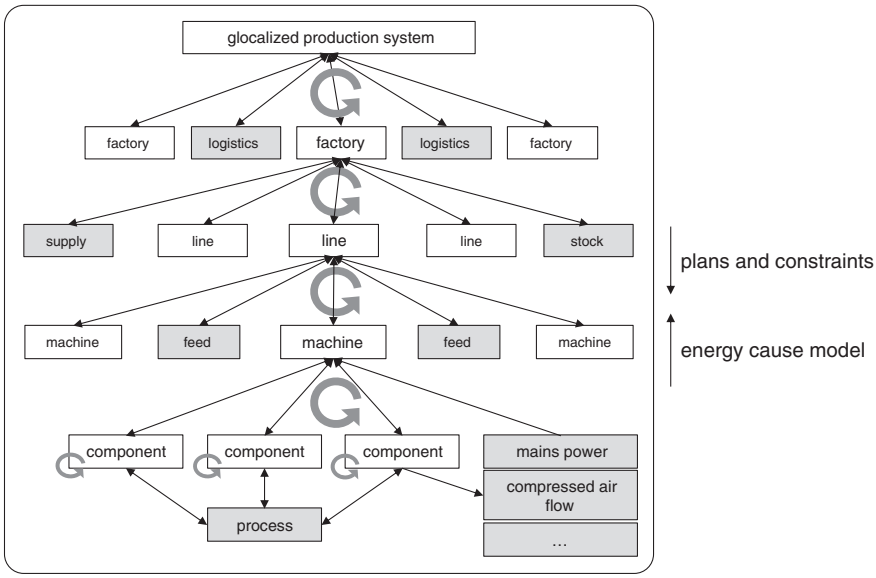

Fig. 2.7 Energy control loops in hierarchically structured value chains (Verl et al. 2011)

According to this peripheral order, the system elements within manufacturing systems are clustered into main processes and supporting processes in the first, second and third periphery. The assignment of processes into one of these four clusters happens according to their individual importance for the production of a predefined range of products (see Fig. 2.8; Schenk et al. 2014):

- Main processes are in the centre of this horizontally hierarchical model. They represent the value adding production machines.
- Processes of the 1st periphery represent processes, which are directly dependent from the main processes and the range of products (e.g. quality assurance).
- Processes of the 2nd periphery do not depend on the range of products, but on the main process (e.g. maintenance).
- Processes of the 3rd periphery represent processes, which are not dependent from the main process. Usually administrative processes and equipment from the staff rooms can be subsumed under this cluster.

The individual importance for the production of a predefined range of products often gives a hint about the degree to which the respective process contributes to the value adding of the value chain. Posselt et al. used a combination of the peripheral order and the degree of value adding of processes to generate rules for a pragmatic and cause-dependent allocation of energy consumption of peripheral processes to multi-product energy value streams (Posselt et al. 2014).

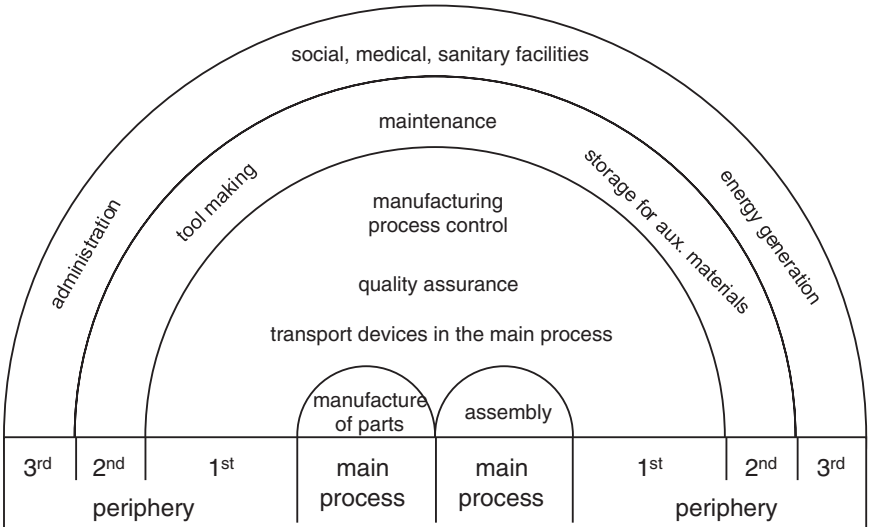

Fig. 2.8 Peripheral order of manufacturing's subsystems (Schenk et al. 2014)

Thiede highlights the importance of a holistic definition of factories to derive and evaluate measures for improving their energy efficiency. He horizontally divides the factory into the following three interacting subsystems, which together result in a complex control system (see Fig. 2.9; Thiede 2012):

- production (machines and employees, coordinated by production planning and control)
- technical building services (ensuring the required production conditions in terms of temperature, moisture and purity through cooling, heating and conditioning of the air)
- building shell (physically separating the internal value chain from the environment)

Manifold further differentiations for possible horizontally hierarchical clusters of manufacturing system elements can be imaginable. However, following the aforementioned ideas, it is necessary to respect the (often dynamic) interdependencies and interaction of value adding and not directly value adding processes at every level of abstraction of value chains.

This is especially true when, e.g., the energy demand of value adding and not directly value adding processes are compared. Using the example of an aluminium die casting cell, only about one third of the energy demand is determined by the die casting machine itself, while two thirds of the energy demand are caused by peripheral and not value adding processes (Hoffmann and Jordi 2013a).

Such effects need to be considered when the overall energy and resource efficiency of industrial production shall be improved towards a more resource efficient production of goods. Therefore, as a further groundwork, the following sections provide a technical insight in the aluminium die casting technology and

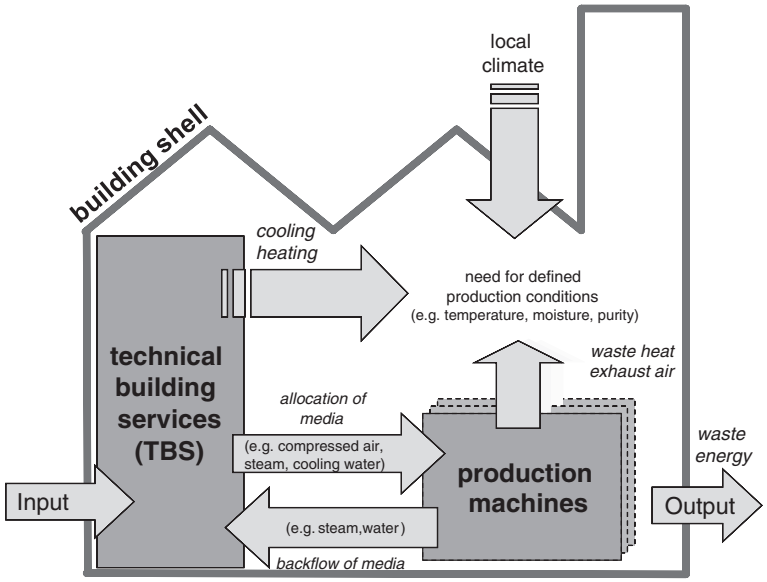

Fig. 2.9 Holistic definition of a factory (Thiede 2012)

its hierarchical system elements. Having this technical description in mind, also a necessary definition of energy and resource efficiency will be given, followed by a brief introduction of existing methodological support for their improvement. Subsequently, a deeper insight in the environmental challenges of the aluminium die casting technology will be provided.

2.1.2 Aluminium Die Casting

In this section the aluminium die casting technology is introduced based on the preceding conception of hierarchically organized industrial value chains, which can constitute different system levels of an industrial network. This technology also forms a corresponding hierarchically organized value chain (see Fig. 2.10; Heinemann et al. 2012). After an identification of the aluminium die casting value chain within the system of global aluminium flows and an overview over the German aluminium production volumes, the single steps of the value chain will be introduced in sequence. As a starting point of the value chain description, a broad perspective is taken, and the necessary activities for the generation and classification of the required raw materials from pure (primary) metals to recycled (secondary) metal products get introduced. These input flows are processed to alloyed aluminium ingots by the internal process chain of the alloy supplier (aluminium recycling company and smelting works). Its linkage to the foundry within the

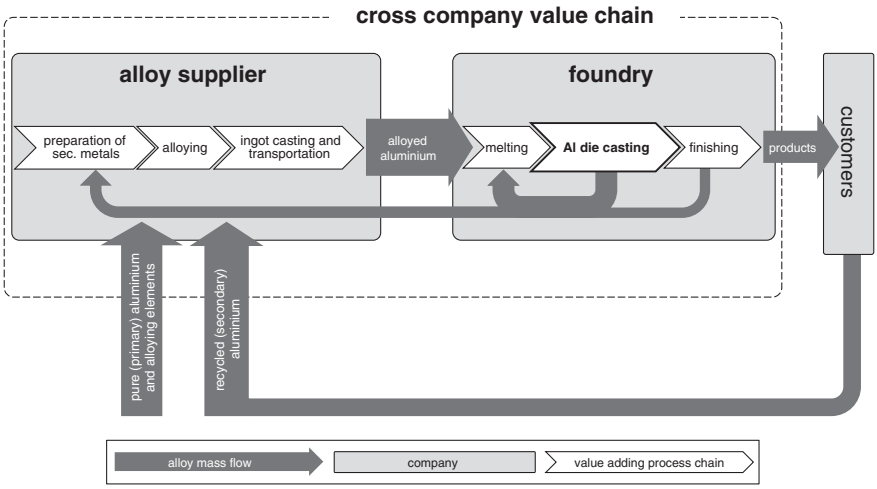

Fig. 2.10 Basic structure of the hierarchical aluminium die casting value chain (process sequence and alloy mass flow) (see also Heinemann et al. 2012)

cross company value chain is described through a brief overview over alloy transportation scenarios. The delivered ingots are transformed into final products by the internal process chain of the foundry. It also incorporates the die casting process itself, which has been classified before. This process gets further described from a technical perspective as closing point to this section.

2.1.2.1 Classification of the Aluminium Die Casting Process

Manufacturing technology is vital for the creation of products with defined shapes and characteristic. As manufacturing technology is manifold, the manufacturing processes can be divided into six main groups according to their main principal of manipulating the product's nature (Grote and Antonsson 2009). The DIN 8580 standard defines and divides all manufacturing processes (see Fig. 2.11) (DIN 8580 2003).

Amongst these main groups of manufacturing processes the main group of primary shaping can be further divided into seven sub groups according to the initial material state (see Fig. 2.12) (DIN 8580 2003; de Ciurana 2008).

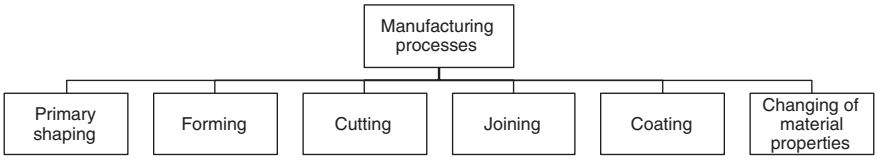

Fig. 2.11 Classification of manufacturing processes (main groups) (DIN 8580 2003)

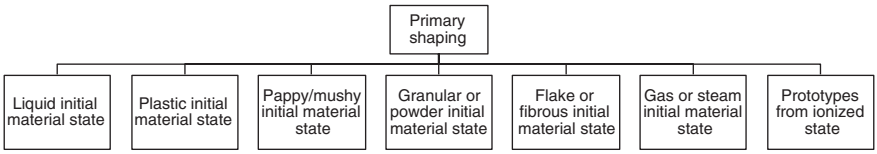

Fig. 2.12 Sub groups of the manufacturing process primary shaping (DIN 8580 2003; de Ciurana 2008)

Contrary to the other main groups of manufacturing processes, the group of primary shaping processes carries the ability to create most of the final products shape, characteristics and features with one single, integrated process step and only demands for some minor further treatment to add extra features or special qualities functional surfaces (Bühring-Polaczek 2014).

This ability leads to a high degree of material efficiency, and a relatively low energy intensity of this group of manufacturing processes compared to other main groups of manufacturing processes. Figure 2.13 illustrates this advantage by comparing the material efficiency and energy intensity of selected manufacturing processes out of the main groups primary shaping, forming and cutting (Fritz and Schulze 2010).

One representative example for such an advantageous process is the high pressure die casting (HPDC) process, which belongs to the sub group of "primary shaping from liquid initial state" (see Fig. 2.14) (DIN 8580 2003).

High pressure die casting is the most important casting process for non-ferrous metals (Westkämper and Warnecke 2010). It usually processes alloys which are based on the following metals (Brunhuber 1980):

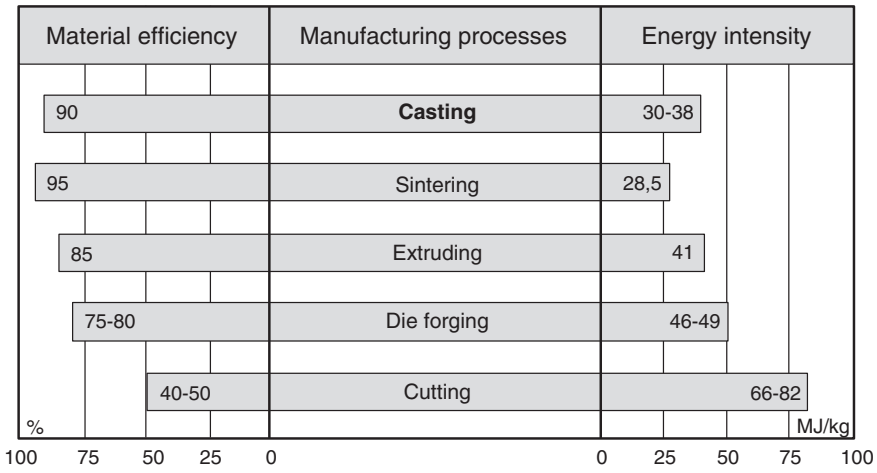

Fig. 2.13 Material efficiency and energy intensity of selected manufacturing processes (Fritz and Schulze 2010)

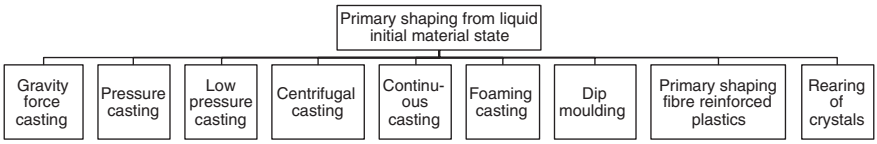

Fig. 2.14 Division of the main group primary shaping (DIN 8580 2003)

- aluminium
- zinc
- magnesium
- copper

However, most of the pressure die casted volumes in Germany are based on aluminium alloys (WirtschaftsVereinigung Metalle 2012). Aluminium die casting alloys distinguish themselves by a very good castability (for complex and thin-walled product geometries), a very good machinability, good resistance to atmospheric corrosion (especially aluminium-silicon alloys) as well as a low aggressiveness against the iron-based dies (Brunhuber 1980; Jochem et al. 2004).

Besides the possibility to create a high number of the final product's functions and characteristics within one fast and integrated process step, the high pressure die casting especially of aluminium parts delivers a wide range of further advantages, which distinguish this process from other manufacturing processes (see Table 2.1).

Besides the aforementioned advantages of the high pressure die casting process some disadvantages have to be taken into account. Table 2.2 delivers a small list of

Table 2.1 Selected advantages of the (aluminium) high pressure die casting process (Rockenschaub 2014; Pithan 2013a; Kalweit et al. 2012; Westkämper and Warnecke 2010)

Economic advantages	High degree of automation, whereas downstream processes—e.g. mechanical treatment—can be directly linked to the automated casting cell
	High productivity, and therefore good applicability, in the automotive parts industry
	High productive capacity
	High profitability as a result from the high degree of automation and productivity
Technological advantages	High dimensional accuracy
	Castability of complex geometries and small wall thicknesses
	Short cycle times
	Very good quality of the structural composition and microstructure of the casted metal
	Smooth cast surfaces
	Composite designs through integrally casted materials are possible
	Near net shape casting and low demand for further mechanical treatment

Table 2.2 Selected disadvantages of the (aluminium) high pressure die casting process (Rockenschaub 2014; Pithan 2013a; Westkämper and Warnecke 2010)

Economic disadvantages	High initial costs for tools (dies) and die casting machines
	High costs for tool replacements due to the high tool costs and cost intensive breakdown times
	Not profitable for small lot sizes
Technological disadvantages	Limited design options
	Danger of porosities due to air entrapments, which decrease the strength value and breaking strain
	High thermal and mechanical stress of the expensive dies
	Limited applicability for welding processes
	Limited applicability for heat treatment

economic as well as technological disadvantages which create a demand for a further development of the high pressure die casting process (Pithan 2013).

As the advantages of the aluminium high pressure die casting technology outbalance the disadvantages for many application scenarios, this technology (like many other casting technologies and aluminium products) has found its way into practical application very successfully. Therefore, the following section gives an overview over the system of global aluminium flows and identifies the aluminium die casting value chain within. The following section also quantifies the general German aluminium production volumes, the distribution of aluminium products over application areas and the German aluminium die casting production volumes to highlight the special relevance of this industry.

2.1.2.2 Global Aluminium Flows and German Aluminium Production Volumes

The environmental relevance of industrial value chains like the aluminium die casting value chain always has to be considered in a global context and regarding the life cycle of the manufactured products. By taking such a broad perspective, industrial value chains appear to be embedded in extensive material flow networks, in which manifold value chains are interlinked and diverse material flows are commuting between the single value chain systems.

However, not many complete maps of global material flows for selected materials are available. Therefore Allwood and Cullen have striven to map the flows of selected materials along their entire life cycle and including also flows of cycle material (Allwood and Cullen 2012). The total global aluminium flows for the year 2007 are shown in Fig. 2.15 (Cullen and Allwood 2012). This figure also identifies the aluminium die casting value chain within the system of global aluminium flows.

Aspects like the effects of bad material efficiency on cycle material volumes, energy intensive post industrial scrap as well as aluminium recycling cascades, which will correlate directly to the absolute material volumes, can already be perceived from the flow visualisation of Cullen and Allwood. Thus, even more aluminium

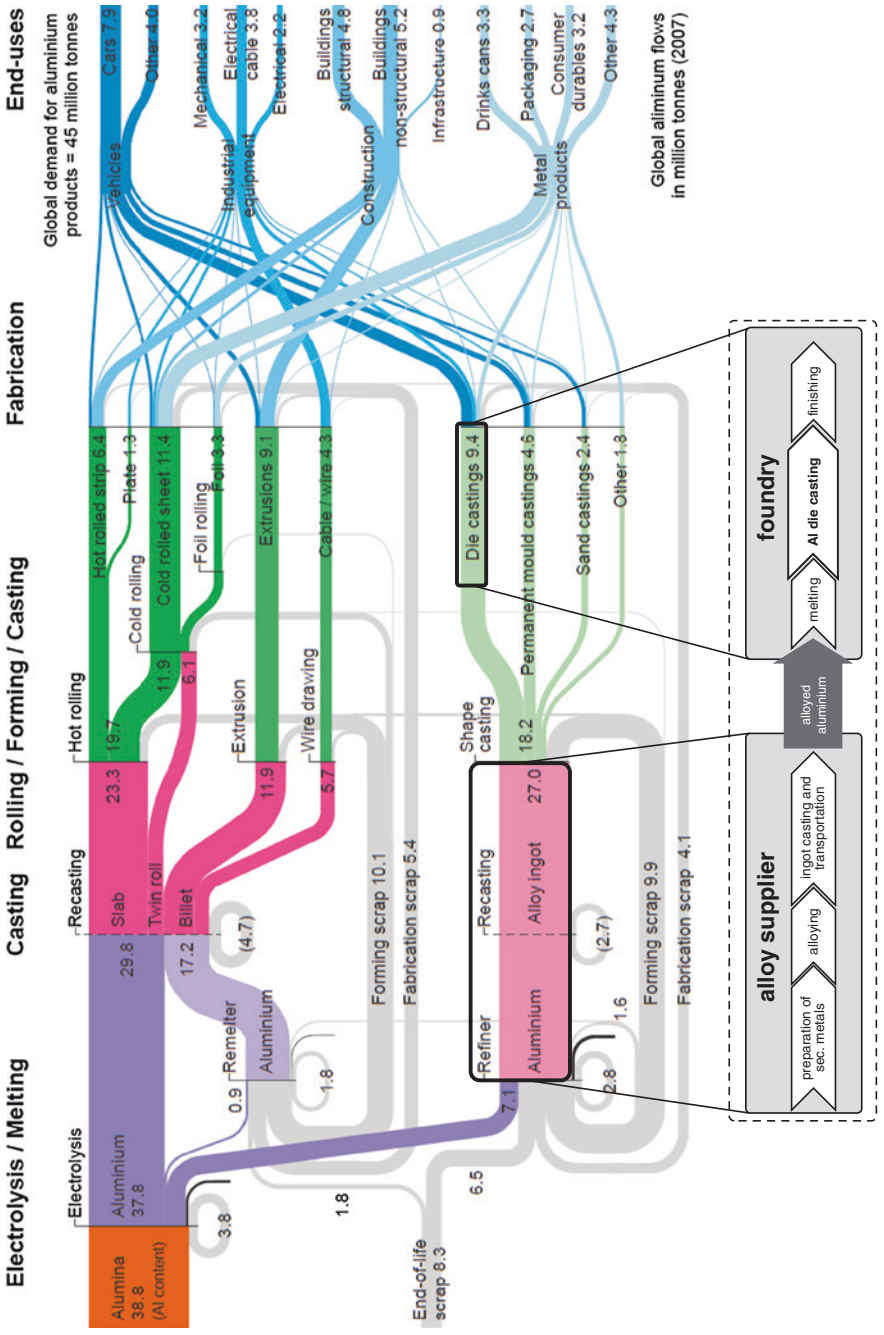

Fig. 2.15 Sankey diagram, tracing the global flow of aluminium and localising the aluminium die casting value chain (adapted from Cullen and Allwood 2013)

(55.2 Mt) is processed as cycle material than the total global demand of aluminium products (45 Mt). Furthermore, cycle material from forming scrap from ingot casting operations (9.9 Mt) incorporates even more material than the total aluminium die casting production output. According to Cullen and Allwood 9.4 Mt of die casted products have been delivered to customers in the year 2007. The majority of these products have been placed in vehicles (mainly cars). With this volume of produced parts, the aluminium die casting industry produces 51.6 % of the global shape castings (18.2 Mt) and about 20.1 % of the total global demand of aluminium products.

Although aluminium die casted parts are mainly based on secondary aluminium alloys still ca. 26 % of the aluminium, which gets processed by the alloy supplier in the aluminium die casting value chain (refiner and recasting) is primary aluminium. It is used for primary aluminium based alloys or for the dilution of secondary aluminium alloys (see also Sect. 2.2.3). The other 74 % of input material for the alloy supplier is scrap aluminium (19.9 Mt) whereas only about one third of these inputs come from end-of-life scrap (6.5 Mt). About two thirds of the alloy supplier's input material comes from post industrial scrap. These figures again point out the potential of better material efficiency and recycling processes in aluminium value chains (Cullen and Allwood 2012).

The same is true for the total global aluminium flows. Around half of all liquid aluminium (ca. 39 Mt) never enters a use-phase as a final product but stays in the aluminium system as cycle material. The resulting aluminium recycling, which basically is favourable as it substitutes high energy costs and emissions from primary aluminium production, requires ca. 8 Mt of primary aluminium for dilution and ca. 6 Mt of high quality aluminium alloys to substitute in-use-stocks of non-recycled aluminium, which are not available for secondary aluminium alloy production (Cullen and Allwood 2013).

However, the introduced global flows of aluminium are not fixed as is shown in Fig. 2.15. By now the global aluminium demand has increased 30-fold since 1950, and will reach two to three times today's level by 2050. Today's aluminium production uses 3.5 % of the global electricity and causes 1 % of the global CO_2 emissions. This development would make it necessary to achieve an 85 % reduction of the CO_2 emissions per tonne of aluminium if a global CO_2 emission reduction of 50 % is aimed for (Cullen and Allwood 2013).

Analyzing the production data of the German aluminium industry from the earlier past reveals that energy intensive primary aluminium production volumes have increased in the year 2013 after a continuous decrease in 2012. Secondary aluminium production volumes are still larger than primary aluminium production volumes, but are decreasing and have reached nearly the production level of primary aluminium (see Fig. 2.16; Trimet Aluminium AG 2013, 2014).

Both trends (increasing primary aluminium production and decreasing secondary aluminium production) seem to continue (see Fig. 2.17; Trimet Aluminium AG 2013, 2014).

The structure of the aluminium product demand and its distribution over application areas in Germany appears to be similar to the global distribution of products, which Cullen and Allwood have visualised. The transportation sector is

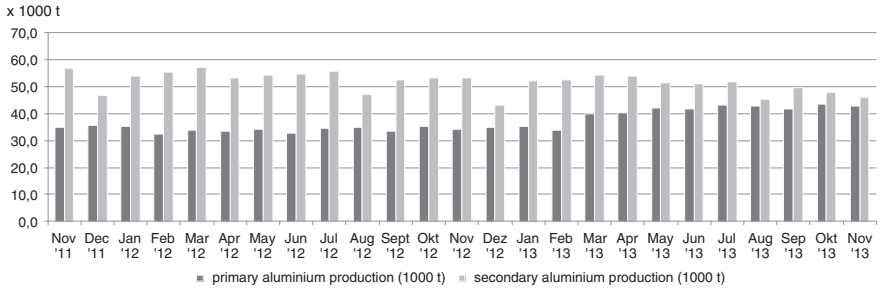

Fig. 2.16 Production output of the German aluminium industry (primary and secondary aluminium production) (Trimet Aluminium AG 2013, 2014)

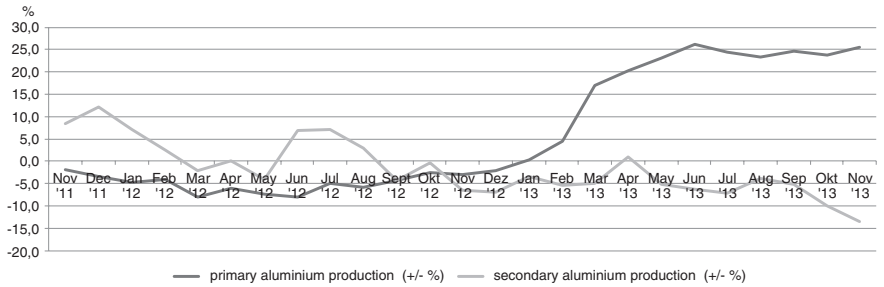

Fig. 2.17 Production volume changes of the German aluminium industry (increase/decrease of the primary and secondary aluminium production compared to the respective month of the previous year) (Trimet Aluminium AG 2013, 2014)

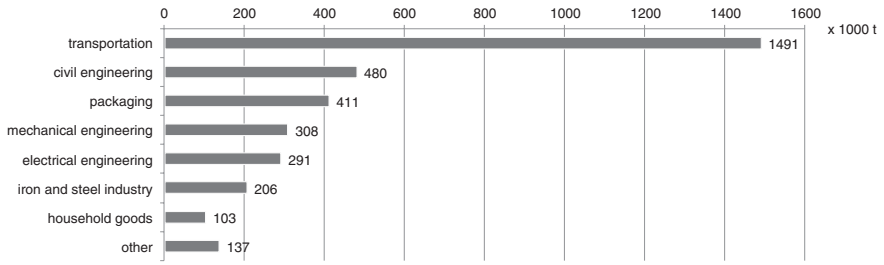

Fig. 2.18 Distribution of aluminium products over application areas in Germany in 2012 (statista.com 2014)

responsible for most of the aluminium demand in Germany as well. It represents a demand of 1.491 Mt (see Fig. 2.18; statista.com 2014; Cullen and Allwood 2012).

The output of the German aluminium die casting industry (ca. 432,400 t) represents a share of ca. 13 % of the German aluminium product demand (ca. 3,427,000 t). Its production volume is stable in recent years with respect to a

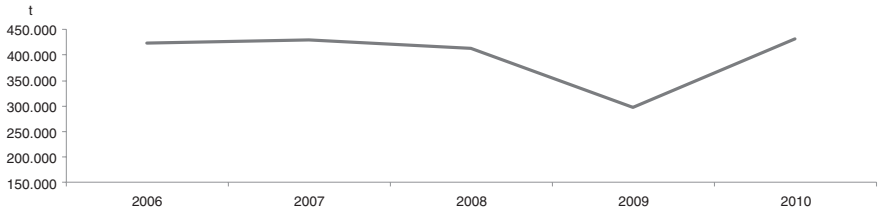

Fig. 2.19 Aluminium die casting production volumes in Germany (aluminium-recycling.com 2014)

weak production period during the heaviest year of the European economic crisis in 2009 (see Fig. 2.19; aluminium-recycling.com 2014; statista.com 2014).

After this introduction of global aluminium flows and German aluminium production volumes, the specific aluminium die casting value chain will be described in the following sections—starting with the introduction of raw material and secondary material input flows.

2.1.2.3 Raw and Secondary Material Input Flows

Due to the fact that the aluminium die casting value chain has to rely on further upstream activities, which provide it with input materials and have an impact on the performance of the overall value chain, this section provides an overview over the raw and secondary material input flows like the generation of primary aluminium and the processed secondary aluminium fractions. Figure 2.20 illustrates these important material flows (in dark grey) and their circular flow in the aluminium die casting value chain.

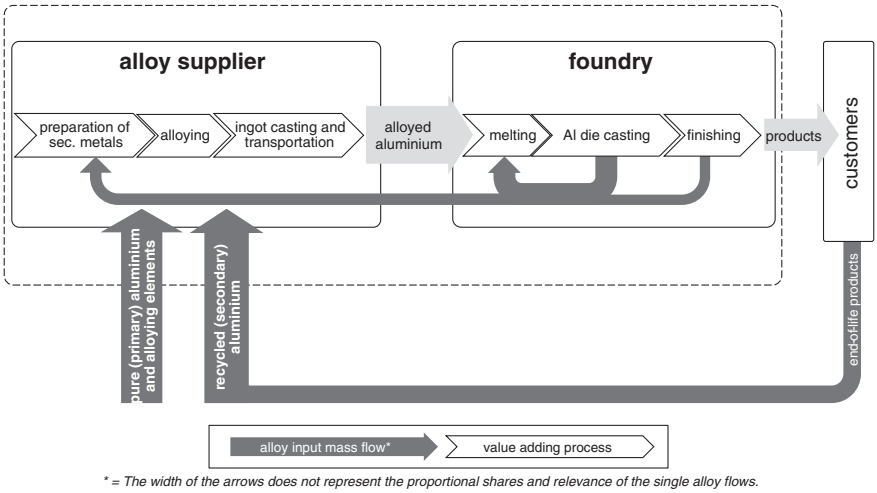

Fig. 2.20 Raw and secondary material input flows (in *dark grey*) of the aluminium die casting value chain

Primary Aluminium Production

Aluminium is a very electronegative metal, which means that its natural manifestation can only be found in chemical compounds, e.g., in oxidic or siliceous minerals. This makes chemical processing necessary to extract the pure aluminium. After the testing of some alternative technologies for the production of primary aluminium over the last decades, the following process sequence has come out to be the only one with industrial relevance along the worldwide aluminium industry: (1) bauxite mining, (2) Bayer process, (3) fused salt electrolysis (Kammer 2012a; Quinkertz 2002). Figure 2.21 visualises the process sequence and basic input flows for electrolytic production of primary aluminium.

The raw material for this process sequence is bauxite. Bauxite is an ore, which incorporates a conglomeration of diverse, mostly aluminium containing minerals such as hydrargillite (Al_2O_3), kaolinite ($Al_2Si_2O_5(OH)_4$), boehmite (AlO(OH)) and diaspore (AlO(OH)). Other iron, silicon, titanium or calcium based minerals need to be separated from the bauxite during the first step of the Bayer process (Quinkertz 2002; Kammer 2012a).

The Bayer process starts with a milling of the bauxite and the addition of sodium hydroxide at a temperature level of 100–360 °C. During this process the aluminium hydroxides dissolve in the sodium hydroxide and generate aluminate while other contaminating compounds precipitate without being dissolved. The conglomeration of these precipitated compounds is usually known as red mud and needs to be landfilled. When the aluminate brine cools down and seed crystals are added the pure aluminium hydroxide precipitates (Kammer 2012a; Dienhart 2003).

In a second step the extracted aluminium hydroxide gets dehydrated (calcinated) by adding thermal energy via rotary furnaces at a temperature level of 1000–1300 °C.

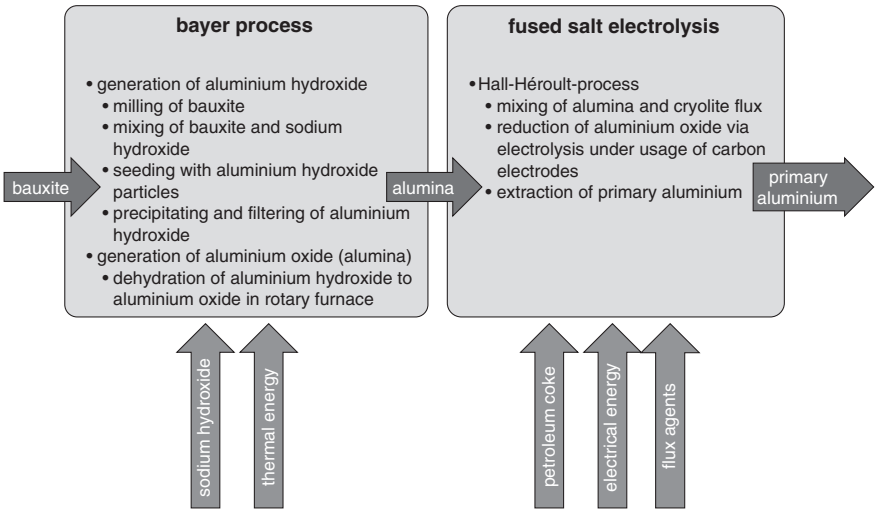

Fig. 2.21 Input flows and process sequence for electrolytic primary aluminium production (Kammer 2012a)

This process creates technically pure aluminium oxide with only negligible contaminations of other oxides (Kammer 2012a; Dienhart 2003).

This pure aluminium oxide can be further processed in a fused salt electrolysis according to the Hault-Héroult-process. The basis for this electrolysis is a solution of the aluminium oxide in liquid cryolite, which decreases the melting temperature of the aluminium oxides from ca. 2050 °C down to ca. 963 °C. By adding further flux agents the electrolysis can be done at a temperature level of about 950–980 °C. The concentration of aluminium oxides in the flux is at about 2 %. As carbon electrodes (out of petroleum coke) are used during the electrolysis, the anode gets corroded by emitting carbon monoxide and carbon dioxide. At the cathode at the bottom of the electrolysis cell pure aluminium gets produced which gets extracted by suction periodically and can be casted to ingots afterwards (Kammer 2012a).

Secondary Aluminium Input Fractions

The main input material for die casting alloys is scrap aluminium. Scrap aluminium can be collected from manifold sources at different qualities. The main scrap aluminium fractions can be distinguished as follows:

- post industrial scrap (gating systems, production waste, etc.)
- capital scrap (end-of-life products)
- dross (oxide skins from liquid alloys in melting or holding furnace)
- swarf (metal chips from mechanical treatment)
- aluminium foils, packaging materials, etc. from municipal waste separation and collection systems

Post-industrial scrap usually stands for relatively clean aluminium waste from foundries or smelting works, which does not enter a use-phase as a product, but can be resmelted directly after the production. Minor contaminations can come from coatings or oxides. The recycling rate of these scrap aluminium fractions is at nearly 100 % (Kammer 2012b; Boin et al. 2000; Kirchner 1989).

Capital scrap describes aluminium products after their use-phase, which have been collected as secondary aluminium fractions. Depending on their individual use case, these end-of-life-products usually are contaminated with paints, lubricants, sealings, other material compounds, etc. The recycling rates of these fractions regarding the contained aluminium vary between 80 and 90 % (Kammer 2012b; Boin et al. 2000; Kirchner 1989).

Dross arises through the oxidation of alloys at the surface of the molten metal mass. These oxides get skimmed from the molten metal mass and therefore can contain 80 % of pure alloy as well. As the contained amounts of liquid alloy tend to further oxidation, the dross often gets covered with salt after the skimming or already inside the melting or holding furnace (Boin et al. 2000; Krone 2000).

Swarf is a post-industrial waste as well, and arises directly during the production phase of the final aluminium product while certain product functionalities are realized through chip removing manufacturing processes. It gets considered as a separate fraction of scrap aluminium due to its disadvantageous ratio of surface

to mass, which makes compressing activities necessary to prevent the swarf from burning during the melting (Boin et al. 2000).

Aluminium foils, packaging materials, etc. from municipal waste separation and collection systems (e.g., the German Duales System Deutschland) belong to the group of capital scrap but form a separate fraction of aluminium scrap due to their huge variation of contained alloys and usually strong contamination (Krone 2000).

The development of the single scrap aluminium fractions' total shares and how they are used in Germany to produce secondary aluminium alloys over the last decades allows the prognosis, that the share of post-industrial scrap in the German alloy production will decrease and the share of capital scrap will increase. This is due to improving scrap metal collection systems in Germany as well as due to increasing demands for post-industrial scrap in newly industrialising countries and in countries which do not operate their own production of primary aluminium like Japan (Boin et al. 2000).

The increasing share of capital scrap forces the German producers of secondary aluminium alloys to question their production equipment (esp. furnaces) as the efficiency and technical feasibility of the installed furnaces depends strongly on the quality and contamination of the inserted scrap aluminium (Boin et al. 2000).

The following section will introduce the process chain of an alloy supplier, which is a producer of secondary aluminium alloys and uses the above introduced raw and secondary material input flows for the generation of aluminium die casting alloys.

2.1.2.4 Process Chain of an Alloy Supplier

Since the later-developed concept shall serve as general guidance for producing companies in the manufacturing industry, the internal process chain of an alloy supplier (aluminium smelting works) will also be considered in detail. This will offer the opportunity to take an important cross company perspective, and evaluate and compare company specific measures which unfold their potential as a lever for upstream or downstream companies.

Assuming that all necessary mechanical treatments and finishing of the die casted part get done inside the foundry, there is only the upstream process chain of the alloy supplier in addition to the raw material generation, which complements the company spanning aluminium die casting value chain (see Fig. 2.22).

The usage of alloys, which are based on recycled (secondary) aluminium that get refined with pure (primary) aluminium as well as other alloying elements, is of major importance in the aluminium casting industry (see exemplarily for the German aluminium die casting industry: GDA 2014). Therefore the considered alloy supplier does not produce the pure aluminium itself, but acts as a smelting works, which combines the required input materials (pure and recycled metals) into the required alloy. Furthermore the alloy supplier focuses on casting alloys which get produced through the refinement of scrap metal inputs and can contain up to 12 % alloying elements (Cullen and Allwood 2013; UNEP 2011b; Rombach 2004; Schucht 1999). The high share of possible alloying elements in casting alloys enables the usage of manifold secondary metal fractions from various sources (see previous paragraphs). Wrought alloys for rolled and extruded

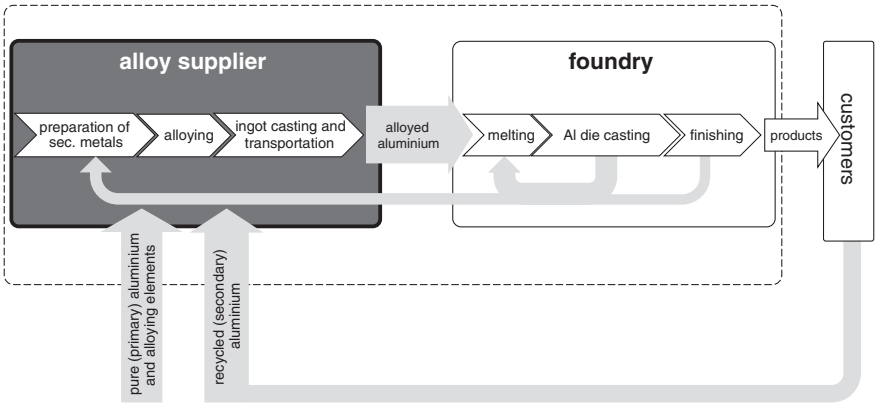

Fig. 2.22 The process chain of an alloy supplier within the aluminium die casting value chain

products that are produced through the remelting of very pure secondary metal inputs are not considered. These alloys must not contain more than 2 % of alloying elements, and therefore are not suitable to be produced through the refinement of scrap metal inputs (Schmitz 2006; Rombach 2004; Schucht 1999).

The process chain of an alloy supplier can be described as a set of activities or interlinked sub-processes similar to the later described foundry. Suppliers of secondary aluminium alloys run the following value adding activities, which are mandatory to combine different kinds of recycling inputs (scrap material and end-of-life products) from different sources and at different qualities (Schmitz 2006a, c):

- preparation of secondary materials and melting of scrap metal inputs
- alloying (setting of alloy characteristics by adding the individual amounts of alloying elements)
- ingot casting and transportation

Figure 2.23 illustrates the sequence of these main activities and their sub-processes as well as the value adding alloy mass flow through the foundry.

Input materials for the production of secondary aluminium casting alloys can be secondary material fractions from manifold sources like end-of-life-products,

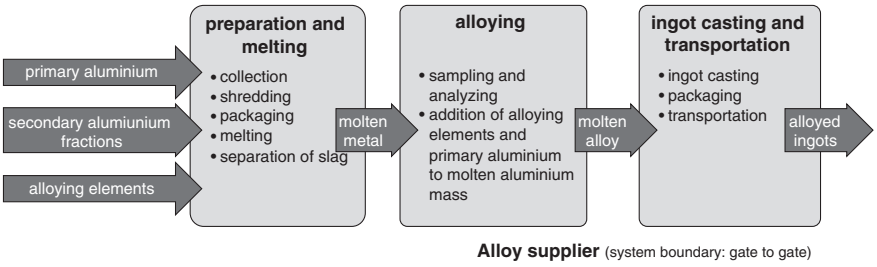

Fig. 2.23 Secondary aluminium alloy production process chain inside an aluminium supplier (production line, possible sub-processes and alloy mass flow)

post-industrial scrap, aluminium fractions from municipal waste, swarf, dross, etc. which need to be collected and transported to the alloy supplier. Depending on the quality of the aluminium fractions, some preparatory activities can become necessary to increase the possible yield of recovered aluminium or to prevent damages in the melting equipment. Such preparatory activities can include sorting and selecting of relatively pure secondary aluminium inputs or defined alloy qualities, de-coating, comminution, packaging and pressing of swarf, squeezing of dross, etc. (Schmitz 2006a).

After basic preparation, the collected aluminium fractions get melted in a drum melting furnace while adding melting salt. This salt extracts various contaminations from the molten metal but creates a slag, which needs to be treated separately after the melting process (Schmitz 2006c).

The molten metal, whose exact composition is not known to the very last detail at this step, gets transferred into a holding furnace (converter). At this holding furnace a sample of the molten metal gets taken and analyzed to detect the actual concentration of alloying elements and remaining contaminating materials. The result of this analysis is used to calculate the amount of alloying elements and pure aluminium, which need to be added to the molten metal afterwards to set up the final composition of the intended alloy (Schmitz 2006c).

Out of the holding furnace the final alloy is transferred into an ingot casting machine, so that the demanded alloy can be packaged and transported easily via lorries to the customer of the alloy supplier. The transportation of alloys to the foundry will be the topic of the following paragraphs.

2.1.2.5 Transportation Scenarios Between Alloy Supplier and Foundry

The most common scenario of metal supplies to a foundry is the transportation of solid ingots like described above to an external foundry (see Fig. 2.24). This external foundry is usually equipped with own melting capacities in its smelter (Kuom and Urbach 2007).

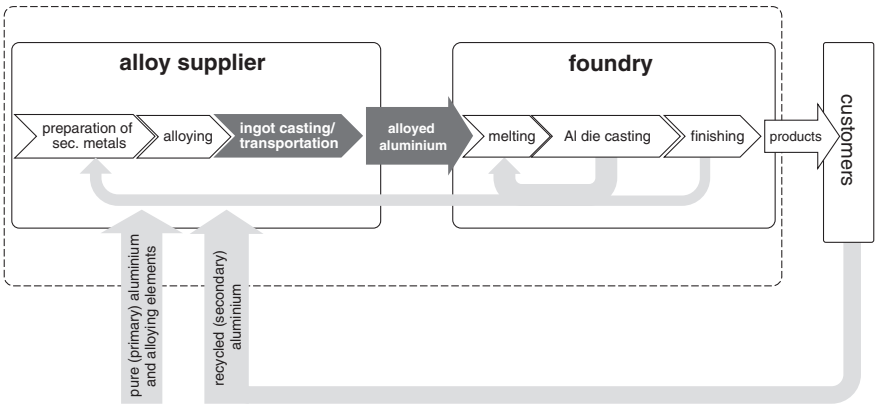

Fig. 2.24 Alloy transportation as linking element between alloy supplier and foundry

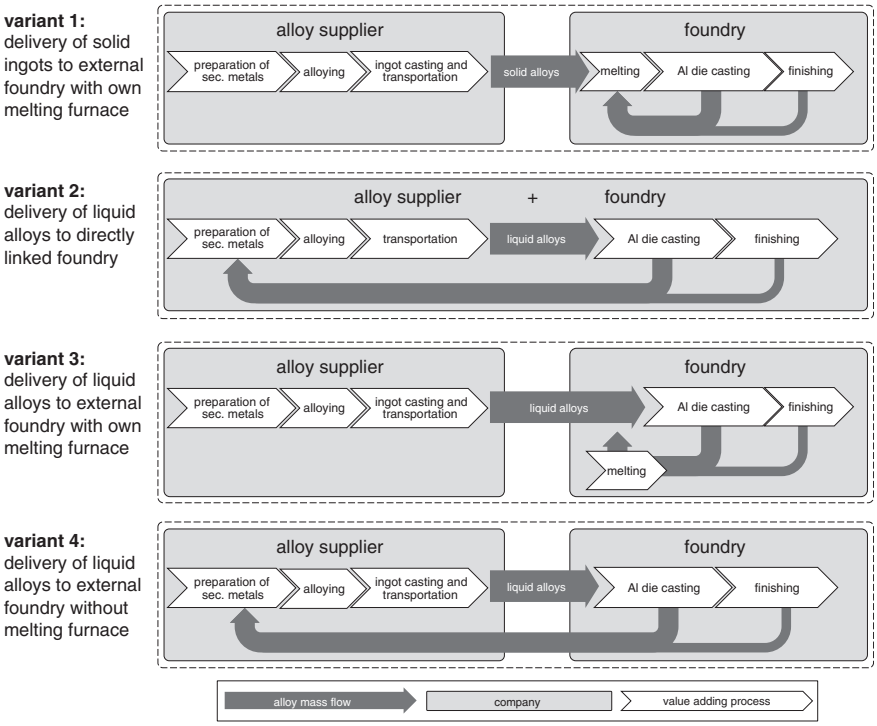

Fig. 2.25 Possible Transportation variants for the supply of aluminium alloys from alloy supplier to foundry (adapted from Heinemann and Kleine 2013)

However, other variants are possible as well, which differentiate in the distance between the alloy supplier and the foundry, in the aggregate state of the alloy and the amount of reversely transported cycle material depending on the availability of melting capacities at the foundry (see Fig. 2.25; Heinemann and Kleine 2013).

The aforementioned variant 1 (delivery of solid ingots to external foundry with own melting furnace) is the most common one because there are many more external foundries than alloy suppliers, of which only some possess a directly linked foundry. Even more important is the fact that solid ingots are tradable commodities, which can be stored and commissioned to various packaging sizes without changing their characteristics and quality. Therefore, the storability of the ingots is not only beneficial for the metal trading alloy supplier, but also for the logistic service provider, who can easily choose and manage the mode of transportation (usually lorries) and mix the ingot packages with other shipments. Furthermore, the storability of the solid ingot supplies also offers a lot of benefits especially for the foundry. At the foundry, safety stocks can be implemented effortlessly with solid ingots and different alloys can be picked easily at any time when they are needed in order to cast products with different mechanical characteristic (Kuom and Urbach 2007; Heinemann and Kleine 2013).

The delivery of liquid alloys decreases this degree of flexibility, as it offers only a very limited storability over time, and therefore is only possible up to a

distance level of 500 km between the alloy supplier and the foundry. Furthermore, the foundry has to establish a very close relationship to the alloy supplier as the supplier has to guarantee a very steady supply of liquid alloy inputs. On the other hand, this transportation variant is only possible for foundries with nearly no changes in the casted alloy, and with only minor volatility in their alloy demand in order to guarantee a steady purchase of further metal inputs from the supplier. The big advantage of liquid alloy supplies lies in the absence of energy intensive melting activities at the foundry, which can directly process the liquid alloys as they enter the facility (Kuom and Urbach 2007; Krone 2000).

In variant 2 these liquid alloy suppliers get delivered in transfer ladles via forklift trucks from the holding furnace at the alloy supplier into the holding furnace at the die casting cell of the directly linked foundry. Obviously, this variant is relatively energy efficient but also very rare due to the little amount of alloy suppliers with directly linked foundries (Heinemann and Kleine 2013).

In the more likely case of a delivery of liquid alloys to external foundries, the molten metal gets transported via specialized lorries that are equipped with isolated transfer ladles in which the superheated alloy stays liquid at a transport temperature of 800–900 °C and a temperature loss of 10–20 K per hour (Kuom and Urbach 2007; Krone 2000). So the time until the liquid alloy cools down to its solidification temperature determines the maximum transportation distance between the alloy supplier and the foundry.

Besides the temperature losses and specialized vehicle equipment, the reverse transportation and smelting of post-industrial scrap (cycle material) also needs to be considered, regarding the possible transportation scenarios for liquid alloy supply to distant foundries. Usually, foundries are still equipped with smelting capacities (variant 3), which can be used in order to resmelt the pure internal cycle material (swarf, discarded products, die cutted gating systems, etc.). In this case no reverse transports from the foundry to the alloy supplier need to be considered, and the lorry of the alloy supplier returns empty to its starting point. However, if the foundry is planned and designed with the purpose to exclusively process liquid delivered alloys, it does not necessarily have to possess its own melting furnace (variant 4). In this case the transportation can be configured in a way that internal cycle material gets transported back to the alloy supplier, where it gets smelted together with the other collected secondary metal inputs (Heinemann and Kleine 2013).

For the following sections the most usual case of alloy transportation (variant 1) is taken as reference scenario. The following section will introduce the internal process chain of a foundry, which is supplied according to this variant.

2.1.2.6 Process Chain of a Die Casting Foundry

The internal aluminium die casting process chain inside a foundry does not only consist of the die casting process itself, but also includes some mandatory as well as facultative upstream and downstream processes (see Fig. 2.26).

The process chain inside a foundry can be described as a set of activities or interlinked sub-processes (Neto et al. 2009a). Every die casting foundry runs the

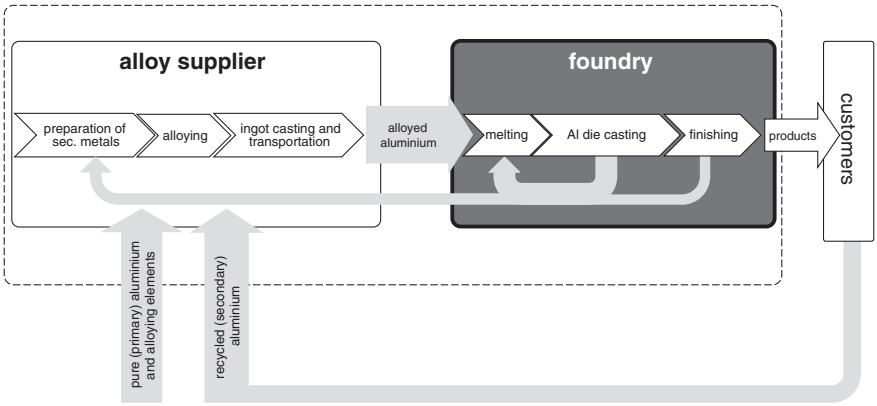

Fig. 2.26 The internal process chain of a foundry within the aluminium die casting value chain

following value adding activities, which are mandatory to produce die casted parts with a defined set of characteristics and functionalities (Neto et al. 2009a):

- melting (of an aluminium alloy)
- casting (shaping the alloy into a semi-product)
- finishing (several operating processes for surface finishing and product cleaning)

Figure 2.27 illustrates the sequence of these main activities and their sub-processes as well as the value adding alloy mass flow through the foundry.

Additionally, the facultative activity of heat treatment can be conducted between the casting and the finishing (Heinemann et al. 2013a; Brunhuber 1980).

The melting of the aluminium alloys usually takes place in separated smelting areas (smelter) inside the foundry. Pot-type furnaces or efficient shaft furnaces are used. Pot type furnaces can smelt up to 400 kg of aluminium alloy per hour and

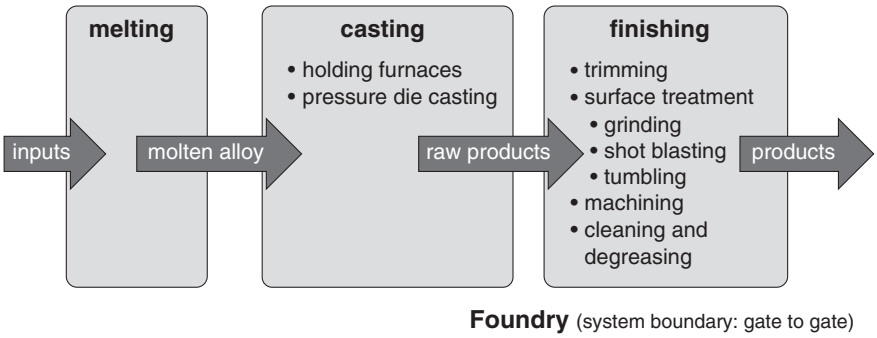

Fig. 2.27 Aluminium die casting process chain inside a foundry (production line, possible sub-processes and alloy mass flow) (Neto et al. 2008)

usually have a holding capacity of up to 1500 kg. The more energy efficient and productive shaft furnaces can smelt between 300 and 7000 kg of aluminium alloys per hour and have a holding capacity of up to 20,000 kg (Malpohl and Hillen 2009).

To reduce possible entrapments of hydrogen and oxidised metal particles, which decrease the machinability and quality of the cast, an additional treatment of the molten metal can be conducted. The liquid metal gets rinsed with inert gases like argon or nitrogen, which is flushed through the metal via an impeller (Kättlitz 2008).

When the metal is molten it gets transported to the casting area. This transport usually is done via forklift trucks in transfer ladles. At the die casting cell, the metal gets poured into a holding furnace, where the temperature of the liquid metal gets controlled above the solidification point. The holding furnace doses the required metal volume into the casting chamber, which is needed for one shot.

Out of the casting chamber the metal is squeezed into the mould cavity, where it solidifies. After the removal of the solid cast from the mould cavity, the gating system and sprue gets cut or sawed off from the casted raw product. The separated sprue, gating system other chips and possible reject parts get transported back to the smelter, where they get smelted again together with new alloy input material. Due to the fact that some shares of the molten metal get smelted, casted and cut off again and again this share of metal is called cycle material.

After the raw product has left the die casting cell, it can be further processed or finished in the mechanical treatment section of the foundry. Due to the great variety of possible treatments that can be done to the raw product in the mechanical treatment section, there is no standard set of clearly defined processes, which can be found at any die casting foundry. Nevertheless, several processes out of the main group cutting (e.g. drilling, milling, grinding) followed by further surface treatments and cleaning procedures can be found often as well as packaging and palletizing operations. Depending on the demanded quality and quality rate of the final product, several quality inspections as well as reworking operations can be found in an aluminium die casting process chain in a foundry (Neto et al. 2008).

If necessary, a heat treatment can be done to the raw product between the casting and the finishing in the mechanical treatment area. Commonly, a T4, T6 or T7 heat treatment is conducted to aluminium die casted parts (Koch et al. 2011). This means that the sub-processes solution annealing, quenching and artificial ageing are partially or completely performed. Due to the danger of potential gas entrapments of die casted parts, a temperature of about 250 °C should not be exceeded to avoid the formation of blisters. The heat treatment gets done preferably in convection ovens which can control a temperature level at a maximum deviation of 5 °C from the target temperature (Honsel 2014; DIN EN 515 1993). The ovens can be operated continuously via transfer lines, or as batch-type furnaces—depending on the batch size of the individual product (Kleine and Heinemann 2013). Most relevant process parameters of the heat treatment, which determine the mechanical properties of the product as well as the energy intensity of the process, are the temperatures and throughput times of the heat treatment's sub-processes (Rockenschaub et al. 2006).

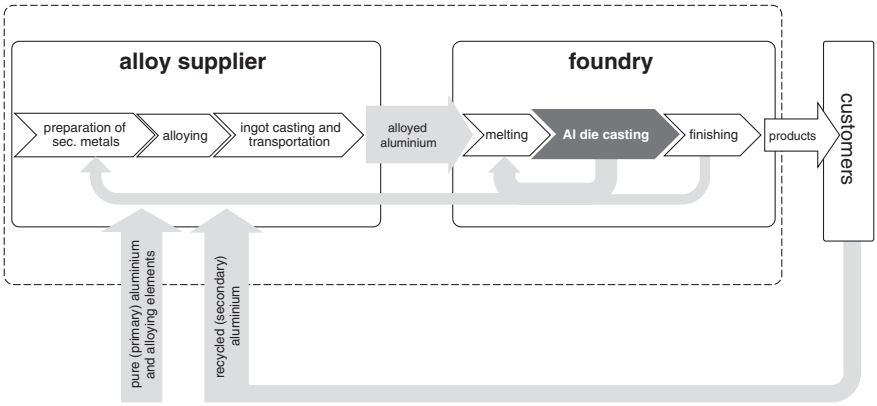

Fig. 2.28 The die casting process within the aluminium die casting value chain

2.1.2.7 Technical Description of the Aluminium Die Casting Process

The die casting process, which is eponymous for the above introduced value chain, will be introduced in the following section. The specific process sequence will be described before explaining its embedding in the die casting cell (see Fig. 2.28).

Process Sequence

Within the die casting process, liquid metal is forced into the cavity of a steel mould under high pressure. The squeezing of the liquid metal into the cavity is done by a plunger at a pressure level of up to 1200 bar. Due to this high pressure, closing forces of up to several tens of thousands kN have to be applied to the dies by the die casting machine. Despite the high pressure and temperature, the steel mould (die) is reusable up to 300,000 cycles (shots) of the die casting process (Westkämper and Warnecke 2010; Dalquist and Gutowski 2004).

Each cycle follows the same sequence, which is depicted in Fig. 2.29. As soon as the die halves are locked, the liquid metal is filled into a shot chamber (1). Afterwards, a plunger squeezes the metal into the cavity (2). Inside the cavity, the metal solidifies while the plunger keeps the metal under pressure for the required dwell time (3). After the solidification of the metal the two dies are separated so that the cast can be released (4), the plunger returns to its initial position and the dies can be prepared for the next shot (Aluminium Laufen AG 2014; Dalquist and Gutowski 2004).

The preparation of the dies includes some air-cleaning and relubrication with release agents (Dalquist and Gutowski 2004). The temperature of the dies is controlled continuously via tempering units, which serve tempering channels inside the dies with hot hydraulic fluids (Speckenheuer and Deisenroth 1989).

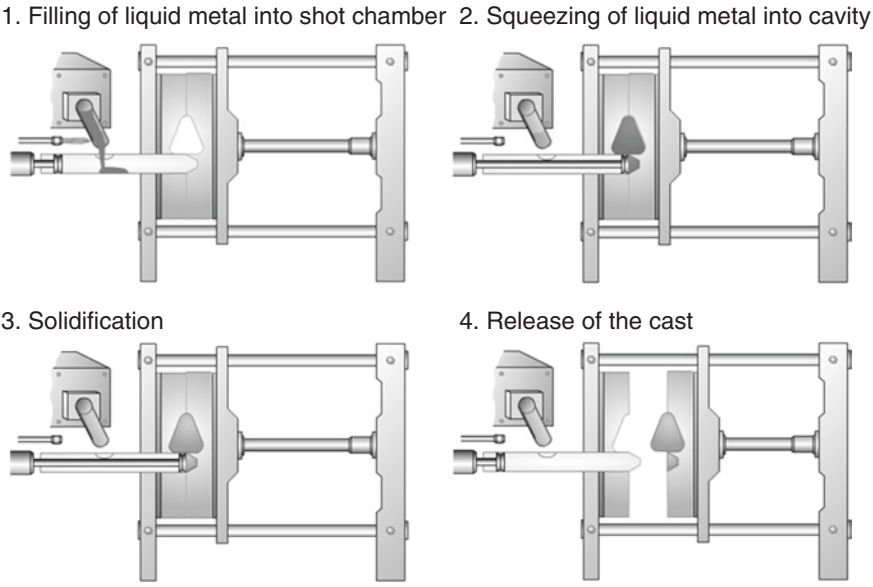

Fig. 2.29 Phases of the die casting process (Aluminium Laufen AG 2014)

Die Casting Cell and Equipment

The main device for conducting the die casting process is the die casting machine. Nevertheless, the die casting machine needs to be embedded in a die casting cell that is equipped with a set of necessary peripheral equipment. The most important elements of the die casting cell will be introduced in the following section.

The **die casting machine** can be broken down into three main components (Hoffmann and Jordi 2013b; Brunhuber 1980): Pump group or power unit, clamping unit, injection system.

The pump group delivers the hydraulic pressure, which is needed to operate the moving parts of the die casting machines. An electric motor powers pumps that compress hydraulic fluids up to pressure levels of 160–210 bars.

The clamping unit moves and closes the die casting mould. For this purpose, the non-fixed carrier plate gets moved along the machine base on slide shoes. Additional operations are the hydraulic control of the optional casting core systems as well as the activation of the repressing and ejector units.

The injection system's main task is to move the plunger, which squeezes the liquid metal into the cavity of the die casting mould. The injection system controls the movement of the plunger in order to guarantee a smooth entry of the metal into the gating system of the mould, a fast filling of the mould, and a sufficient holding-pressure while the metal is solidifying. The plunger movement also has to support the ejection system when the solid cast gets removed from the mould.

Figure 2.30 illustrates an example of a cold-chamber die casting machine with a double plate clamping unit. Alternatively, toggle clamping units can be applied and a holding furnace can be integrated into the die casting machine (hot-chamber die casting machine) (Hoffmann and Jordi 2013b; Nogowizin 2011; Brunhuber 1980).

The die casting cell is complemented by the following equipment: (Neto et al. 2008; Heinemann et al. 2013b; Brunhuber 1980)

- **holding furnace** (controlling the temperature of the liquid metal in the die casting cell, and dosing it into the casting chamber of the die casting machine)
- **die casting mould** (defining the shape of the case by being its negative)
- **tempering units** (controlling the temperature of the die casting moulds in order to guarantee a sufficient time for the solidification of the metal and preventing it from freezing on the surface of the mould, reducing the thermal stress of the mould)
- **handling equipment** (robot for automatically removing the cast from the mould and transferring it to the subsequent process step)
- **cutting device** (die cutter or saw for the removing of gating system and remainders from the final casted product)
- **spraying robot** (air-cleaning of the mould and application of release agents to the mould surface)

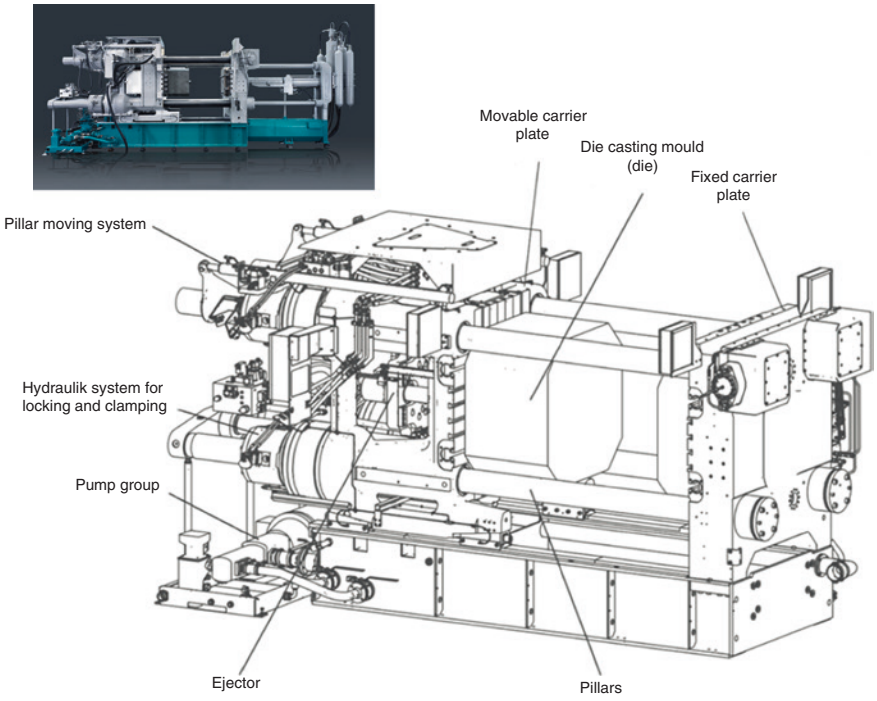

Fig. 2.30 Die casting machine (double plate clamping unit) (Hoffmann and Jordi 2013b)

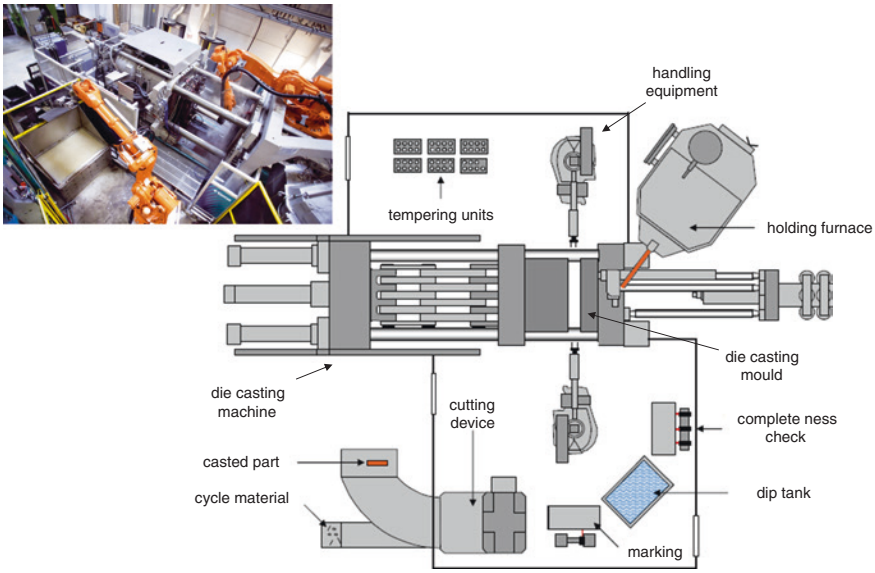

Fig. 2.31 Aluminium die casting cell (Kerber 2013; foundry-planet.com 2014)

The die casting cell is visualized in Fig. 2.31. It shows a sample configuration of the above mentioned equipment in a die casting cell schematically and adds a photograph of a similar, real aluminium die casting cell.

2.2 Environmental Aspects of Aluminium Die Casting

The preceding section introduced aluminium die casting from a technical perspective. The subsequent section provides an insight into the environmental challenges of aluminium die casting. Therefore, relevant terms like energy and resource efficiency, productivity and intensity as well as relevant methods to overcome environmental challenges in production will be introduced briefly.

2.2.1 Energy and Resource Efficiency

Environmental challenges result from energy and resource transformation. Metrics for measuring and comparing the quantitative input and output relation of such transformations are, e.g., the productivity, input related intensity or efficiency. Thus, the efficiency in particular is a central focus of many national energy and sustainability policies. However, only little attention has been given to a standardised and universal definition of this concept (Patterson 1996). Therefore, the terms

productivity, intensity and efficiency for the evaluation of energy and resource transforming production systems will be explained briefly in the following paragraphs to constitute a common understanding for the further course of discussion.

From a strategic point of view, efficiency is one of the three strategies towards sustainable development. In this context, the strategies of sufficiency (self-determined limitation of environmentally harmful activities) and consistency (compliance of anthropogenic resource flows with common natural flows) are complemented by efficiency (WCED 1987; Dyckhoff and Souren 2008). Striving towards efficiency in production follows the idea of technological progress, which enables stable levels of utility or output (e.g., of products and processes) with continuously reduced input flows. Alternatively, an expansion of utility and production volumes while maintaining a stable level of input flows is a complementary example of increasing efficiency (Dyckhoff and Souren 2008).

Hence, metrics are necessary, which enable an assessment of actual input and output ratios. One common metric to assess the ratio of output factors to input factors of a transformation process is the **productivity** metric (e.g., Gronau and Lindemann 2010).

$$productivity = \frac{output}{input}$$

The productivity metric aims at evaluating physical input and output flows. Therefore, it is easily applicable and can be used to create a quick performance indicator of an observed system by metering its actual input and output flows. However, it adds qualitative information about the observed system only if there is a reference system against which the derived productivity value can be benchmarked. If systems with quantitatively and qualitatively constant output flows are observed or aimed for, Cantner et al. recommend the **input intensity** metric for the evaluation of input and output ratios (Cantner et al. 2007). The input intensity metric is the reciprocal value of the productivity metric. The denominator is constant when comparing different observed systems.

$$input\ intensity = \frac{input}{output_{const}}.$$

The input intensity metric therefore expresses the demand of certain input factors to create a fixed output unit. Thereby, it is a very intuitive metric to evaluate and compare the effect of improvement measures, which reduce the factor input of production processes by maintaining a defined product output (Cantner et al. 2007; Patterson 1996). Since the following discussion acts on the same assumption, that the output of the observed systems qualitatively and quantitatively stays the same, whatever measure is applied to this system, the input intensity metric will be the main metric for evaluating and comparing production systems and improvement measures.[1]

[1]The terms input intensity and intensity will be used synonymously.

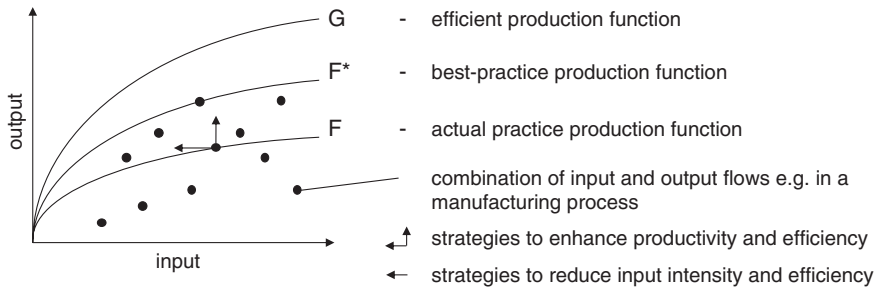

Fig. 2.32 Efficient, best- and actual-practice production functions (according to Cantner et al. 2007)

Input and output ratios or possible combinations of input and output flows are also specific characteristics of technologies. Production functions depict all possible input and output combinations of one technology (see Fig. 2.32).

This perspective introduces the concept of **efficiency**. A production function is efficient if there is no output flow, which can be produced with less input flows or if there is no input flow, which can produce more output flows in a different production function. According to this definition, technologies can only be efficient or not efficient without any graduation in between (Dyckhoff and Spengler 2007). As this optimum of an efficient production function (G, see Fig. 2.32) is rather of a theoretical nature and cannot be achieved in real production environments, actual-practice production functions (F) and best-practice production functions (F*) can be observed in reality. Best-practice functions represent the best possible combination of input and output combinations at the actual state of the art (Cantner et al. 2007). As an extension to this classical view on efficiency, the OECD defines efficiency as "the degree to which a production process reflects best practice" (OECD 2001). Thus, efficiency is not longer an absolute attribute of a theoretical production function, but can be expressed relatively by comparing actual practice with best practice. For such a comparison the above introduced productivity or input intensity metrics are feasible. Efficiency then represents the ratio of actual input intensity (resp. productivity) to best practice input intensity (resp. productivity) (OECD 2001).[2]

$$efficiency = \frac{input\ intensity_{actual}}{input\ intensity_{best\ practice}};\ efficiency = \frac{productivity_{actual}}{productivity_{best\ practice}}$$

Therefore, strategies for increasing efficiency can either increase the productivity or decrease the input intensity (see Fig. 2.32; Cantner et al. 2007; Dyckhoff and Souren 2008; see also Zein 2012). Further detailed overviews over concepts,

[2]Other authors and authorities define efficiency as synonym of productivity (e.g. DIN EN ISO 50001 2011; VDI 4800-1 2014). However, this perspective will not be taken in the following course of discussion.

indicators and methodological issues regarding (energy) efficiency are provided by Patterson and Zein (Patterson 1996; Zein 2012).

The above introduced metrics are applicable for many evaluation perspectives on production (e.g. labour-intensity, productivity of production equipment) (e.g. Gronau and Lindemann 2010). In the following chapters, physical input flows of energy carriers and materials will be focused and reduced to evaluate and improve the energy and resource efficiency of aluminium die casting.

2.2.2 Methods and Tools for Increasing Energy and Resource Efficiency

To reduce the energy and resource intensity in production with the goal to increase the energy and resource efficiency in a structured way, a methodological support is recommended (see e.g. Herrmann et al. 2010b). In this context, a methodological course of action, especially in the fields of data acquisition, modelling and visualisation, simulation and evaluation, helps to strive towards reduced energy and resource intensities. Therefore a brief insight in these methods will be given in the following section.

First, current developments for data acquisition in the context of energy and resource flows will be described as a basis for the generation of data sets, which will be processed by the other introduced methodologies or tools. Second, modelling approaches will be introduced, which depict their observed processes as a transformation of physical inputs into physical outputs. By generating such input/output matrices, e.g., life cycle inventories for the elaboration of life cycle assessments can be enabled. Thereby, a basis for a visualisation of resource flows is created, which enrich the information of purely quantitative approaches with intuitive, qualitative visual information about flow rates and volumes. Furthermore, these approaches add an underlying model about the correlation of the depicted flows, which makes first simulations possible. Simulation towards resource efficiency includes static as well as dynamic approaches, which will be addressed briefly. Afterwards examples for an environmental evaluation get introduced, which enrich the generated data about energy and material flows along the value chain with a life cycle spanning perspective on the resulting product, and with an assessment of the resulting environmental impacts (e.g. via a life cycle assessment).

2.2.2.1 Data Acquisition

Transformed resources on the process, process chain and value chain level are manifold. Thus the state of the art about the metering and monitoring of resource flows on different hierarchical levels is wide and complex (O'Driscoll et al. 2012). The most prominent resource in production, regarding the available metering

approaches and strategies, is electricity. Kara et al. present an overview over the topic of electricity metering and monitoring in manufacturing systems. They state that from an electricity consumer perspective there are three hierarchical levels within a factory. According to that, electricity metering and monitoring can increase transparency about the electricity consumption of each hierarchical level and therefore support different further energy related activities. Examples are energy billing on factory level, identification of consumption hot-spots on department level or machine efficiency redesign on process level (see Fig. 2.33; Kara et al. 2011).

Kara et al. give an overview over basic electricity metering equipment for stationary and mobile application and give recommendations about suitable resolutions depending on the degree of dynamic behaviour of the object of interest. Furthermore, for each hierarchical level of the factory they define affected cost factors resulting from electricity consumption (e.g., peak power demand, specific energy demand, THD feedback) and potential benefits through electricity metering (e.g., adaption of energy supply contracts, energy intensive process scheduling, energy forecasting in production design) (Kara et al. 2011).

O'Driscoll and O'Donnel provide an update for the overview of metering equipment. They enrich it with an overview that covers communication platforms and protocols as well as with an overview over the current regulation and certification for energy and power monitoring (O'Driscoll and O'Donnel 2013).

A proposal for a technical implementation of a multi-level metering and monitoring architecture gets presented by Verl et al. They establish energy control loops in which metering based energy demand and cause models (feedbacks to higher

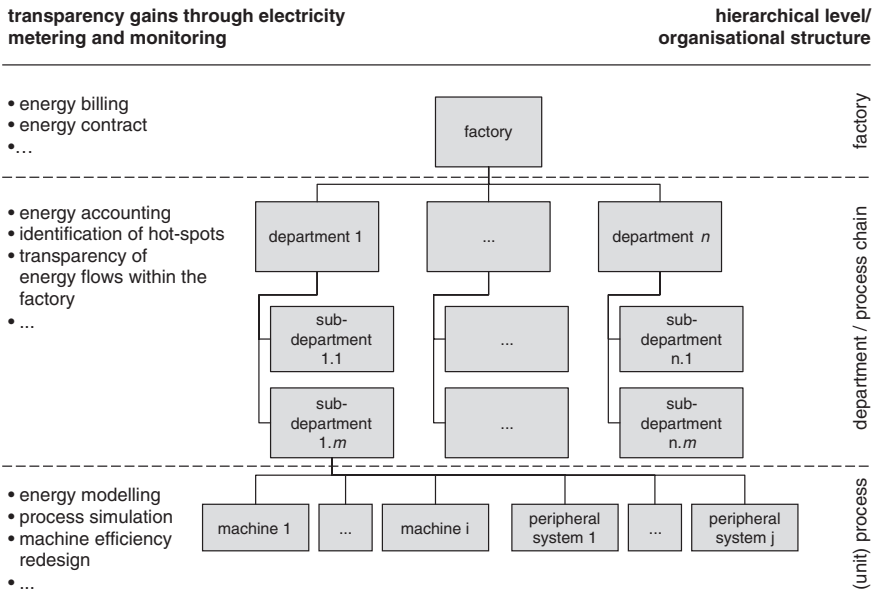

Fig. 2.33 Hierarchical levels of electricity consuming entities in a factory (Kara et al. 2011)

hierarchical system levels) build the basis for the derivation of plans and constraints for the operation of the actual system. By formulating such models for the individual system elements, a model based prediction of the energy demand, as well as an energy oriented planning and scheduling, becomes possible (Verl et al. 2011; see also Sect. 2.1.1, Fig. 2.7).

The generation of transparency about the usage of energy carriers, as well as auxiliary material flows via economically feasible metering devices and data processing equipment, has been in the focus of the EnHiPro project. Here generic metering strategies and metering data processing equipment, especially for the needs of small and medium enterprises (SME), have been developed. They build the basis for a continuous improvement circle towards energy and auxiliary material efficient SMEs (Herrmann et al. 2013c; Thiede et al. 2012, 2013).

In contrast to this SME focused approach the KAP project develops methodologies and equipment for complex event processing and real-time business intelligence on the shop floor of highly dynamic production systems, in order to feed evaluation and data mining algorithms. These algorithms shall support energy oriented production planning with respect to individually developed production performance indicators (kap-project.eu 2014; Swat et al. 2013; Emec et al. 2013).

The VDMA 24499 worksheet supports the metering of the machine specific electrical power demand of die casting machines with mobile metering devices for benchmarking reasons. Therefore, the VDMA 24499 worksheet defines standard process parameters for die casting machines depending on their closing force. Thereby, reproducible and comparable process sequences are defined for comparable metering results (VDMA 24499 2012; Hoffmann and Jordi 2013a; Kerber 2014).

Furthermore, simple data gathering methods like counting of parts or batches, interviews or the analysis of corporate production archives or databases can be done. In order to make such manually generated data more robust, statistical methodologies can be applied. Thus Bast and Strehle analyse gravity casting process chains and consolidate data about production parameters, quality rates and casting defects for the sub processes casting core production, moulding, and alloy supply. Bast and Strehle apply linear regression, multiple linear regression, maximum likelihood method, neuronal networks as well as cognitive networks to their generated data base and illustrate their potential for the identification of possible improvement measures for the reduction of scrap parts due to casting defects (Bast and Strehle 2010).

The evaluation and visualisation of data which has been generated via such procedures gets supported heavily by the use of input-/output matrices or modelling techniques as they will be introduced in the following section.

2.2.2.2 Modelling and Visualisation

On the manufacturing process or machine level, several approaches for modelling the energy and resource demand exist. As observed before, again the electricity

demand has been the focus of most attempts to model the resource consumption. Balogun and Mativenga provide a comprehensive overview over energy oriented machine tool models (Balogun and Mativenga 2013).[3] They state that most of the approaches for modelling the energy consumption of machine tools take a machine state oriented perspective, which is similar to the basic principles of the methodology, which has been proposed by the Cooperative Effort in Process Emission project (CO2PE!) (Kellens 2013; Kellens et al. 2012). Furthermore, Balogun and Mativenga identify the following equation by Gutowski et al. to be a good basis for modelling and analyzing the direct energy demand in machining (Gutowski et al. 2006):

$$E = (P_0 + k\dot{v})$$

This equation processes the variables E [direct energy demand in a machining process (Ws)], P [power during operation readiness, before the machine starts cutting (W)], k [specific energy requirement for machining a particular work piece material (Ws/mm^3)] and $\dot{v}$ [material removal rate (mm^3/s)]. The equation has been further developed by several approaches (e.g. Mori et al. 2011; Diaz et al. 2011; He et al. 2012).

Balogun and Mativenga also identified another family of modelling approaches which gets constituted by Diaz et al., Draganescu et al. and Li and Kara. These modelling approaches analyse the machine tool's energy demand as a function of the material removal rate and individual coefficients, which need to be derived specifically via empirical studies (Balogun and Mativenga 2013; Diaz et al. 2011; Draganescu et al. 2003; Li and Kara 2011; Kara and Li 2011). Based on the same modelling philosophy, further manufacturing processes have been analysed and modelled. E.g., Li et al. empirically derived models for the specific energy consumption of turning, extruding and grinding processes (Li et al. 2012, 2013; Li and Kara 2011). Qureshi et al. and Chien and Dornfeld added further models about the injection moulding process (Chien and Dornfeld 2013; Qureshi et al. 2012).

Similar specific models for aluminium die casting processes do not exist yet. For the specific case of aluminium die casting, there are models about the (dynamic) flow of material and heat through the parts of the die casting machine or cell. However, their purpose is to support mould designers creating long lasting moulds. Therefore, they often fail to translate these flows consistently into energy demands. Nevertheless, a small number of approaches exist, which try to assess the energy consumption of shaping processes via modelling the thermo dynamical and fluid mechanical behaviour of the shaping process.

[3]Balogun and Mativenga covered the findings of (Kordonowy 2001; Dahmus and Gutowski 2004; Gutowski et al. 2006; Devoldere et al. 2007; Diaz et al. 2009; Vijayaraghavan and Dornfeld 2010; Rajemi et al. 2010; Anderberg et al. 2010; Avram and Xirouchakis 2011). Each of them performed in-depth studies about the state related energy demand of different manufacturing processes. The energy demand during operation readiness without value adding was identified as the machine state which contributes most to the energy demand of the whole process.

Ribeiro et al. model the heat flows within injection moulding machines, which can be considered to be familiar with die casting machines. They use thermodynamic equations from Mattis et al. (1996) and Thiriez and Gutowski (2006), and add process parameters like the cooling time to improve the design of die cooling channels (Ribeiro et al. 2012; Mattis et al. 1996; Thiriez and Gutowski 2006). A similar goal is pursued by Sundmaeker et al. (2013).

Specifically for the aluminium die casting process, Röders et al. have set up a static model about the overall heat transfers within an aluminium die casting cell. This static model was specifically set up to understand the heat balance of the die itself to find measures for an energy demand reduction. Figure 2.34 visualizes temperature fields of parts of the die casting cell, which have been analysed to derive the static model about the heat balance of the considered dies The considered heat transfers are visualised via coloured arrows (Röders et al. 2006; see also Sect. 2.2.3).

This way of visualising flows in production systems with coloured arrows is based on the idea of the Sankey diagram. Sankey diagrams were developed in the late 19th century. E.g., Schmidt explains this methodology extensively and reflects their history as well as application as one important method to support energy and resource efficiency in industrial production. Within a Sankey diagram, physical or monetary flows are depicted as arrows, which connect single transformation processes. The width of the arrows is proportional to their individual quantity. Thus, the structure, quantity, source and sink of (energy and material) flows can be visualised and compared very intuitively (Schmidt 2008).

An example for a Sankey diagram based visualisation of energy and material flows in an aluminium (gravity die casting) foundry has been provided by Krause et al. (see Fig. 2.35; Krause et al. 2012). It is divided in two visualisation

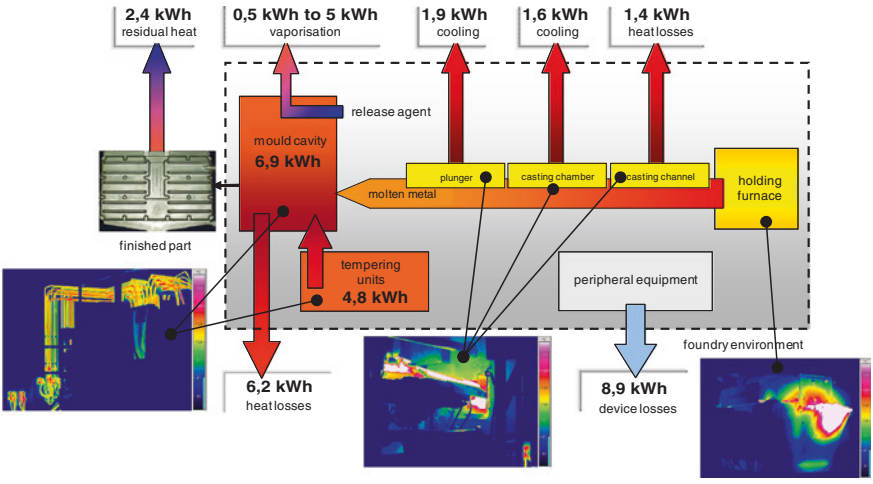

Fig. 2.34 Visualized heat flows in the aluminium die casting cell (Röders et al. 2006)

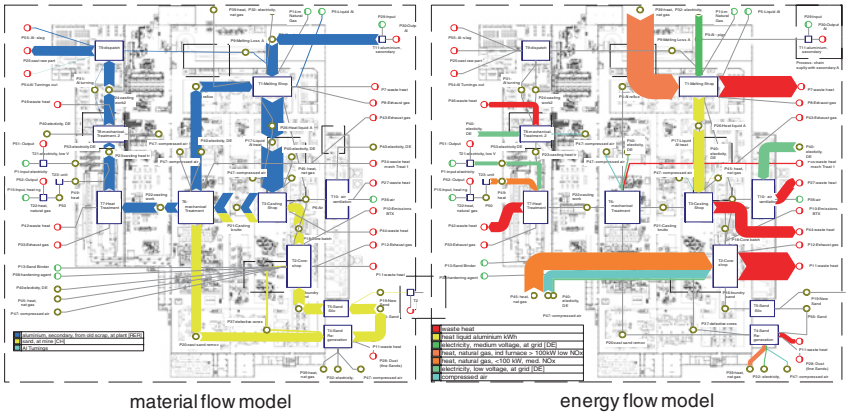

Fig. 2.35 Visualisation of material and energy flow in a gravity die casting foundry (Krause et al. 2012)

perspectives. Both perspectives build upon the same structure of modelled processes. The first perspective visualises the material flows, which connect the modelled processes. The second perspective visualises the energy flows between the same system elements. Therefore, the differences in the flow structures as well as the main influencing system elements can be identified and depicted based on the same model and visualisation approach.

A simple but powerful basis for the creation of Sankey diagrams are input/output balances of the observed transformation processes. They oppose all relevant input flows at the necessary quantities to the resulting output flows and quantities of a transformation process. Thus, the relative composition of input and output flows can be modelled and scaled up or down for the individually required product quantity. This way of modelling transformation processes within productions systems is one basic methodology within the overall concept of material and energy flow analysis (e.g. Lambrecht and Thißen 2014). Later, it will be pursued to model the energy and material flows of aluminium die casting.

2.2.2.3 Simulation

Simulation describes a procedure, in which a model is created of a real existing or imaginary system so that the model can be analysed by conducting experiments. The goal of this procedure is to gain knowledge about the system's behaviour and reaction to scenario experiments in order to generate recommendations for action (e.g. Hedtstück 2013). Thereby, it is a powerful tool to assess improvement scenarios for energy and resource efficiency in a virtual environment before their physical implementation.

Thiede provides a very comprehensive overview over energy oriented approaches for manufacturing system simulation. He states that discrete event

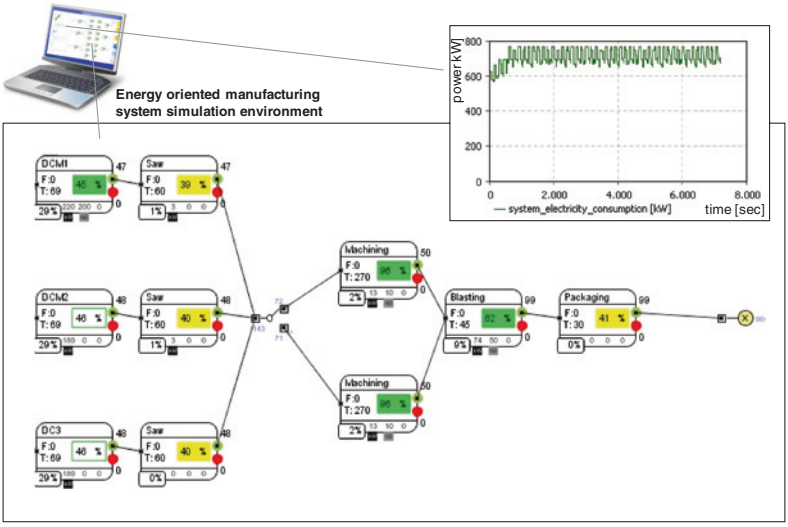

Fig. 2.36 Sample DES based model of an aluminium die casting process chain, modelled in an energy oriented material flow simulation (Thiede 2012)

simulation (DES) is the most relevant simulation class to support the methodological analysis and improvement of energy and resource efficiency in production (Thiede 2012).

Discrete event simulation models and calculates all dynamic events, which occur during one discrete process cycle. In doing so, for each event a specific routine can be executed, which affects the state of the simulated process (Hedtstück 2013).

This dynamic activation of system states and the evaluation of the caused results specifically qualify DES for the simulation of dynamic (state dependent) energy and resource demands in manufacturing systems. Furthermore, DES is already state of the art for commercial simulation tools for material flow simulation in industrial production (Thiede 2012). Thiede himself introduced a concept and sample application for an energy oriented material flow simulation, which integrates the simulation and evaluation of the state-related energy demand of production equipment with a material flow simulation. An exemplary case study about an aluminium die casting process chain has been conducted and fields of action for energy efficiency improvements could be identified (Thiede 2012) (Fig. 2.36).

In contrast to this system perspective on production, a broad variety of simulation approaches exist, which focus the modelling and evaluation of single production processes. For the case of aluminium die casting, the software MAGMASOFT™[4] provides an extensive simulation suite to simulate the process cycle within a die casting cavity at a time resolution of about one millisecond.

[4]See: http://www.magmasoft.de/.

Depending on more than hundred process parameters e.g., the mass flow into the cavity, its solidification over the observed time period and the resulting quality criteria can be modelled (Cleary et al. 2002, 2010). Evaluated quality criteria are e.g., porosities and shrinkage (Campatelli and Scippa 2012; Schneider 2011). To simulate the solidification behaviour of the molten metal, also the heat transfer through the dies and the cooling systems gets simulated. Thus, thermal balances can also be calculated and their variation over time. This can be an input variable to a superior evaluation system, which calculates the resulting energy demand of the die casting cell. Recently, software approaches like MAGMASOFT™ have been extended with optimisation algorithms. Therefore, under given restrictions, optimal process parameters for a previously defined target function can be suggested by the simulation software without the further need for extended empirical process knowledge of the software user (e.g. Hahn and Sturm 2012). Following this approach, the volume of the cycle material (regarding the geometrical parameters of the gating system, sprue, etc.) can also be included in the target function for an optimisation to reduce the overall material demand of this process (Sturm 2011). Similar simulation approaches are implemented in the software suites such as FLOW-3D™[5] or QuikCAST™.[6]

Besides the introduced dynamic simulation approaches on manufacturing system and process level also static simulation is possible. The previously introduced understanding of simulation described as a procedure, which creates and utilises a parameteriseable model for virtual experiments. Thus, static (not time-dependent) and model-based scenario calculations are also included in this definition.

One example for such a static simulation is the calculation of connected energy and material flows in production networks, in which the individual process's input and output flows are modelled via an input/output balance (Wang et al. 2014). E.g., the software Umberto™[7] provides an automated calculation of such harmonized energy and material flows along a modelled system of transformation processes. On the basis of the aforementioned input/output balances for each transformation process, this software computes the resulting energy and material demands (as well as emissions) of each process step to calculate a defined quantity of a specified reference output flow (Möller 2000; Wohlgemuth 2005).

By varying single input/output balances of the structure of the connected flows, scenario oriented simulation experiments are possible to calculate and compare the resulting energy and material flows without a physical implementation (e.g., Ghadimi et al. 2014).

[5]See: http://www.flow3d.de/.

[6]See https://www.esi-group.com/software-services/virtual-manufacturing/casting/procast-quikcast.

[7]See: http://www.Umberto.de/.

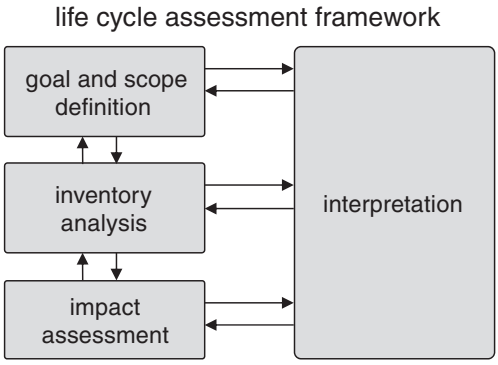

Fig. 2.37 Phases of a life cycle assessment (DIN EN ISO 14040 2006)

2.2.2.4 Evaluation

The previously introduced software Umberto™ also offers functionalities to conduct an evaluation of the modelled production system. This evaluation can be done from an economic perspective e.g., via applying a software based material flow cost accounting (MFCA) (Viere et al. 2010). However, an environmental perspective is pursued here. To support this perspective, the Umberto™ software offers the functionality to conduct a life cycle assessment (LCA), based on the previously conducted energy and material flow analysis and modelling (see e.g., Herva et al. 2012). Software tools to conduct a LCA are e.g., GaBi™,[8] SimaPro™[9] or openLCA.[10] A life cycle assessment follows the following phases: goal and scope definition, inventory analysis, impact assessment and interpretation (see Fig. 2.37; DIN EN ISO 14040 2006).

During the goal and scope definition, the system boundary, the aim and the depth of the study are defined (DIN EN ISO 14040 2006). The inventory analysis (also: life cycle inventory—LCI) compiles and quantifies all relevant input and output flows of the observed system and over the regarded temporal system boundaries. These input and output flows are broken down to the level of elementary flows, which directly enter and leave the system to and from its surrounding ecosystem. Usually, a whole life cycle of the investigated object sets this temporal system boundary (DIN EN ISO 14040 2006). The inventory analysis can be supported via an energy and material flow analysis by applying the above introduced methodologies. Therefore, an understanding of the system's internal flows can be enhanced and potential fields of action for later improvements can be derived (e.g. Herva et al. 2012). The third phase (impact assessment) translates the quantified elementary flows into potential environmental impacts of the observed system. Therefore, impact categories are defined, which characterise the resulting

[8]See: http://www.gabi-software.com.

[9]See: http://www.simapro.de.

[10]See: http://www.openlca.org/.

environmental impacts. By conducting life cycle impact assessments (LCIA) conversion factors for each elementary flow into the different impact categories have been calculated. Thus, for each input and output flow of an observed system, its resulting impact according to different impact categories can be estimated (DIN EN ISO 14040 2006).

A widely used methodology for conducting an LCIA is provided by the Institute of Environmental Sciences (Centrum voor Milieukunde, CML) at the Leiden University, Netherlands. According to this methodology, the following impact categories have been defined: Depletion of abiotic resources, impacts of land use (land competition), climate change, stratospheric ozone depletion, human toxicity, ecotoxicity (freshwater aquatic ecotoxicity, marine aquatic ecotoxicity, and terrestrial ecotoxicity), photo-oxidant formation, acidification, eutrophication (Guinée et al. 2002). Each impact category is expressed via characterising equivalence factors. E.g., all flows, which contribute to the impact category global warming potential, are expressed in carbon dioxide equivalents (CO_2eq.). This means, that their impact is scaled according to the equivalent amount of CO_2, which would have caused the same impact.

The impact categories, which are provided through the CML methodology can be characterised as midpoint impact categories, as they represent a problem oriented approach. They translate impacts into environmental schemes, which are expressed in the titles of the individual categories. Endpoint impact categories (like in the Eco-Indicator 99 methodology) follow a damage oriented approach (Goedkoop and Spriensma 2000). They translate impacts into more general issues of concern, which are represented by impact categories like human health, natural environment or natural resources (Bare et al. 2000).

The functionalities for modelling energy and material flows of production processes, simulating the resulting overall resource demand of whole production systems and evaluating them via an LCA are integrated in the software Umberto™. Therefore, this software is selected to support the later concept development and application.

Having the above described methodological support for the analysis, modelling and evaluation of energy and material flows in mind, the following section describes the specific environmental challenges and impacts of aluminium die casting from a technical perspective.

2.2.3 Environmental Impacts of Aluminium Die Casting

Following the taken perspective on energy and resource intensities and on the hierarchically organized aluminium die casting value chain, its environmental relevance will be introduced in the following section. After the aluminium die casting value chain has been technically introduced top-down from global aluminium flows to the die casting process in Sect. 2.1.2, it will now be discussed with a bottom-up-perspective. Starting from a process perspective over a process chain

perspective (individual for foundry and alloy supplier) to the value chain perspective, selected energy and resource flows as well as environmental challenges (e.g., emissions, material efficiency) will be addressed.

2.2.3.1 Process Perspective

Input and Output Flows

Although manufacturing processes of the main group primary shaping are still known as comparatively energy and resource efficient, (see Sect. 2.1.2; Fritz and Schulze 2010; Duflou et al. 2012) these processes also offer a lot of potential for a further reduction of their specific energy and resource intensity and environmental impact. Using the example of aluminium die casting, primary shaping processes demand lot of energy carriers, raw materials and auxiliary materials, which are exemplarily listed in Fig. 2.38 (Neto et al. 2008; Heinemann et al. 2013b; Dalquist and Gutowski 2004; U.S. Department of Energy 1999; Kim et al. 2003). Besides these input flows, diverse output flows occur in the die casting process and the die casting cell, which can be (waste-) emissions, (waste-) effluents and solid waste besides (wanted) semi-manufactured products (Neto 2008; Dalquist and Gutowski 2004). Figure 2.38 visualises and lists the physical input and output flows of the aluminium die casting process and the die casting cell as one integrated process model.

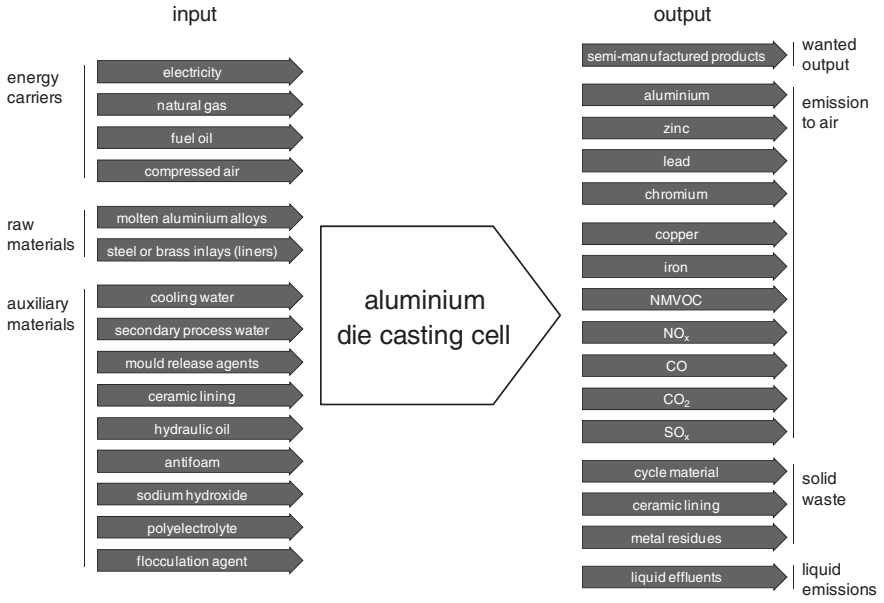

Fig. 2.38 Integrated process model of physical input and output flows of the aluminium die casting cell

Material Efficiency

Obviously, the biggest volumes and masses of the demanded materials are constituted by the processed aluminium alloys. This fact highlights the importance of material efficiency in the die casting process (Herrmann et al. 2011a; Hartmann 2013).

About one third of all aluminium products are near net shape castings. This means that about 30 % of their shot weight is removed from the product after the casting process, and gets resmelted as cycle material within the foundry. This ratio of non-value adding casted material to total shot weight stands for a very good material efficiency, compared to other manufacturing processes (Allwood et al. 2012).

Nevertheless, this ratio can vary a lot especially for different aluminium die casted products depending on the complexity of the product's geometry and the complexity of the gating system as well as the volume of the remainder, which depends on the geometry of the casting chamber and the plunger. Regarding some very complex products, up to 70 % of the shot weight cannot add value to the final product and have to be removed and resmelted iteratively within the foundry (see Fig. 2.39; Dilger et al. 2011).

This bad material efficiency is determined by the predefined geometry of the mould's cavity. Additionally, it often gets amplified by rejects, which result from suboptimal process parameters of the die casting machine during the ramp up phase of a new products (Heinemann and Herrmann 2013).

Energy Intensity

Besides the material efficiency, the energy intensity of the die casting process also offers options for improvement. Figure 2.40 shows an overview of the energy balance of the die casting cell, which is characterized by high non-value adding heat

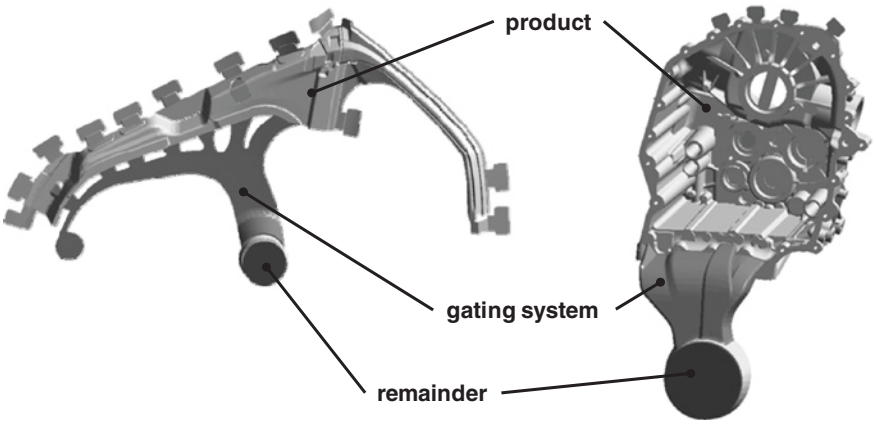

Fig. 2.39 Die casted product with gating system and remainder (Heinemann and Herrmann 2013)

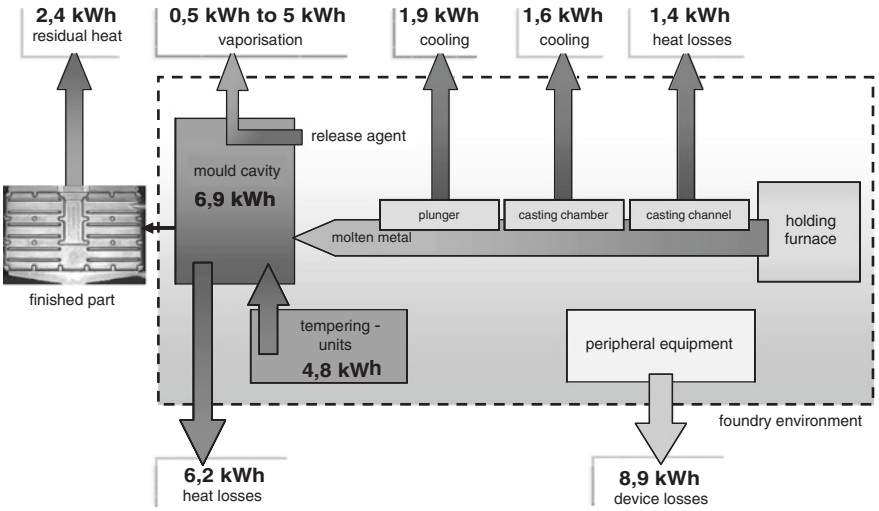

Fig. 2.40 Energy/heat flows in the aluminium die casting cell (Röders et al. 2006)

flows out of the die casting cell into the factory environment. The energy input of the die casting process is converted into heat and kinetic energy. Inside the die casting cell, which is the system boundary of Fig. 2.40, the energy is also transported via additional flows e.g., through the molten metal from the holding furnace into the mould cavity. The mould itself gets additional heat input from tempering units in order to guarantee a certain temperature level during the entry of the molten metal. Furthermore, the same tempering units can transport excess heat out of the mould via cooling channels. Further heat gets dissipated out of the mould and the die casting cell via the extraction of the warm cast, via the vaporisation of water and release agents, which get sprayed on the hot mould between the casting shots, as well as via the heat emissions of the mould (Röders et al. 2006).

Figure 2.40 also illustrates the interplay of all components of the die casting cell for the generation of a cast, as well as for the determination of the total energy intensity of the process. Regarding the total amount of dissipated energy in the die casting cell, the energy and resource intensity of the die casting process occurs to be non-satisfactory although the energy intensity is comparatively low compared to other manufacturing processes.

Focussing only on the electricity demand, Fig. 2.41 depicts the contribution of the single elements of the die casting cell to the cell's energy demand.

Again this breakdown of the electricity demand in a die casting cell points out the interplay of the main process with its peripheral equipment. The biggest contributors to the electricity demand beside the die casting machine are the heat generating processes, which take place in the tempering units and the holding furnace. Together with the die casting machine, they account for nearly three-fourths of the energy demand of the die casting cell during one process cycle. The peripheral

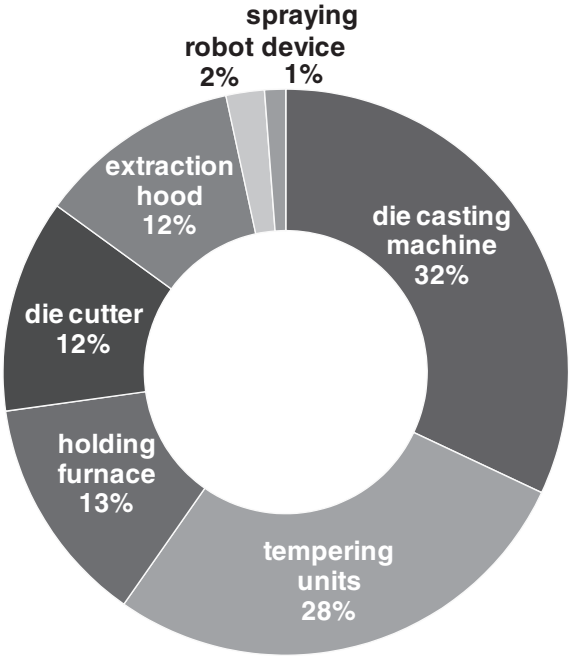

Fig. 2.41 Energy demand shares within a die casting cell during one process cycle (Hoffmann and Jordi 2013a; Jordi 2012)

machines die cutter and extraction hood account for nearly as much electricity demand as the holding furnace. Other peripheral processes sum up only to a negligible share of the cell's electricity demand.

2.2.3.2 Foundry Perspective

Energy Intensity

The aluminium die casting process chain defines the main shares of the energy and resource demand of the overall aluminium die casting foundry. Therefore, the total energy and resource demand of a foundry can give a hint about the dimension and relevance of the value adding process chain itself.

Electricity and natural gas are the main energy carriers that are processed in an aluminium die casting foundry. Electricity is used mainly for the following applications (Hoffmann and Jordi 2013c):

- building services (e.g., lighting, air conditioning, compressed air generation, exhaust air systems)
- IT infrastructure in administrative offices
- die casting cell (empowering hydraulic pump groups)
- furnaces (pot-type and shaft furnaces in smelters, holding furnaces in die casting cell)
- tempering units

Natural gas is used mainly for the following applications (Hoffmann and Jordi 2013c):

- melting of aluminium alloys
- heating the offices and production areas

The absolute amount of demanded energy carriers in the smelter is directly linked and proportional to the total mass of the molten metal (Neto et al. 2008; Solding et al. 2009). Extending the perspective and considering the entire foundry, the specific energy intensity along the aluminium die casting process chain seems to be connected to the overall capacity of the individual foundry. Thus, the specific energy intensity along the whole process chain in a foundry seems to decrease if the total mass of casted products increases. Verifying this assumption, Fig. 2.42 shows the total energy demand of 19 European aluminium die casting foundries in relation to their yearly output of aluminium die casted products (Jordi 2010; Hoffmann and Jordi 2013c).

This shows that for the energy intensity (energy input per product output) of aluminium die casting foundries there is a range from ca. 2–10 kWh/kg. As this range exists, it implies that there is room for improvements for all foundries that cannot rank themselves at the preferable frontier of this range.

This range of specific energy intensities also gets reflected when only the demand of single energy carriers is considered (see Table 2.3). This table lists the minimal, maximal and average energy intensities of 19 selected European aluminium die casting foundries, distributed over the energy carriers electricity and natural gas.

An earlier, non-representative survey among a small number of members of the North American Die Casting Association (NADCA) revealed a range of energy

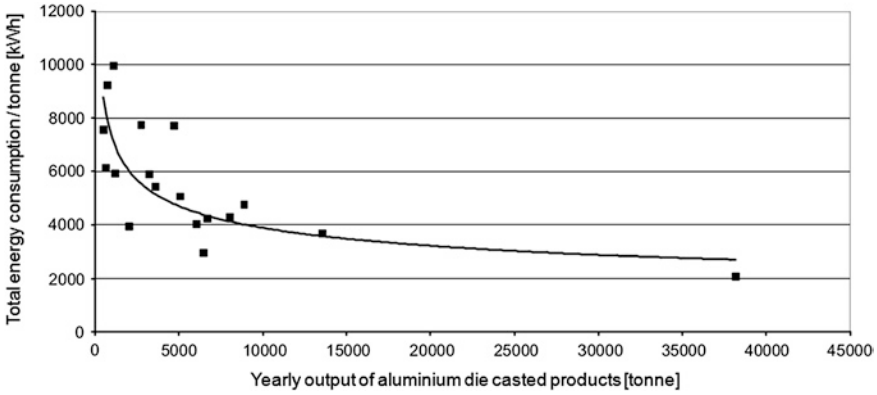

Fig. 2.42 Total energy demand (electricity, natural gas and fuel oil) of 19 foundries compared to their yearly production output (Jordi 2010; Hoffmann and Jordi 2013c)

Table 2.3 Specific energy intensity of 19 selected aluminium die casting foundries (displayed separately for electricity and natural gas) (Hoffmann and Jordi 2013c; Jordi 2012)

Energy intensity (kWh/t)	Minimum	Maximum	Average
Natural gas	1050	7390	3000
Electricity	790	4412	2603

Table 2.4 Specific energy intensities from North American sample foundries (displayed for the individual foundries with the biggest and the lowest energy intensity) (Brevick et al. 2004)

Energy intensity (kWh/t)	Minimum	Maximum
Natural gas	1179	17,598
Electricity	1241	1455
Total energy intensity	2419	19,053

intensities, which can be seen in Table 2.4. The responding die casting foundries had an annual output between 6713 and 24,983 t of aluminium die casted products (Brevick et al. 2004).

It can be observed that the smallest energy intensity (2.4 kWh/kg) is also close to the best European result (2 kWh/kg). In contrast, the largest energy intensity from the U.S. survey is nearly ten times higher, which is double the energy intensity compared to the largest result from the European survey. This fact becomes even more relevant, as the max. energy demanding foundry is already supplied with liquid aluminium alloys. This fact should decrease the energy demand of the smelter section of the foundry. However, the foundry with the biggest energy intensity is also the foundry with the smallest production output in this survey, which corresponds to the aforementioned assumption that bigger capacities and production volumes of foundries allow the implementation and operation of more energy efficient production processes.

Material Efficiency

One major influencing factor for the energy consumption of process chains inside aluminium die casting foundries is the mass of processed metal. In this context not only the absolute mass of metal input into the foundry system is relevant, but also the amount of internal cycle material as it gets resmelted again and again.

This challenge becomes evident when the average specific heat of aluminium alloys $\left(880\text{–}930\,\frac{\mathrm{J}}{\mathrm{kg}*\mathrm{K}}\right)$ as well as the range of melting and solidification temperatures (510–645 °C) are taken into consideration together with the fact, that up to 70 % of the shot weight of a product can be non-value adding cycle material (Honsel 2014).

But cycle material does not only have its source in the die casting cell: the mechanical treatment of the semi-manufactured casts also produces cycle material in the form of swarf (Allwood et al. 2012). Besides, rejects usually get detected in the mechanical treatment section as the main quality gates are located here (Pries et al. 2013; Heinemann et al. 2013b).

Besides the cycle material, which can be reused in the process chain directly, metal losses also decrease the material efficiency of the process chain within the foundry. According to Neto, these losses occur in all processes along the process chain. About 0.04 % of the mass of alloy inputs gets lost via air emissions, and 0.72 % of the mass of alloy inputs are lost as dross in the melting section of the foundry. In the die casting cell, a small share of the material (0.0005 % of the alloy entering the casting sub-process) also gets lost via air emissions. Lost swarf particles and other losses in the finishing department, can account for up to 2 % of the metal losses. Drag-out of aluminium via liquid effluents is negligible. The total losses along the process chain have to be compensated by adding up to 6 % more input material compared to the output of the process chain (Neto et al. 2008).

Due to the low material efficiency of the die casting process chain, a large extra amount of metal needs to be smelted iteratively and energy intensively to compensate the metal losses, and to resmelt the cycle material. Figure 2.43 illustrates this relation between material efficiency and energy intensity of the die casting process chain. Thus, with every cast a large portion of the used energy has not added value but was used to keeping material in the loop within the system.

2.2.3.3 Alloy Supplier Perspective

Energy and Material Efficiency

According to a study by the Austrian Federal Environment Agency, the specific energy intensity, as well as the material efficiency (yield) of an alloy supplier,

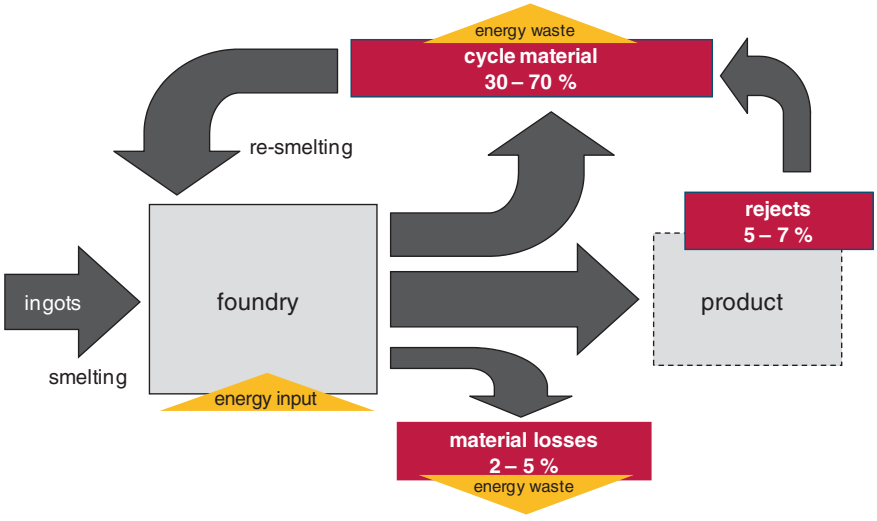

Fig. 2.43 Alloy mass flows, material efficiency and related energy flows in the aluminium die casting process chain inside a foundry (Herrmann et al. 2013b; Dilger et al. 2011)

which focuses on the generation of secondary aluminium alloys, strongly depends on the installed type of equipment. The energy intensity and yield of metal of the possible smelting aggregates especially depends a lot on their individual design and original purpose. Each smelting aggregate design is favourable for specific qualities of aluminium scrap input material. The quality of the scrap inputs is influenced by its granularity, the size of the single blocks or particles and the degree of organic contamination, which determines the amount of required salt additives. Table 2.5 lists possible types of smelting aggregates, the individual metal yield and specific energy intensity for the production of 1 t of molten metal as well as the individual quality of scrap input, which the smelting aggregate was intentionally designed for (Boin et al. 2000).

It needs to be stated that all introduced oven designs are also able to smelt other qualities of scrap input aluminium, and usually only a limited number of ovens and smelting aggregate designs are installed at an alloy supplier. Therefore, from an energy and material efficiency perspective, it is even more important that the alloy supplier chooses the right kind of equipment and input quality for his activities. If a pre-selection of the input qualities is not possible, a pre-treatment of the scrap input aluminium should be done (e.g., sorting, smouldering) in order to qualify the scrap also for more efficient oven designs (Boin et al. 2000).

Waste and Emissions

Besides input oriented aspects such as energy intensity and material efficiency, the consideration of process emissions also is of environmental relevance for the alloy

Table 2.5 Typical energy intensities and metal yields of secondary aluminium production processes (Boin et al. 2000)

Process, smelting aggregate design	Scrap input, input material	Typical yield of metal (%)	Energy intensity (kWh/t)
Swarf drying	Wet swarf and turnings	80–90	600–1050
Melting			
-Induction furnace	Pigs, ingots, swarf and turnings	95–99	700–928
-Closed-well-furnace	Clean scrap, organically contaminated scrap	88–95	700–1194
-Rotary drum furnace (static)	Swarf and turnings, pellets, shredder scrap, post industrial scrap	75–92	1225–1306
-Rotary drum furnace (static + O2-burner)	Swarf and turnings, pellets, shredder scrap, post industrial scrap	75–92	519–569
-Rotary drum furnace (tilting)	Dross, pellets	50–80	Approx. 742
Refining, alloying, holding	Alloying elements (e.g., Si, Cu, Zn, Ti, Mn, Mg, Ni)	95–98	400–722
Total alloy supplier		75–85	1200–2500

supplier. Similar to the consumption of input materials and energy carriers, waste in the form of solid salt-slag, as well as the composition of gaseous emissions, also depends on the chosen type of smelting aggregate. Further kinds of waste or residues are filter dust, furnace lining and dross. Table 2.6 shows the origin of the kinds of waste as well as their amount, which occurs during the production of 1 t of secondary aluminium alloys (Boin et al. 2000).

Table 2.7 shows the typical levels of emissions to air from selected furnaces, which can be used in the secondary aluminium production and the scrap quality, which was intended to be smelted in a furnace of the individual design. The emissions are referenced to 1 t of metal, which leaves the furnace as valuable output (Boin et al. 2000).

2.2.3.4 Value Chain Perspective

Material Efficiency and CO_2eq. Emissions

As mentioned above, the energy intensities of the aluminium die casting process and of its value chain go hand in hand with the overall material efficiency. The same goes for the corresponding CO_2eq. emissions of the value chain.

The energy intensities of the foundry and aluminium supplier have already been addressed in the previous paragraphs. Therefore this section shall link both

Table 2.6 Waste from secondary aluminium production (Boin et al. 2000)

Waste and/or residues	Origin	Volume (kg/t Al)
Salt slag	Melting in rotary drum furnace	300–500
Filter dust	Exhaust gas cleaning	10–35
Furnace lining	Melting furnace	Approx. 2
Dross	All furnaces not using salt, cleaning of smelter, foundries	Approx. 25

Table 2.7 Typical levels of emissions to air from selected processes in the secondary aluminium production (Boin et al. 2000)

Smelting aggregate	Scrap input	Emissions to air (g/t metal)					
		HCl	HF	Dust	NO_2	VOC	CO
Tilting hearth furnace	Clean scrap blocks	2–20	0.1–1.5	1–45	200–900	5–40	30–180
Closed-well-furnace	Clean scrap blocks, organically contaminated scrap	20–600	0.2–1.5	2–25	8–900	5–35	20–100
Rotary drum furnace (static)	Swarf and turnings, pellets, shredder scrap	50–400	3–15	4–55		150–250	

stakeholders, and give a hint on the resulting CO_2eq. emissions, which also result from further upstream activities of the value chain like the raw material generation.

Figure 2.44 illustrates this link by merging the visualized interaction of material and energy flows of the foundry and the alloy supplier in one common picture. This picture gets enriched with information about the carbon dioxide equivalent emissions, which occur from the consumption of energy carriers in the foundry and the alloy supplier, as well as from the upstream processes for the generation of input materials such as primary aluminium, scrap aluminium and alloying elements (Herrmann et al. 2013b).

It becomes obvious that the issue of material efficiency and intensity has a major influence on the energy consumption. The material efficiency of the aluminium die casting process determines the amount of cycle material, which needs to be resmelted. Furthermore, the overall material intensity, as well as the share of processed primary and secondary aluminium, determines a large share of the carbon dioxide equivalent emissions of the value chain (Herrmann et al. 2013b; Heinemann et al. 2013b). Thus, the foundry's consumption of energy carriers for the production of 1 t of final aluminium die casted products accounts for more than 2 t of CO_2eq emissions. The necessary upstream production and supply of alloyed aluminium ingots accounts for more than 1.6 t of CO_2eq. emissions (secondary aluminium alloys) and for more than 11.5 t of CO_2eq. emissions (in the case of primary aluminium alloys) respectively (Herrmann et al. 2013b; Heinemann et al. 2013b). The different environmental challenges using primary or secondary metal inputs will be analysed in the following section.

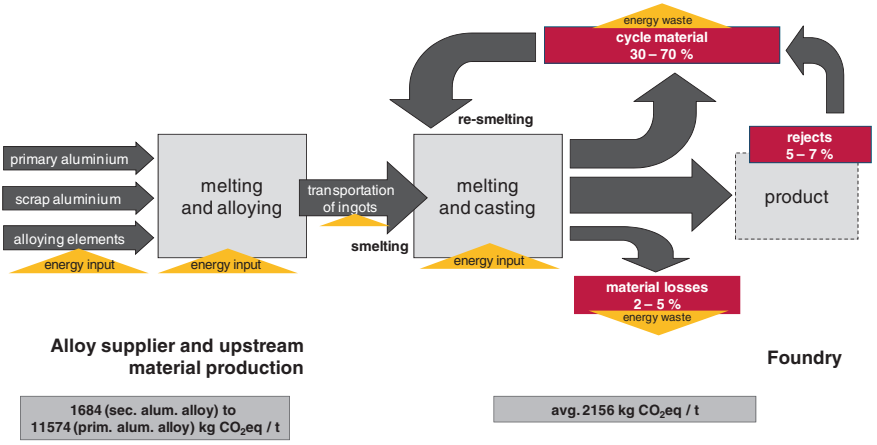

Fig. 2.44 Alloy mass flows and energy flows, material efficiency and related CO_2eq.-emissions along the aluminium die casting value chain (Herrmann et al. 2013b)

Primary Versus Secondary Aluminium Production

As stated above there is a significant difference in the global warming potential (in terms of carbon dioxide equivalent emissions) for producing aluminium alloys which are based on primary or secondary aluminium. The same is true for other environmental impact categories as a life cycle assessment from the European Aluminium Association can confirm (see Fig. 2.45; EAA 2013)

From the results of this life cycle assessment it can be seen that in every environmental impact category, the production of primary aluminium causes significantly more environmental harm than the secondary aluminium production. Furthermore the relevance of the large amount of demanded energy can be interpreted from this assessment.

Logožar et al., Quinkertz and Dienhart identified that the main energy demand contributors for producing 1 t of primary aluminium ingots represent the consumption of electricity, which increases its contribution to the carbon dioxide equivalent emissions, compared to the consumption of fossil fuels (Logožar et al. 2006; Quinkertz 2002; Dienhart 2003; www.umweltdatenbank.de 2014).

The total energy input (thermal energy and electricity), which is needed for the production of 1 t of primary aluminium, sums up to a range from 18610 to 33610 kWh (from bauxite mining to electrolysis) (Dienhart 2003).

Chapman and Roberts compare the energy intensities of primary and secondary metals for aluminium as well as for copper and steel. Again, the energy oriented advantage of secondary metals gets highlighted, especially when considering the comparatively large energy demand for the primary aluminium production,

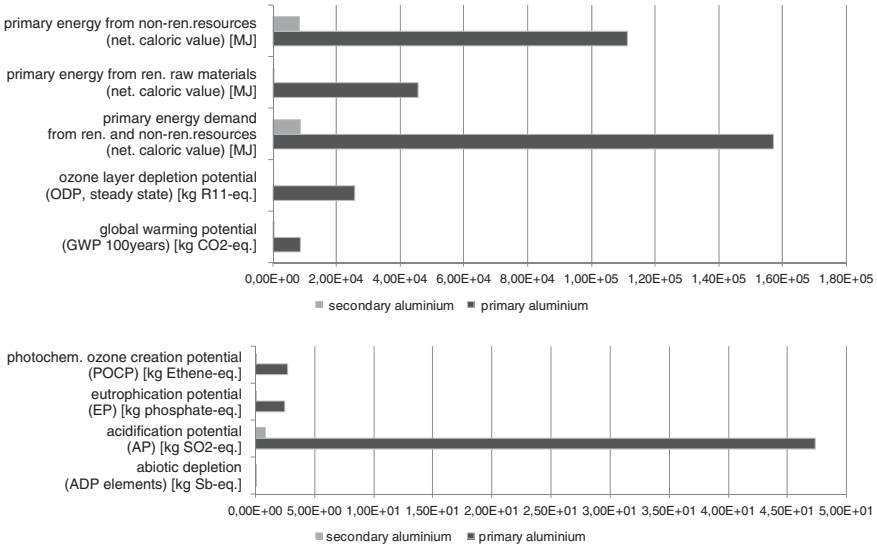

Fig. 2.45 Main environmental impacts from primary aluminium and secondary aluminium production (per t of ingot) (EAA 2013)

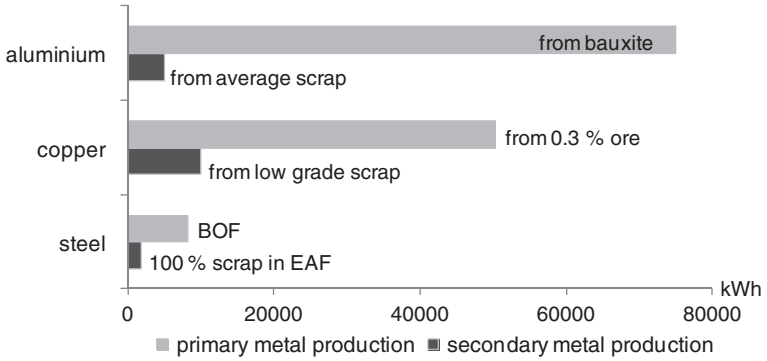

Fig. 2.46 Comparison of energy inputs for various metals: primary versus secondary production (Chapman and Roberts 1983; Wernick and Themelis 1998)

which was even higher two decades before the study of Dienhart (see Fig. 2.46; Chapman and Roberts 1983).

However, even if the large energy consumption and environmental impact of the primary aluminium production makes secondary aluminium appear more favourable, secondary aluminium is not feasible for all possible technical fields of application. Besides, the collection and preparation of the scrap metal inputs for the generation of secondary aluminium, as well as downgrading effects during redundant recycling circles, also create challenges for the increased use of secondary aluminium.

Recycling, Downgrading and in-Use-Stocks of Aluminium

Aluminium is often called a sustainable metal as its recycling should be redundantly possible without any decrease in the metal quality. This statement includes the assumption, that due to the good recyclability, a large share of the global demand can be satisfied by secondary aluminium (e.g., Efthymiou et al. 2010; Baldwin 2007; EAA 2007).

There are two arguments that contradict to this statement. On the one hand, a continuous recycling of aluminium end-of-life products usually leads to a concentration of alloying elements, which limits the possible use of the resulting secondary alloy (downgrading). This effect can only be abated by adding primary aluminium to reduce the concentration of contaminating elements/impurities (e.g., Paraskevas et al. 2013; Gaustad et al. 2011; Wernick and Themelis 1998). On the other hand, due to its long life time, large in-use-stocks and often poor recycling quotas of many aluminium products, there is not enough scrap aluminium input material to satisfy the global aluminium demand. Therefore, primary aluminium has to enter the global aluminium system continuously (e.g., Liu and Müller 2013; Rombach 2013).

Rombach performed a meta-analysis of different studies, which investigated the global recycling content of six different metals. Although the absolute results have to be compared and interpreted with caution due to inconsistent underlying calculation schemes, the resulting table is feasible to highlight the relatively small recycled content of aluminium. Rombach explains this small recycled content with incomplete collection of scrap, losses during the scrap processing and the large in-use-stock of aluminium products (see Table 2.8; Rombach 2013). Table 2.8 also reminds about the amounts of circulating post industrial scrap, which does not enter the use phase of a product, but gets resmelted directly in the value chain.

Liu and Müller illustrated that this global in-use-stock of aluminium is not even large, but also steadily growing (Liu and Müller 2013).

According to Rombach the total in-use-stock of aluminium has a size of about 700 Mt, which would be ca. 75 % of the total amount of the primary aluminium that has ever been produced. In 2010, 50 Mt of new aluminium products entered the use phase, whereas in the same year only 11 Mt of aluminium scrap have been collected and recycled. So the difference between product output and aluminium scrap input needs to be replenished by primary aluminium.

Nevertheless, recycling of aluminium is an important issue to decrease the energy intensity of aluminium products. Furthermore, the large in-use-stocks of aluminium can be considered as future raw material sources. Thus efficient recycling of aluminium alloys, which ideally maintain the quality and specifications of the recycled alloy, will become more and more important.

But the maintaining of alloy specifications is an especially critical issue in aluminium recycling as mentioned above. Besides magnesium and zinc, all other alloying elements are almost impossible to remove once they have been added to the alloy (Nakajima et al. 2010).

Due to increasing and further downgrading in-use-stocks of already downgraded aluminium alloys from automotive applications, Modaresi and Müller forecast that in 2050 an annual amount of 3.3–18.3 Mt of aluminium scrap will leave the industrial system without being recycled. This resource loss corresponds to 3–18 % of the primary aluminium production of the year 2050 and also represents a loss of energy saving potential of 240 TWh/year, which is close to the total annual energy demand of a medium-sized country like Spain (268 TWh/year) (Modaresi and Müller 2012).

Table 2.8 Recycled content of global metal production

Metal	World (%)	Europe (%)	Year
Steel	40[a]	50[a]	2008, 2004
Nickel	40	49[a]	2008, 2000
Aluminium	**22** (**37** %[a])	**23** (**40** %[a])	2010, 2007
Copper	37	65[a]	2006
Zinc	31	49 (Germany)	1997
Lead	57	74	2005

[a]Including post industrial scrap Rombach (2013)

Paraskevas et al. have visualized the problem of alloy downgrading during cascading recycling circles (Fig. 2.47; Paraskevas et al. 2013).

Due to the concentration of impurities, primary aluminium alloys as well as unalloyed primary aluminium degrade to low alloyed wrought aluminium alloys after the first recycling cycle. These alloys get transformed into high alloyed cast aluminium alloys after further recycling cycles, unless the molten aluminium scrap does not get diluted with primary aluminium. Another strategy to avoid the downgrading of the metal quality is to collect and sort only very clean high quality aluminium scrap of exactly that alloy, which shall be achieved after remelting the scrap inputs. Paraskevas et al. illustrated also the resulting open and closed recycling loops from these two abatement strategies (dilution with primary aluminium, single alloy strategy) (see Fig. 2.48; Paraskevas et al. 2013; see also: Graedel et al. 2011; Dubreuil et al. 2010).

Obviously, the single alloy strategy forces the alloy supplier and the foundry to gain maximum control over the scrap aluminium flows. So it can be applied usually only for post industrial scrap. Otherwise a strong collaboration with the

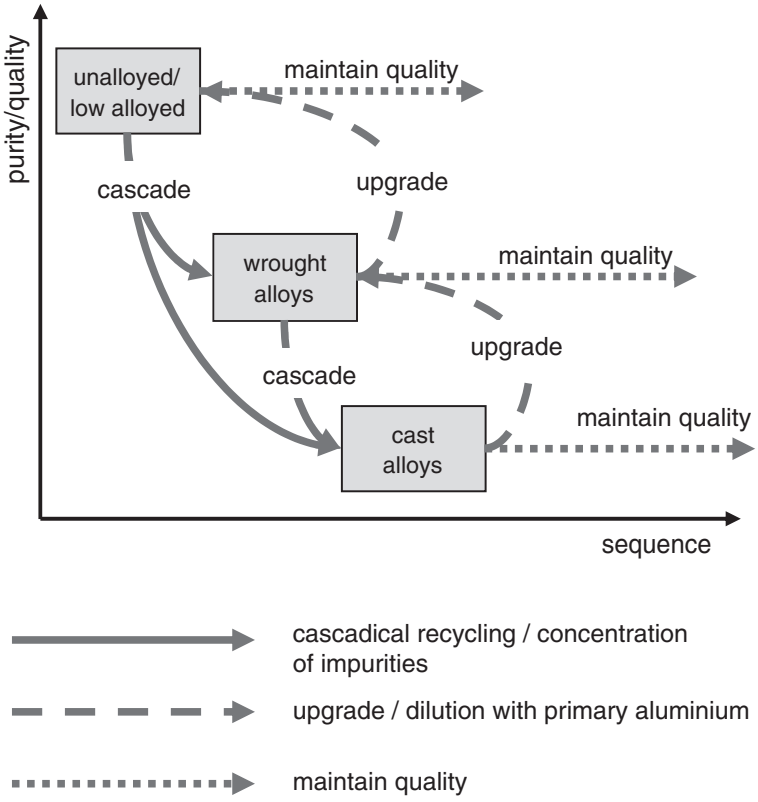

Fig. 2.47 Aluminium cascade recycling chain (Paraskevas et al. 2013)

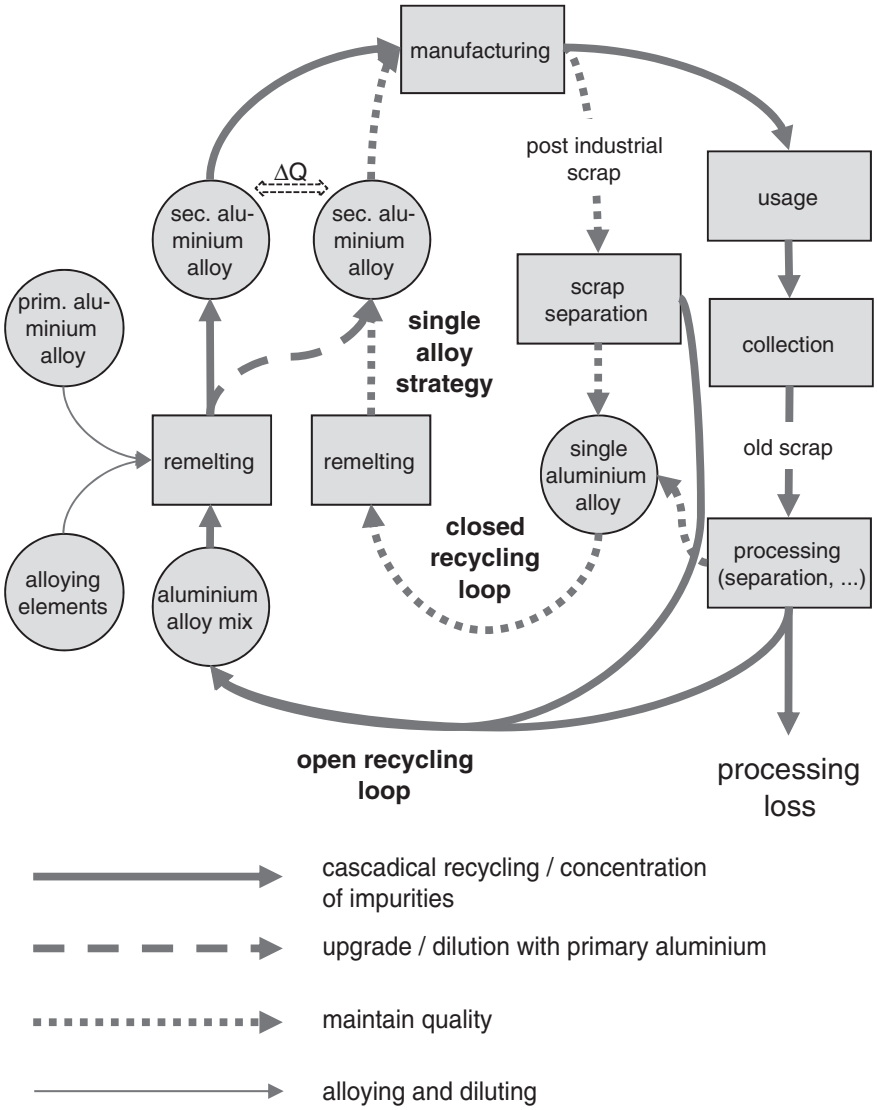

Fig. 2.48 Aluminium recycling options (Paraskevas et al. 2013)

customer of the final aluminium products as well as good control over the collecting system needs to be established (Paraskevas et al. 2013).

To support such strategies Koffler and Florin suggest the introduction of more diversified scrap metal prices, which are based on the scrap's pureness respectively on its incorporated concentration of alloying elements and other contaminants (Koffler and Florin 2013).

Concluding the aforementioned issues about aluminium recycling, downgrading and in-use-stocks it has to be stated, that despite its relatively good recyclability, the global society's demand for aluminium products can never be satisfied completely with secondary aluminium alloys. Thus, regarding the large environmental burdens from primary aluminium production, increasing material efficiency during manufacturing processes and decreasing material intensities of aluminium products are vital for making aluminium value chains more sustainable. The following chapter introduces first existing approaches, which try to cope with these challenges by increasing the energy and resource efficiency of industrial production.

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