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Materials and sustainable development

Paul KOLTUN

CSIRO, Process Science and Engineering, Gate 5, Normanby Rd., Clayton, Victoria, 3168, Australia

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Abstract: Sustainable development is a concept, which involves social, ecological and economic objectives, and requires to sustain the integrity of resources exploitation, the direction of investments, the orientation of technological development and institutional change. Although there is still much confusion and conflict about exact meaning of sustainable development, many agree that sustainable development is about satisfying social, environmental, and economic goals. While the concept is generally accepted and relatively easy to comprehend, the difficulty arises in trying to apply the principles of sustainable development in practice. One of the difficulties is need to measure the “level of sustainability”. The desirable characteristics for sustainability indicators have to include: simple to calculate, useful for decision making, and robust in indicating progress toward sustainability. The exergy analysis approach based on full life cycle assessment (LCA) of the materials and technologies is a useful metrics to evaluate mitigation of greenhouse gas (GHG) emissions associated with industrial eco materials and technologies. The metrics is used for reducing dimensionality on the input side by combining material and energy streams and output side reducing different characterisation factors to a single “unsustainability” indicator in a theoretically rigorous manner. The adopted approach has been illustrated on a few examples associated with Australian aluminium industry.

Key words: sustainability measurement; exergy analysis; life cycle assessment (LCA); eco-efficiency

1 Introduction

For the past few decades the need for introducing environmental requirements into design and development of materials and products became a vital issue. The sustainable development agenda is now significant within public and industrial sectors and is one of the fundamental objectives. Current world economies are materials and energy intensive. One of the most advanced, US economy, is among the most material intensive economies in the world, extracting more than 10 t of “active” material per person each year. And most of these materials become waste relatively quickly (only 6 % of this active material is embodied in durable goods; the other 94% is converted into waste within a few months of being extracted[1]. Finite resources and space and increasing global population are fuelling the 'more from less' imperative. The management of natural resources and reducing the environmental impact of materials and manufacturing technologies is key area of importance. The way that we currently produce goods and services is unsustainable and contributes significantly toward many of today’s environmental problems. European Union (EU), the “Ecodesign Directive” ensures that manufacturers consider energy use and other environmental impacts during the conception and design phase of a product[2]. And it has been extended to cover products which do not necessarily consume energy during use but which have an indirect impact on energy consumption. Fig.1 illustrates the transition from *business as usual* to sustainable development. A new focus on sustainable development requires a new way of thinking.

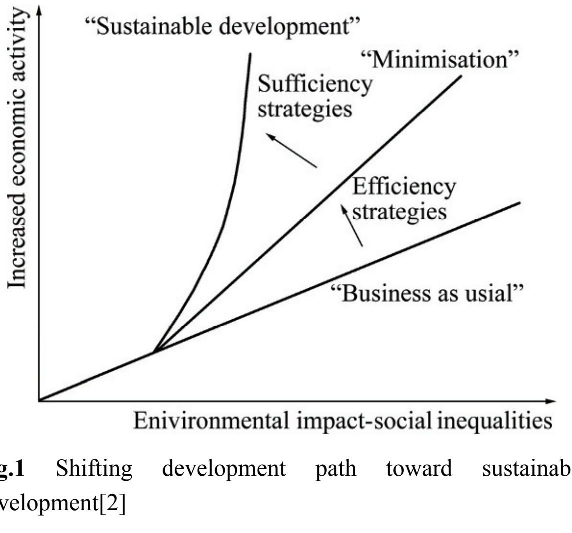

Fig.1 Shifting development path toward sustainable development[2]

Corresponding author: Paul KOLTUN; Email: paul.koltun@csiro.au

Unfortunately, sustainability is a broad but not precisely defined term, it's basically a guiding principle or a goal laid down by the United Nations Conference on Environment and Development (UNCED) in Rio de Janeiro, 1992 (attended by representatives from 150 countries) in which an action plan was adopted, known as Agenda 21[3] for the pursuit of the sustainable development. It was pointed out that achieving sustainable economic development will require changes in industrial processes, in the type and amount of resources used and in products which are manufactured[4]. The most commonly used current definition of sustainability came from the report[5] in 1987 as *meet the needs of the present without compromising the ability of future generations to meet their own needs*. This report prompted numerous actions, which called on governments, local authorities, businesses and consumers to define and adopt strategies for sustainable development.

However, there is considerable controversy over the appropriate definition of sustainability. There have been many debates on the exact mining and what should be ascribed to the term *sustainability*. Apparently from the mentioned above[5] it was suggested that the sustainability is: *"A process of change in which the exploitation of resources, the direction of investments, the orientation of technical development, and institutional change are all in harmony and enhance both current and future potential to meet human needs and aspirations."*[6]. There are number of other definitions in the literature. Besides from being unsatisfactory from the stand-point of reflecting non-economic elements of sustainability, these definitions share another common feature: they are unquantifiable and unverifiable.

Although there is still much confusion and conflict about exact meaning of sustainable development, many agree that sustainable development is about satisfying social, environmental, and economic goals. Thus, it is necessary to consider the data that we should collect and the metrics that we should use in order to capture the three aspects of sustainability. Fig.2 illustrates sustainability for materials production and technological processes.

While the concept of sustainability is generally accepted and relatively easy to comprehend, the difficulty arises in trying to apply the principles of sustainable development in practice. It is understandable that cleaner production of materials, goods and services is the way for sustainable development (i.e. production in a way in which resources and energy are used in an efficient way and only small amounts of waste and emissions are produced). Another important factor is use of renewable resources. Minimising use of resources and cutting back emissions can also decrease the costs of a given process. The difficulty here is how to measure the *level of sustainability*. The second law of thermodynamics indicates that no technological solution can lead to sustainability. This law implies that decreasing entropy in a system must result in an even greater increase in entropy in the surroundings[7]. However, a comparison of the state of sustainability between different systems is possible. To make this comparison it is important to develop metrics that can be used to measure the guiding principle of sustainability. There are two classes of metrics in development to indicate the state and performance of a system: 1) content indicators—indicate the state of a system; 2) performance indicators—measure the behaviour of a system and mostly dedicated of measuring of improving the sustainability characteristics of a system[8]. Dozens of indicators have been suggested for use in determining improvements made to materials production and technological processes (See, for example[8−11]. In spite numbers of different approaches have been proposed to define the indicators, there is still no standardised methodology to enable a consistent comparison and identification of more sustainable options. Before a new indicator is proposed for measurement of sustainability (more precisely to say unsustainability) level, it is important to understand indicators which are already in use.

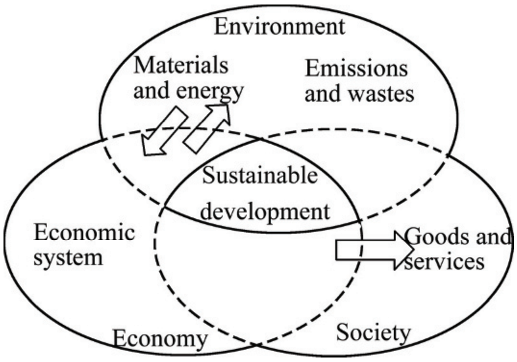

Fig.2 A model of sustainable development

2 Review of different currently adopted sustainability metrics

The world wide adopted approach for measuring of sustainable development is using sustainable development indicators (SDI). Indicators are a key tool for encouraging progress toward sustainable development. To be effective, they must communicate useful information that enables situations to be understood and decisions to be made[12]. Any set of SDI, however, must cover the environmental, social, and economic impacts of a process or product and consider inter- and intra-generational equity. The numbers of approaches have been developed by various researches[13−14]. Many of these approaches put the emphasis on the environment only[15−16]. Such SDI are more indicators of environmental performance than those of sustainable development. A related approach has been developed by the World Resource Institute (WRI)[17], which concentrates more on using resources and emissions rather than impacts. This approach suggests to use four keys of environmental performance indicators for a manufacturing process or industrial activity: material use, energy consumption, pollutant release, and non-product output. The other more advance approaches alongside with the environmental try to include additional factors, such as twelve principles of eco-design[18], additionally including financial and social factors[19]. The more comprehensive approach was suggested in Ref.[20], where the standardisation of SDI has been proposed. Those indicators should enable to identify more sustainable options through: a) comparison of similar products made by different companies; b) comparison of different processes producing the same product; c) benchmarking of units within corporation; d)rating a company against other companies in the (sub-) sector; e)assessing progress towards sustainable development of (sub-) sector[20]. The life cycle thinking is embedded in the methodology and indicators are based on the function of the system delivers. The set of proposed indicators in this approach is presented in Table 1.

Although the proposed SDI recognise the importance of life cycle consideration, on the other hand they are too complicated as they include a large number of indicators which may be difficult to quantify or understand. This increases the difficulty of their implementation in practice and even does not guide the decision-making process effectively.

Other developments are based on eco-efficiency approach or eco-efficiency indicators which analyze both environmental and economic aspects in an integrated fashion. For example, World Business Council for Sustainable Development (WBCSD), a coalition of 120 international companies from more than 20 major industrial sectors, designed tool to promote improving environmental and economic performance at a company level by addressing the whole life cycle of a product or process[21]. The seven measures of proposed eco-efficiency are: 1) material intensity of goods and services; 2) energy intensity of goods and services; 3) toxic desperations; 4) material recyclability; 5) sustainable use of renewable resources; 6) product durability; 7) service intensity of goods and services. These measures of environmental performances should be normalised with respect to an economic indicator taken to be value added. Social factors are not integrated in the eco-efficiency approach although they are recognised. The models are transferred into monetary units for benefits and risks of non-economic dimensions (environment).

There are number similar approaches to eco-efficiency indicators (for example, Refs.[22−23]) These SDI typically include measures of pollutant output, process performance, and direct and indirect effects of an activity on the environment and society. In general, these approaches categorise the environmental effects of industrial processes into input side and output side indicators, as shown in Fig.3. The input and output

Table 1 Standardised triple bottom line (TBL) indicators for sustainable development[20]

Environmental indicator		Economic indicator		Social indicator	
Environmental impacts	Environmental efficiency	Financial indicators	Human-capital indicators	Ethics indicators	Welfare indicators
Resource use	Material and energy intensity	Value added	Employment contribution	Preservation of cultural values	Income distribution
Global warming	Material recyclability	Contribution to GDP			
			Staff turnover	Stakeholders inclusion	Work Satisfaction
Ozone depletion	Product durability	Expenditure to environmental protection			
			Expenditure on health and safety	Involvement in community projects	
Acidification	Service intensity				Satisfaction of social needs
Eutrophication	Voluntary actions	Environmental liabilities	Investment in staff development	International standards of conduct: business dealings, child labour, fair prices, collaboration with corrupt regimes	
Photochemical Smog	Environmental management				
		Ethical investments			
	Environmental improvements				
Human toxicity					
Solid waste	Assessment of suppliers				
				Intergenerational	

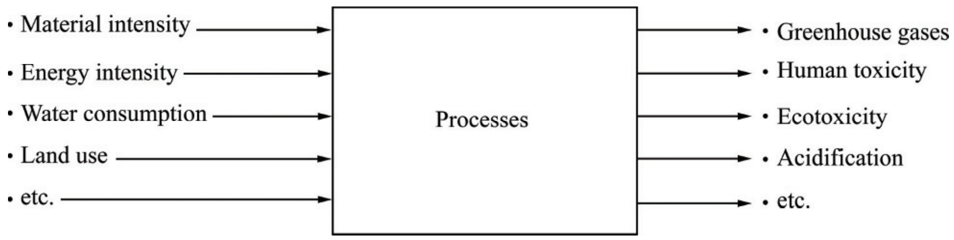

Fig.3 Sustainability indicators[23]

variables are normalized by measures, such as mass of product, dollars of value added, or dollars of revenue[23]. Unfortunately, such approaches for practical metrics face shortcomings. Some of those shortcomings are: a) large number of often conflicting metrics and variables which make the task quite challenging; b) adding the mass or energy of different streams to compute the material or energy intensity focuses only on the first law of thermodynamics and ignores the second law, which can lead to results such as higher quality but scarce energy source; c) eco-cost is calculated only on emissions based from Life Cycle Assessment (LCA), which have to be subjectively weighted due to different environmental impacts.

The use of thermodynamic methods at multiple spatial scales to overcome these shortcomings while retaining the attractive characteristics of practical sustainability metrics is highly desirable. Industrial progress toward sustainability requires meaningful, practical and scientifically sound SDI. The use of thermodynamic methods for evaluating sustainability of industrial products and processes is motivated by the fact that all activities on the Earth rely on the availability of energy and its conversion to various goods and services. Ultimately, all planetary activities depend on exergy or available energy [24], making it the ultimate limiting resource. Exergy provides a scientific way to compare and combine streams of material and energy, and represents environmental impact and information content. It has been most popular for analyzing chemical and thermal processes to improve their efficiency[25].

3 Development of exergy based indicator for evaluating eco-efficiency

As mentioned above the desirable characteristics for industrial sustainability indicators have to include: simple to calculate, useful for decision making, understandable to different audiences, cost-effective and robust in indicating progress toward sustainability metrics. The proposed here approach enhances the metrics described in Ref.[26]. This approach uses exergy for reducing dimensionality of the input and output sides in Fig.3 by combining material and energy streams in a theoretically rigorous manner, as the every technological process far from thermodynamic equilibrium requires low entropy energy (This is the case for natural ecosystems also, as well as for the human economy[27]). When referring to the purely material and energetic dimension of the economic process the term industrial metabolism was introduced. It comprises the extraction of energy and matter from the environment and the disposal of dissipated energy and degraded matter into the environment. In a metaphorical sense, industrial metabolism is understood as interconnected system of all materials and energy transformations that enable the economic system to function, i.e., to produce and consume[28]. On this basis the economic process comprises three different kinds of activities: production, consumption and reduction. Producers employ low entropy energy to transform raw materials into consumable goods. These are used by consumers to increase their welfare. After use, they constitute waste. For this reason current economy is not self-contained but vitally depends on interference with the natural environment. As such the economy-environment interaction is an exchange of energy and matter and laws of thermodynamics provide a useful analytical framework. Thus, society’s metabolism may be rigorously deduced in energetic and material terms[29]. Therefore, for applications in the areas of mechanical and chemical engineering, as well as in economics, it is useful to relate the system’s ability to perform work to a standardised reference state of the environment. The concepts of energy and energy efficiency are inadequate to properly analyze such processes, since they do not account for the inevitable loss of the quality of energy as dictated by the second law of thermodynamics. To avoid these difficulties the concept of exergy was introduced, which is also commonly called available energy or available work and combining the insights from both the First and Second Laws of Thermodynamics[25]. Fig.4 illustrates the exergy concept for chemical processes.

The exergy analysis is as a powerful instrument to measure sustainable development. An exergy balance can be applied for different levels, from a whole industry to a unit of operation. This combination is possible because the utility of any material or energy stream is in

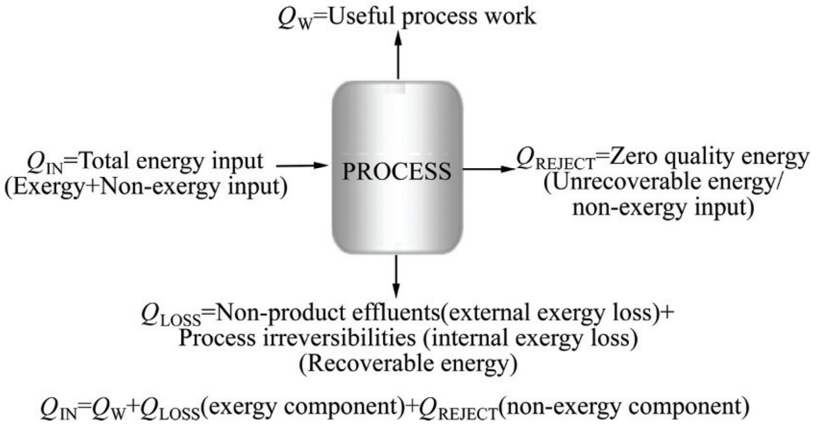

Fig.4 Concept of exergy in chemical processes[30]

its ability to do work, and exergy represents this useful part of any material or energy stream. It is quantified as the thermodynamic distance or distinguishability from the reference environment. The following exergy definition is usually used[31]: Exergy is the maximum amount of work that can be obtained from a stream of matter, heat or work as it comes to equilibrium with a reference environment. It is a measure of the potential of a stream to cause change, as a consequence of not being completely stable relative to the reference environment. Exergy is not subject to a conservation law, but it is destroyed due to process irreversibility. The strong link between exergy consumption and sustainability is based on the fact that all real processes consume exergy and thus, all technological activities are limited by our ability to supply exergy to the processes. As exergy amount is measured (by definition) relatively to the earth's natural environment, it creates another connection between exergy and sustainability. Some examples of differences between energy and exergy are presented in Table 2[32]. It shows that hot water and steam with the same enthalpy have different exergy or quality values Fuels like natural gas have exergetic values comparable to their net combustion value. Work or electricity has the same exergy as enthalpy, but heat has a lower exergy, or quality of energy, compared with work and therefore, heat cannot be converted into work with 100% efficiency.

Table 2 Examples of energy and exergy of different matters (Reference state 298 K, [32])

Material	Energy/J	Exergy/J	Quality
Water 80 °C	100	16	0.16
Steam at 120 °C	100	24	0.24
Natural gas	100	99	0.99
Electricity/Work	100	100	1.00

The concept of exergy regarded as a measure of available energy and related to the sum of entropy production can be presented as[25]

$$\delta E = T_0 \sum \Delta S \tag{1}$$

where T_0 is the temperature of surroundings; $\sum \Delta S$ is the sum of entropy increase.

It should be pointed out that exergy is neither equivalent nor proportional to entropy. Although an increase of entropy also means a loss of exergy, entropy lacks the absolute reference that exergy has to the conditions of the natural environment[33].

The thermostatic state of the system (see Fig.5) can be described by the extensive properties, like: internal energy U, volume V, entropy S and the amount of substances present n_i $(i=1, 2, \cdots N)$, and intensive properties, like: temperature T, pressure P, and chemical potential μ_i. The amount of work that the system can do when it is brought to equilibrium with its environment may be defined as:

$$E = (U - TS + PV + \sum n_i \mu_i + \upsilon^2/2 + zg) - (U - TS + PV + \sum n_i \mu_i + \upsilon^2/2 + zg)_0 \tag{2}$$

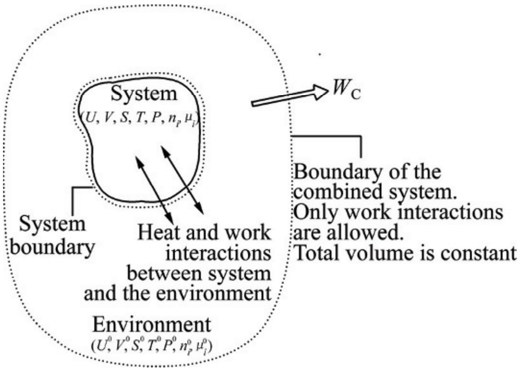

Fig.5 Combined system and environment (T, V, S, T, P, n_i, μ_i are properties of the system and environment, superscript 0 denotes state of the environment; W_C is the work developed by the combined system)

where subscript 0 indicates state of the environment. The first three terms in the brackets represent physical exergy, the forth term chemical exergy the fifth term kinetic exergy, and the last term potential exergy.

In typical industrial processes the kinetic and potential exergy are negligible and only physical and chemical exergy are evaluated. For instance, the exergy value of hydrogen is about 236.12 kJ/mol at physical standard conditions[34], which means that it takes at least 236.12 kJ/mol of work to produce 1 mol of hydrogen from components that are thermodynamically stable.

The equation describing exergy flows through the system is:

$$E_\mathrm{i}=E_\mathrm{p}+E_\mathrm{w}+\Delta E \tag{3}$$

where E is the exergy flow and subscripts i, p, and w denote the exergies of input, useful product(s) and waste, respectively; ΔE denotes destruction of the exergy in processes for product(s) creation. Based on (Eq.3) two measures can be used to assess the performance of process. They are: a) exergetic efficiency (Eq.4) and b) exergy consumption per unit of product (Eq.5).

$$\psi=E_\mathrm{p}/E_\mathrm{i} \tag{4}$$

$$E_\mathrm{c}=\Delta E+E_\mathrm{w}=E_\mathrm{i}-E_\mathrm{p} \tag{5}$$

As such this approach is closely related to life cycle assessment (LCA) and can be also called Exergy LCA (ExLCA). The steps in ExLCA include, defining the goal of the analysis; developing the exergy flow chart; defining the analysis boundary; collecting information and data about the relevant industrial, economic and ecological processes and products; computing the exergy of the inputs and outputs. These steps are similar to the standard LCA [35], but enhance the existing LCA approach. The difference between this approach and the standard LCA is an allocation of recycling processes and materials. The standard allocation is based on crediting recycling processes and trace recycling loops. This will make ExLCA too cumbersome if possible at all. Suggested approach is based on allocation method[36], which allows separate recycling streams and ascribes exergy directly to recycling resources and processes.

Based on such approach cumulative exergy consumption (CExC) analysis can be applied (introduced by Ref.[25]). This method accounts the exergy of all natural resources and recycled resources consumed in all steps of the product making processes and previous processes in production chain. In general the CExC of the production chain identified as E_i in Eq.3 equals:

$$E_\mathrm{i}=\sum_{k=1}^{N}E_{k,n}+\sum_{k=1}^{N}E_{k,r} \tag{6}$$

where N denotes number of process units included in industrial production chain, $E_{k,n}$ and $\mathrm{E}_{k,r}$ are cumulative exergy of natural and recycled resources entering and exergy consumed at the kth unit process, respectively.

Although Eq.6 is a useful tool to measure exergy consumption due to making product(s), it's not suitable as sustainability metric as it doesn't explicitly show exergy of waste produced in the process of product(s) making. The exergy lost in the form of chemically or physically reactive materials in emissions and waste dissipated into the environment has to be also known (Eq.5). However, it is not only unutilised exergy can drive undesired environmental processes, it is more likely that the insertion of unfamiliar (to the environment) chemical species (i.e. chemical potentials) in delicately balanced biological cycles can cause a damage. At the micro-scale, very small amount of some chemicals are enough to disrupt life processes (the general labels for such disruptive chemicals are toxins) For this reason, unexpended exergy can be regarded as having potential for causing environmental harm (entropy increase) far more than exergy content of the waste. Therefore in addition to exergy of waste (emissions) stream in (Eq.5) the extra exergy required for abating the harmful effects of the waste (emissions) on the environment should be also included. The extra exergy required for abatement should be taken as a measure for the lack of the process compatibility with the natural environment and it should be applied for all measures required to close loop of material cycles. In the case of CO_2 emissions this would mean to close the carbon cycle or at least to sequestrate the formed CO_2 (for example, using carbon capture and storage (CCS) processes). Thus, the consequence of using fossil fuels is the extra exergy required for the CO_2 abatement. The abatement processes should also be applied to other effects such as air, water and soil pollutions. Taken into account the abatement processes the more consistently exergy consumption should be expressed based on combination Eq.5 and 6 as:

$$E_c=\sum_{k=1}^{N}E_{k,n}+\sum_{k=1}^{N}E_{k,r}+\left(\sum_{k=1}^{N}E_{k,\mathrm{w}}+\sum_{k=1}^{N}E_{k,\mathrm{a}}\right)-E_\mathrm{P} \tag{7}$$

where $E_{k,w}$ and $E_{k,a}$ are exergy of waste (emissions) stream of the process and exergy for abatement of this stream, respectively; E_P is exergy of the final product.

Although defined in Eq.7 exergy consumption is appropriate metric to measure sustainability (some other examples of using exergy values as sustainability metric are given in Ref.[33]); however, this metric measures only one aspect of sustainability – environmental performance of materials, products, services, etc. The broader approach is based on eco-efficiency metric, which combines environmental and economic goal. Although this metric doesn't include social dimension of sustainability it's a useful metric to measure improvements made to chemical processes and technological processes, evaluation of different materials, manufacturing enterprises or industry as a whole. Usually the eco-efficiency indicators are presented by ratio between environmental and financial variables. The eco-efficiency metric has been defined as: delivery of competitively priced goods and services that satisfy human needs and bring quality of life while progressively reducing ecological impacts and resource intensity throughout the life cycle to a level at least in line with the earth's estimated carrying capacity[37]. The objective of such indicators is value maximisation while minimising resource use and adverse environmental impact. In practice, eco-efficiency is often interpreted mathematically as service value divided by environmental burden:

$$\text{Eco} - \text{efficiency} = \frac{\text{Value of a product}}{\text{Environmental impact of a product}} \tag{8}$$

Sometimes other, but similar equations are used for valuation eco-efficiency [39]:

$$\text{Eco} - \text{efficency} = \frac{\text{GDP}}{\text{DMF}};\ \text{Eco} - \text{efficency} = \frac{\text{EDP}}{\text{DMF}} \tag{9}$$

where GDP is gross domestic product; EDP is environmentally adjusted domestic product; DMF is direct materials flow.

Different eco-efficiency indicators have been adopted by many industries and remain important measures of their performance. These indicators drive industries toward reducing environmental or energy footprint of operations, thereby reducing environmental impacts without any loss of productivity or business value. Common examples of such indicators include energy intensity, material intensity, water consumption/quality, consumption of non-renewable resources, and emissions of air pollutants, toxics or greenhouse gases. However, all currently adopted versions of eco-efficiency indicators are subjects for a big difficulty of quantification of its denominator as it's impossible to calculate the sum of environmental impacts, which have different characterisations (global warming, ozone depletion, carcinogenic, photochemical oxidation, etc.) unless the weighting factors are introduced, which means that produced results are usually very subjective. The additional problem of Eqs.8−9 is calculating the ratio as numerator and denominator are measured in different units. Therefore, it's almost not possible to make comparison for different kind of products and services in term of eco-efficiency. Also, such defined eco-efficiency metric couldn't information on of how close (or how far) to sustainability product (or service) under consideration.

To avoid mentioned above problems it suggested here to evaluate eco-efficiency based on the following expression:

$$e = \frac{P_{\text{V}}}{E_{\text{C}}} \tag{10}$$

where E_C is exergy of all natural resources and recycled resources consumed in all steps of the product making processes in production chain plus exergy required for abatement of the all waste (emissions) streams (Eq.7); P_{V} is the product value expressed in exergy units (J).

The three main modules have to be performed to obtain eco-efficiency index from Eq.10:

1) Materials and energy consumption for production, use stage, and disposal of any product, using Life Cycle Analysis principles.

2) Analysis of exergy balance through all the processes during life cycle of the product.

3) Compile data to show environmental and economical cost expressed in exergy units and help to design improvements

In the framework of such defined eco-efficiency the third module - an expression of product (service) value in exergy units is a crucial element. In general, if a product's services satisfy the customer's needs and the price meets the customer's budget, a transaction is made. Companies, as well, convert money to buy new materials and energy (e.g. exergy) to make products (services) or invest money for production new products, which again demand energy. Therefore, price for exergy can be used as a proxy for a product's service value. Conversion value of the product (service) to an exergy can be done on a basis of a company (industry, national or world) statistical data for energy consumption (depends upon of the goal of sustainability analysis) and prices for different energy sources used. For example, contribution of the major energy sources to the energy consumption in Australia and average prices per 1 GJ of energy for analysis's made in this work taken from Ref.[38] presented in Table 3.

The average price for 1 GJ of energy can be obtained from following expression:

$$P_{\text{a}}(\$/\text{J}) = \sum R_{\text{i}} * P_{\text{i}} \tag{11}$$

Based on the expression (11) and data presented in Table 3, the average price for 1 GJ of energy in Australia is P_{a}= AU$3.17

Table 3 Contribution of different sources and their prices of energy to Australian electricity mix (based on data from years 2003−2010)

No.	Energy source	Contribution to total energy consumption, R_i/%	Price per 1 GJ, P_i/$AU
1	Electricity	7.6	14.6
2	Black coal	54.5	2.1
3	Brown coal	21.1	0.5
4	Natural gas	15.0	3.9
5	Oil	1.8	12.50

Taking into account expressions (10) and (11) and subtracting consumed exergy from the product value the exergy-based eco-efficiency metric can be derived as:

$$e=\frac{V/P_a-E_{\mathrm{C}}}{E_{\mathrm{C}}}=\frac{V/P_a}{E_{\mathrm{C}}}-1 \tag{12}$$

where V is the price of the product.

Such analysis in the future can be simplified, when hydrogen economy will emerge then instead of different primary energy sources only one energy carrier – hydrogen will be used (Currently price for hydrogen energy is too high, approximately AU$20 per 1GJ).

It has to be highlighted here, that such metric not measures sustainability, but rather measures unsustainability level of different products and processes, the less this value of e is, the more unsustainable product or process is. Such eco-efficiency metric allows industry, enterprise etc. provide information on environmental performance vis-à-vis financial performance in a systematic and consistent manner over different time periods. Based on the value obtained from Eq.12 users are able to compare the eco-efficiency statements of an enterprise or industry over time so that they can identify trends in their eco-efficiency position and performance. It's also possible to compare the eco-efficiency statements of different enterprises or industries. This indicator not only satisfy all guidelines for eco-efficiency indicators developed by Ref.[39] it also allow to determine the sustainability level of products, services, industries etc. based on the value of the expression (12). The developed metric not only allow determine the sustainability of different products (services), but allow rank them in term of sustainability to the society, so it allows eliminate least sustainable products or services from society use.

The value of the indicator can vary within the range from minus one to plus infinity. The negative value of the indicator means that a product, service or industry as a whole is completely unsustainable, as the exergy amount spent for making a product (service) or activity is bigger then exergy valued by society for this product (service) or industry. The bigger positive value of the indicator e is, the closer to the sustainability the product (service) from economic-environmental point of view. However, as mentioned above, the sustainability of economic-environmental activity of the human society can be reached only asymptotically, when defined eco-efficiency indicator will reach infinity.

A few case studies have been conducted to illustrate use of the developed eco-efficiency metric.

4 Examples of application of exergy based eco-efficiency metric

4.1 Assessment of sustainability performance of Australian aluminium industry

The Australian aluminium industry is one of the most energy intensive in Australia (approximately 15% of produced electricity is consumed by aluminium industry [40]). The industry significantly contributes to the Australian economy, as well as, it produces substantial environmental impact and emits a lot of greenhouse gases (GHG) mostly due high energy consumption. Aluminium based products made in Australia include secondary aluminium together with primary aluminium in relation 3:7[40].

Using developed metric an assessment of eco-efficiency performance has been conducted for Australian aluminium industry taking into account the materials flow chain based on data published in Ref.[41] The boundary of the product system will include "cradle-to-grave" LCA illustrated in Fig.6.

The life cycle is modelled by a steady-state process with a constant rate of flow materials. The model under consideration neglects the much smaller contributions associated with inputs or outputs other than those directly involved in operating processes. Thus exergy spent on the infrastructure is neglected, which is lead to results errors within range of 5% (The infrastructure contribution is typically in the order of 5%[42]). For the simplification reason only GHG emissions have been taken into consideration in this analysis. Indeed, carbon dioxide is the dominant fraction of emissions load and accounts for more than 95% of the total mass of emissions. Adopted in this analysis assumptions are considered acceptable within the general accuracy of the analysis, which is estimated to be within a range of 15%.

The LCA is based on Australian aluminium sector as it was in 2005, but the processes are typical of most modern aluminium producers. A mass balance for each aluminium production process was built in this analysis based on data published in Ref.[43]. The background processes such as electricity production are not modelled and are assumed to be fixed. Data for these processes have been taken from Ref.[44]. Data for all processes

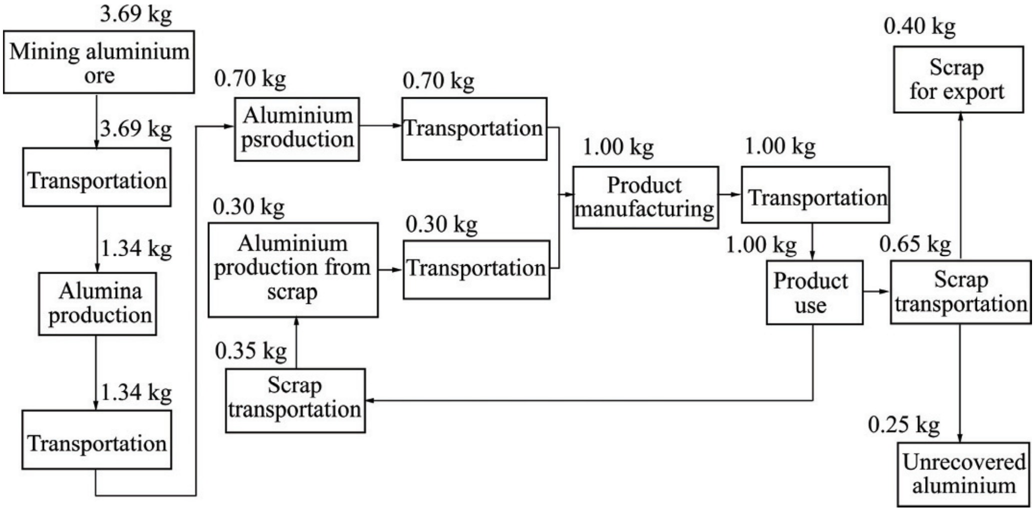

Fig.6 Process model of Australian aluminium life cycle (including masses of aluminium and scrap flows)

have been normalised for production of 1kg of aluminium delivered to the manufacture and use stages. Such approach allows compare all processes on the same basis and estimate their contributions to overall exergy consumption.

The aluminium production route is based on Hall-Heroult electrolytic process which is the main commercial process of aluminium production adopted over hundred years ago. According this process alumina (Al_2O_3) is dissolved in a molten cryolite bath (Na_3AlF_6) and electrolytically decomposed in bath operating at temperatures below 1 000 C.

Fig.7 shows the exergy consumption, GHG emissions (in kg of CO_2 equivalent) and relative contribution of each process per 1 kg of primary aluminium production. The total exergy consumption in producing 1 kg of aluminium is 221.8 MJ. The similar approach for the exergy consumption per 1 kg of secondary aluminium (Fig.8) reveals that total exergy consumption in this case is only 29.3 MJ. Obtained figures show that production of 1 kg of recycled aluminium consumes only about 13.2% of exergy in comparison with primary aluminium. As secondary aluminium exhibits no property degradation, hence recycling of aluminium creates a huge advantage towards sustainability of aluminium based products.

The results presented in Fig.7 show the largest single area of exergy consumption belongs to electricity production. This is consequence of low overall exergetic efficiency of electricity generation in Australia. The main area of exergy loss in electrical power generation is conventional steam-cycle, where high exergy of fuel is converted to thermal energy with much lower exergy (more than 50% of exergy of fuel is lost). The situation should be improved by using much more thermodynamically effective electricity generation process such as combined gas turbines cycle or direct conversion of chemical exergy of fuel to electricity (for example, by using fuel cells).

Materials transportation at different stages of production (shown in Fig.7 and 8) is also a significant consumer of exergy (although a mild assumption of an average distance between places with 300km has been adopted in the model). The presented analysis showed that with regard to minimising overall exergy consumption transportation factor should be considered.

According developed approach for calculate eco-efficiency metric a cumulative exergy of abatement processes(CExA) has to be added to get overall exergy consumption. It has been estimated that CExA for CO_2 emissions is 5.86 MJ/kg CO_2[45]. Take into account total exergy of aluminium is −3.52 MJ/kg[46] and price of aluminium metal -(according London Metal Exchange the price is US$2025/mt[47]) the eco-efficiency indicator shown in Eq.12 can be calculated. Using these figures and results presented in Fig.7 and 8 the following values have been obtained for eco-efficiency value for primary and secondary aluminium, respectively, produced in Australia $e_{\mathrm{Al\_P}} = 0.82$ and $e_{\mathrm{Al\_S}} = 14.02$.

Based on developed approach the eco-efficiency indicator for steel is estimated also. It has been shown that CexC for steel is –22 MJ/kg and 8.6 MJ/kg for primary and secondary steel, respectively[48] and GHG emissions are 5.30 kg of CO_2 eq./kg and 1.33 kg of CO_2 eq./kg[49]. The exergy of mild steel is −2.0 MJ/kg[46]. Using price for mild carbon steel of approximately US$500/mt[47] the obtained eco-efficiency value for primary and secondary steels are: $e_{\mathrm{St\_P}}=2.09$ and $e_{\mathrm{St\_S}} = 9.95$, respectively.

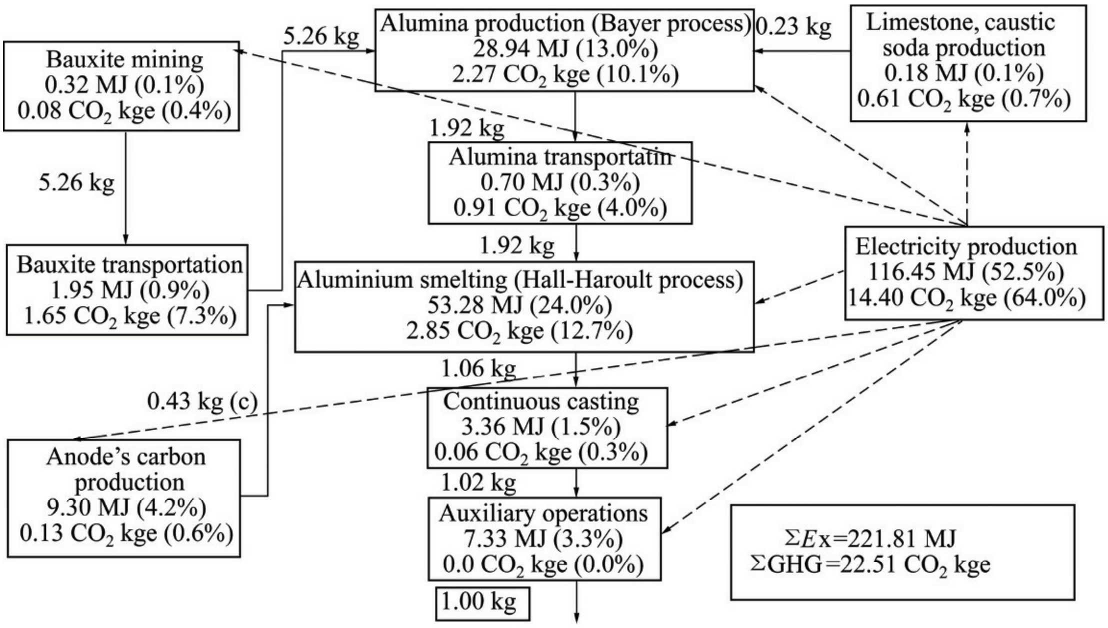

Fig.7 Hall-Haroult aluminium production route in Australia (Exergy consumption and GHG emissions done in kg of CO_2 equivalents, are shown. The percentages of total exergy consumptions and GHG emissions are given in brackets)

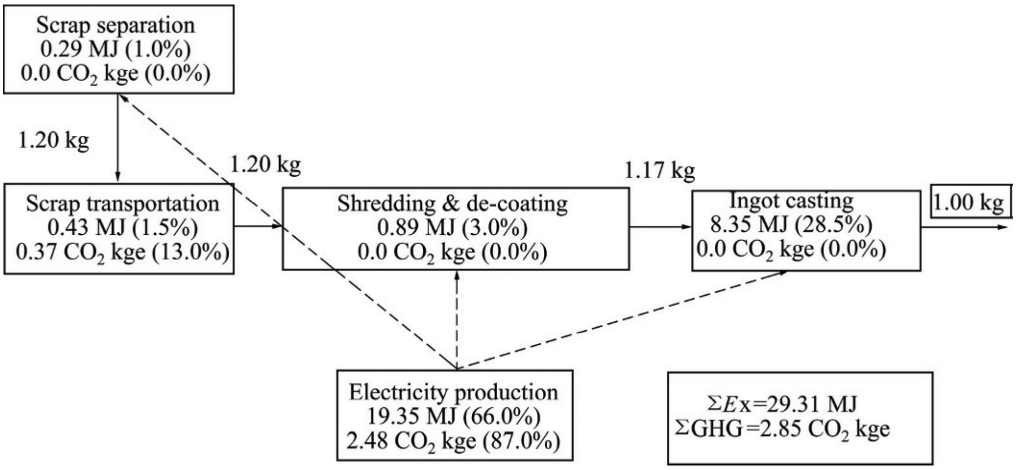

Fig.8 Secondary aluminium production route (Exergy consumption and GHG emissions (done in kg of CO_2 equivalents) are shown. The percentages of total exergy consumptions and GHG emissions are given in brackets)

Obtained results show a significant advantaged of recycling steel in comparison with primary steel, as well as for aluminium. It can be seen also that eco-efficiency of the world primary steel production is much higher then for Australian primary aluminium. Such result is consequence of the structure of Australian electricity generation industry, which almost fully relay on coal burning power stations emitting a huge amount of CO_2. However, despite such disadvantage Australian secondary aluminium has bigger eco-efficiency in comparison with world secondary steel. Such fact can be seen as better potential for aluminium as a structural material in comparison with steel in the future.

The obtained results also show that exergy required for abatement process is in the same level as exergy consumed for aluminium production: 221.8 MJ for production and 131.9 for abatement The similar results for steel even worse: 22.0 MJ for production and 31.1 MJ for abatement.

The presented comparisons exhibits another advantage of developed metric, which allows quantify all consumptions and emissions at the same scale. It is also possible to calculate eco-efficiency of often used mix of materials (primary and secondary). For example, eco-efficiency value for aluminium mix using in Australia (70% primary and 30% secondary) is equal: $e_{\mathrm{Al\_M}}$=1.48. If aluminium mix used in Europe for car component manufacturing (40% primary and 60% secondary, [43]) would be used in Australia, the eco-efficiency would be: $e_{\mathrm{Al\_M}}$=2.86. In comparison, the sustainability index for world steel mix (50% primary, and 50% secondary, [49]) is: $e_{\mathrm{St\_M}}$=3.82.

4.2 Assessment of sustainability performance of Australian aluminium industry

Although presented results show relatively high value of eco-efficiency metric of aluminium mix currently using in Australia ($e_{\mathrm{Al\_M}}$=4.78), but aluminium itself represents non consumer product. So, it necessary to calculate an eco-efficiency for whole life cycle from “cradle-to-c grave” of aluminium based consumer product. As an example of such product an aluminium car component, namely converter housing (CH) is chosen(The CH and its “cradle-to-crave“ life cycle are shown in Fig.9 and 10).

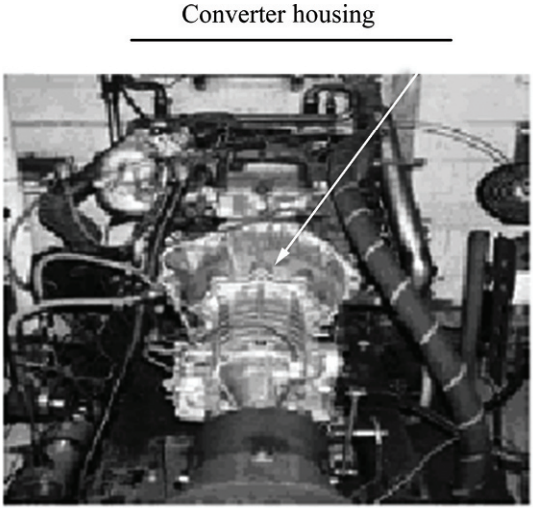

Fig.9 Aluminium converter housing (CH) assembled within a car

The main route for aluminium car component production is high pressure die casting process (a brief description of different process-stages involved in such route of production including mass of metal on each stage of production is presented in Fig.10 [50]). The average exergy consumption (from electricity, natural gas and petrol) and GHG emissions (from overall emissions) based on CH production route are: 37.6 MJ and 4.38 kg of CO_2 eq/kg, respectively[50].

The whole “cradle-to-grave” life cycle of the CH under consideration is presented in Fig.11. The exergy consumption and GHG emissions for use stage of LCA have been obtained using the following assumptions: 1) the average driving distance for car during its life is approximately 2×10^5 km; 2) fuel consumption is evenly distributed for unit weight of the car; 3) the fuel consumption is 8.5 l per 100 km of driving, mass of the car is 1 300 kg and GHG emission per one litre of fuel is 2.85 kg of CO_2 eq., respectively[51]. Based on these assumptions the calculated figures for exergy consumption and GHG emission per 1 kg of car mass during its life are: 455.0 MJ and 37.26 kg of CO_2 eq., respectively.

Applying these figures for developed eco-efficiency metric and take into account that price for aluminium die-casting products (approximately double the price for aluminium metal), the approximate figure of eco-efficiency value for the whole life cycle of CH is: $e_{\mathrm{Al\_CH}}$=0.29.

This figure is only slightly above the zero (as pointed above the zero value separates completely unsustainable product). The result presents a very low efficiency of contemporary vehicles, which almost three times reduces eco-efficiency for aluminium base component in comparison with aluminium metal. It’s easy to show that using steel for the same purpose leading even to worse eco-efficiency value (aluminium CH actually substituted cast iron CH used in vehicles before). For example, the same car component (CH) made from steel (say using mix of primary and secondary steel −50% by 50%) will weight approximately 7.3 kg. Making assumptions that production of such CH consumes the same amount of exergy per unit weight basis and price of the CH would be the same (as it does the same service with the same quality as aluminium CH) the calculated eco-efficiency value is: $e_{\mathrm{St\_CH}}$=−0.16**,** which is below unsustainable level.

Presented results show that developed eco-efficiency metric for car components is very close or fall below unsustainable level. Therefore, consider a huge vehicle’s fleet it is unavoidable for society going towards sustainability to significantly rise vehicle efficiency. This efficiency rise should be done by different ways: reducing vehicle’s weight, using alternative fuels, using more recycled materials and etc.

5 Summary

The eco-efficiency metric based on fundamental laws of thermodynamics using exergy approach applicable in the field of sustainability assessment has been developed. The adopted metric allows compare and assess different product services and even whole industries based on their physical-chemical framework. This dimensionless metric is able to evaluate different materials and technological options consider their cumulative exergy consumption and cumulative exergy of abatement processes due to use of energy and materials and producing wastes and emissions.

It is has been shown that exergy can serve as a basis for life cycle analysis in assessing the sustainability using eco-efficiency metric. Rather than deal with

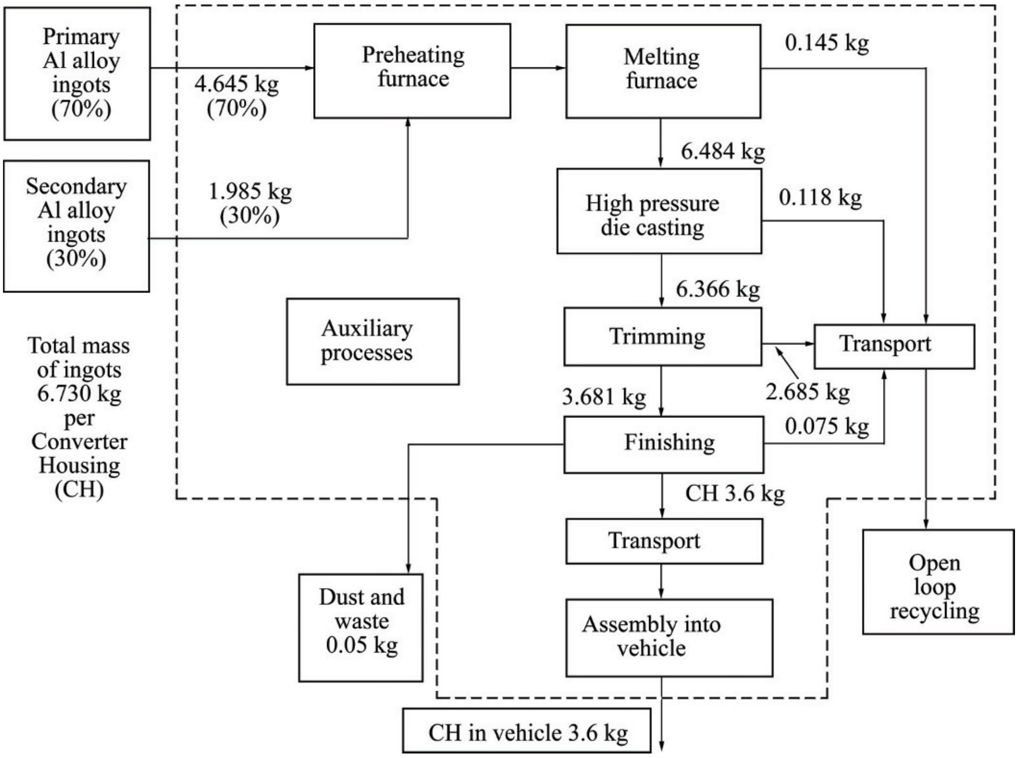

Fig.10 Process model of manufacturing aluminium CH

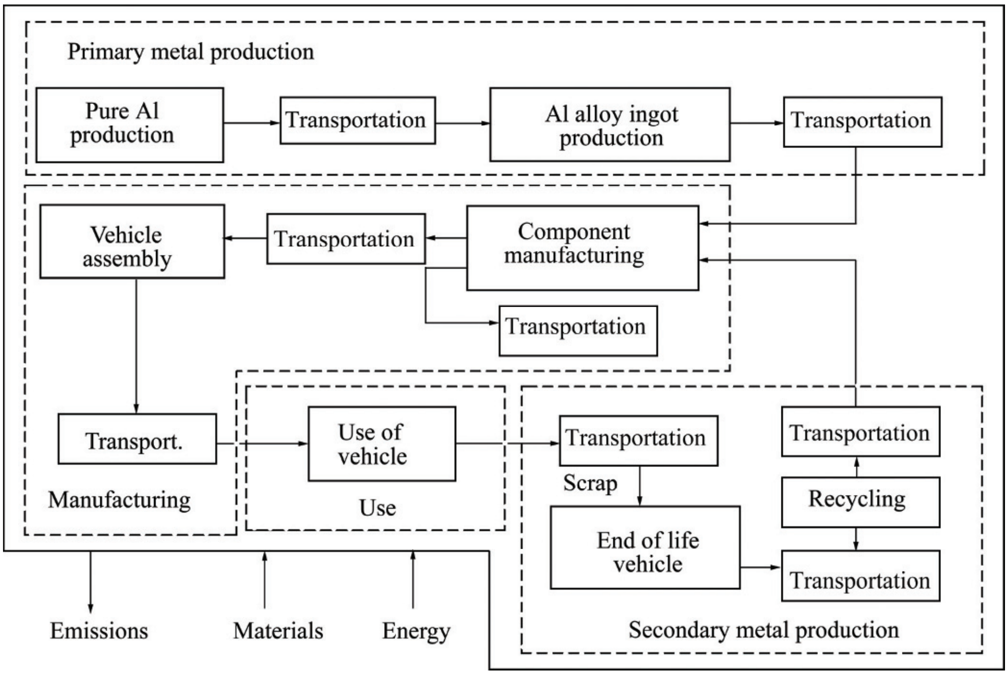

Fig.11 Generic product system considered for ‘cradle-to-grave” LCA of aluminium CH

problems of weighting different aspects of environmental impact as general life cycle analysis does, this analysis allows compare different products, services, etc. on the basis of the same scale. So, such approach allows to build full hierarchy of products (cervices) on the basis of their eco-efficiency criteria. Therefore, it is possible to identify least sustainable products or services (mainly products and services with eco-efficiency metric less than zero) and to eliminate those products (services) from society use or transfer them to more sustainable level.

The two case studies have been conducted to illustrate the application of developed eco-efficiency metric: estimation eco-efficiency of Australian aluminium industry and aluminium based car component (converter housing). It has been shown that although the industry has passed sustainability test (eco-efficiency metric is higher than zero), however, the absolute value of the metric is not high and must be improved. One way of doing so is significant increasing of recycled aluminium products. It also has been shown that car components don't pass sustainability test due to low efficiency of contemporary vehicles.

It also has to be mentioned that for the broader implementation of exergy based eco-efficiency metric more data for exergy of different raw materials and data for exergy consumption of different primary technologies and abatement processes, which are currently missing, have to be created.

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