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A Review of Footprint analysis tools for monitoring impacts on sustainability

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ABSTRACT

This study presents an overview of footprints as defined indicators that can be used to measure sustainability. An overview of the definitions and units of measurement associated with environmental, social, and economic footprints is important because the definitions of footprints vary and are often expressed unclearly. Composite footprints combining two or more individual footprints are also assessed. These combinations produce multi-objective optimisation problems. Several tools for footprint(s)' evaluation are presented, including some of the numerous carbon footprint calculators, available calculators for other footprints, some ecological footprints-based, graph-based, and mathematical programming tools. A comprehensive overview is offered of footprint-based sustainability assessment.

1. Introduction

Sustainability, especially environmental sustainability, has emerged as a key issue amongst governments, policymakers, researchers, and the public. Increasing efforts and resources have been devoted to research during environmental studies, including the assessment of various harmful impacts. Environmental impacts are usually defined through a Life Cycle Assessment (LCA). LCA is also called Life Cycle Analysis, and is conventionally characterised as a "cradle-to-grave" approach, as an open loop. Over recent years a "cradle-to-cradle" – or closed loop – perspective has been introduced, which attempts to reach 100% utilisation of all types of waste (McDonough and Braungart, 2002; Haggar, 2007).

Usually, LCA is only associated with environmental components (Von Blottnitz and Curran, 2007; Öberg et al., 2012). However, sustainable development (SD), representing development that "meets the needs of the present without compromising the abilities of future generations to meet their own needs" (WCED, 1987), requires an integration of not only environmental but also economic and social components at all levels (OECD, 2004; Jørgensen et al., 2008). Sometimes SD also incorporates a fourth dimension, an institutional (Herva et al., 2011; Valentin and Spangenberg, 2000) or a cultural (Nurse, 2006) component. Some authors have discussed more than four dimensions of SD. Five dimensions, or even seven, have been cited (Perlas, 1994). The five-dimensional format includes technical, economic, social/ethical, environmental, and institutional sustainability (Ilskog, 2008). The seven-dimensional format requires that sustainable solutions should be i) socially-just and equitable, ii) respectful of cultural pluralism, iii) ecologically sound, iv) economically-viable, v) based on science that considers the material and non-material bases of life equally, vi) technologically appropriate and vii) designed to empower and develop human capacity and potential (Perlas, 1994). The goal of SD is to find a balance amongst these objectives. This search for a balance is the area within which the application of mathematical programming (MP) and other tools for sustainability evaluation can provide valuable support (Grossmann and Guillén-Gosálbez, 2010).

The actual measurements of sustainability and SD remain an open question. Indicators that can be used to measure SD need to be developed in order to provide a basis for decision-making. Many different concepts and methods have already been developed for the environmental, economic, and/or social evaluations of particular processes, products or activities (EC, 2010; Jeswani et al., 2010), e.g., LCA, Social LCA (SLCA), Life Cycle Cost Analysis (LCCA), the ecological footprint (EF), the environmental sustainability index, the measurement of net savings, and others. Previous reviews of indicators for measuring sustainability have included studies by

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Hák et al. (2007), Ness et al. (2007), Singh et al. (2009), Herva et al. (2011), Roca and Searcy (2012), etc. Hák et al. (2007) assessed in their book the state of the art in sustainability indicators and different challenges and approaches to sustainability indicators including some case studies. Ness et al. (2007) divided the sustainability assessment into three main categories: indicators/indices, product-related assessment, and integrated assessment tools. Singh et al. (2009) provided an overview of various sustainability indices and compiled the information related to sustainability indices formulation strategy, scaling, normalization, weighting and aggregation methodology. Herva et al. (2011) reviewed environmental indicators developed in the last years that were found suitable to be applied at corporate level for the evaluation of production processes and products. The indicators were classified into four main groups: (i) Indicators of Energy and Material Flows; (ii) Indicators with a Territorial Dimension; (iii) Indicators of LCA; and (iv) Indicators of Environmental Risk Assessment. Roca and Searcy (2012) identified the indicators that are currently disclosed in corporate sustainability reports.

Over recent years, tools have emerged known as footprints. These new tools are used for the assessment of sustainability and its components. The EF was developed in 1992 by Rees (Rees, 1992), and the water footprint (WF) was developed in 2002 by Hoekstra and Hung (Hoekstra and Hung, 2002). It is generally understood that the carbon footprint (CF) was most probably derived from the global warming potential (GWP), and was first defined in scientific literature in 2003 by Høgevold (Høgevold, 2003). Other footprints are not as well-known as yet, and have only emerged recently. A literature review indicates that the major categories of footprints developed to date are carbon, ecological, and water footprints, forming the so called “footprint family” (Galli et al., 2011, 2012). Many other lesser known footprints exist, including nitrogen, social, and economic footprints. Various definitions exist for some footprints (e.g., for the CF). Moreover, the definitions of some footprints (e.g., economic footprints) are unspecified. There is no standard and clear definition of a “footprint” or of the differences between the indicators of potential environmental impacts (e.g., the GWP) and footprints (e.g., the CF).

This paper is an attempt to provide an overview of single and composite footprint definitions, their units of measurement, and the tools for footprint evaluations, in order to show the scientific community a common ground and the diversities behind different footprints, ideally to support more systematic definitions and usages of footprints. A multi-objective optimisation (MOO) of the system(s) must be performed because SD integrates three or more categories or objectives, in order to obtain integrated sustainable solutions. It provides a balanced picture that could certainly be considered as one of the key elements for obtaining a comprehensive picture. In addition, a number of tools and applications are presented, in which different sustainability aspects are combined within MOO problems.

This research was devoted to a literature survey using different scientific databases and Internet sources, comprising those measurements and definitions mainly associated with footprints, and tools for footprints' evaluation. The search was geared to finding sources that introduced specific footprints and those that had the more accurate existing definitions. This paper highlights only some of the applications regarding various footprints, because of the large scope of this research area, and space limitation. The sources for this article were preferably scientific papers (obtained from ScienceDirect <www.sciencedirect.com> or Scopus <www.scopus.com>), but also the reports from the European Commission (EC), the United Nations Environment Programme (UNEP), Global Footprint Network (GFN), World Wide Fund for Nature (WWF), and others. Some of references are not of “proven quality”, however, definitions for some footprints do not exist in scientific literature or in reports from organisations, as yet. This is the case with the majority of tools for footprint evaluation. Usually there is one or even more definitions and measurement units for one footprint, however for many footprints there is often no definition and/or measurement unit available, as well as plenty of newly-developed footprints. This is therefore an important reason for this research, that footprints should be supported by a common, unambiguous terminology. The overview performed in this study may highlight areas for potential modifications and improvements regarding different footprints, especially social and economic, however implementing such modifications goes beyond the scope of this paper.

2. Definitions of footprints

A “footprint” is a quantitative measurement describing the appropriation of natural resources by humans (Hoekstra, 2008). A footprint describes how human activities can impose different types of burdens and impacts on global sustainability (UNEP/SETAC, 2009). SD usually considers three dimensions or pillars: environmental protection (ecology), economic prosperity, and the social dimension (OECD, 2004 and 2008). This overview of footprints is, therefore, presented in terms of the environmental, social, and economic dimensions of the subject.

It should be noted that footprints are usually considered as being measured in units of area. However the data expressed in area units show high variability and highly possible errors regarding results. The conversion into a land area would have to be based on a variety of different assumptions and would increase those uncertainties and errors associated with a particular footprint estimate (see e.g. Wiedmann and Minx, 2008; Lenzen, 2006). Converting some of the footprints to area units can prove to be problematic, especially for processes that are not primarily area-based, such as a chemical processes (De Benedetto and Klemeš, 2009a). EF and its categories, the Sustainable Process Index (SPI), and the Sustainable Environmental Performance Indicator (SEPI) are always defined in units of area, however footprints other than these, are not usually defined (only) in area units, see below. Most footprints also have limited data availability and uncertainty of data. Performing the footprint analyses can be costly regarding data, resources, and be time intensive. Except for major categories of footprints there is also a lack of applications for other footprints, and therefore more general conclusions about their strengths and limitations cannot be appropriately derived yet at this early stage of their development.

2.1. Environmental footprints

2.1.1. Carbon footprint (CF)

Over the past few years, the CF has become one of the most important environmental protection indicators (Wiedmann and Minx, 2008; Lam et al., 2010; Galli et al., 2012). CF usually stands for the amount of CO_2 and other greenhouse gases (GHGs), emitted over the full life cycle of a process or product (UK POST, 2006; BSI, 2008). The CF is quantified using such indicators as the GWP (EC, 2007), which represents the quantities of GHGs that contribute to global warming and climate change. A specific time horizon is considered, usually 100 years (IPPC, 2009). A similar definition is that the CF is a result of Life Cycle Thinking applied to global warming (climate change) (EC, 2007). The land-based definition of the CF is that the CF represents the land area required for the sequestration of fossil-fuel CO_2 emissions from the atmosphere through afforestation (De Benedetto and Klemeš, 2009a). Wiedmann and Minx (2008) proposed that the CF is a measurement of the exclusive direct (on-site, internal), and indirect (off-site, external, embodied, upstream, and downstream) CO_2 emissions of an activity, or over the life cycle of a product, measured in mass units. Wright et al. (2011) suggested that only two carbon-based gases CO_2 and CH_4, the data collection of which is relatively straightforward, should be used when determining a CF. CF includes the activities of individuals, populations, governments, companies, organizations, processes, industrial sectors, etc. (Galli et al., 2012).

Other different terms relating to GHG emissions have been suggested and/or used, such as climate footprint (Wiedmann and Minx, 2008; Wright et al., 2011), CO_2 footprint (Huijbregts et al., 2008), GHG footprint (Downie and Stubbs, 2011; Wiedmann and Barrett, 2011), methane footprint (Wiedmann and Barrett, 2011), and GWP footprint (Meisterling et al., 2009).

2.1.2. *Water footprint (WF)*

The WF is closely linked to the concept of virtual water (Hoekstra and Chapagain, 2006) and represents the total volume of direct and indirect fresh water used, consumed, and/or polluted. A WF consists of blue, green, and grey water footprints, which represent the consumption of surface and ground water, the consumption of rainwater, and the volume of water required to dilute pollutants to water quality standards, respectively (Mekonnen and Hoekstra, 2010; Klemeš et al., 2009). A WF is a method for quantifying water usage for a particular product, for any well-defined group of consumers (e.g., an individual, city, province, state, or nation) or producers (e.g., a public organization, private enterprise, or economic sector). A WF is measured in terms of water volumes consumed (evaporated or incorporated into the product) and polluted per unit of time or per functional unit (Galli et al., 2011, 2012). The strength of the WF concept is that it provides a broad perspective on the water management of the system, and allows for a deeper understanding of water usage. The WF integrates water usage and pollution over the complete supply chain (Galli et al., 2011). The weaknesses of the WF are that it represents just the quantity of water used without an estimation of the related environmental impacts, the lack of required data, the estimation of grey WF is subjective (Jeswani and Azapagic, 2011), and no uncertainty studies are available even though uncertainty can be significant (Galli et al., 2011, 2012).

A Blue Footprint™ (BWF) is a measurement of the impact of water usage by individuals and societies on the world's fresh water resources. The BWF takes into account the water consumption (water quantity), resource stress (the water stress index) and quality (the water impact index) (Grossman, 2010) and is expressed in volumetric units equivalent to water (Auguste, 2010). The water pollution footprint (WPF) represents the amounts of substances emitted into water (Sánchez-Chóliz and Duarte, 2005).

2.1.3. *Energy footprint (ENF)*

Various definitions of an ENF have been offered. The Global Footprint Network (2009) defined it as the sum of all those areas used to provide non-food and non-feed energy. The ENF is the sum of the areas of carbon uptake land, hydropower land, forested land for wood fuel, and crop land for fuel crops. Palmer (1998) defined an ENF as a measurement of the land required to absorb those CO_2 emissions originating from energy usage. Another definition of an ENF is that it represents the area required to sustain energy consumption, and is measured as the area of forest that would be required to absorb the resulting CO_2 emissions, excluding the proportion absorbed by the oceans, and the area occupied by hydroelectric dams and reservoirs for hydropower (WWF, 2002). De Benedetto and Klemeš (2009a) calculated an ENF by multiplying the final energy usages of different energy carriers by their land indices, and adding the results to the footprint of the whole supply chain. Yet another definition of an ENF is that it corresponds to the demand for non-renewable energy resources (Schindler, 2010). The ENF can be measured in local (the surface area of a specified region's average biologically-productive land and sea over a given year (GFN, 2009)) or global (the surface area of the Earth's average biologically-productive land and sea over a given year (Wiedmann and Lenzen, 2007; GFN, 2009)) area units or in units of energy per functional unit.

The ENF includes sub-footprints, such as the fossil or fossil energy footprint (Stoeglehner and Narodoslawsky, 2009), nuclear energy footprint (Stoeglehner et al., 2005), renewable energy footprint (Chen and Lin, 2008), wind energy footprint (Santhanam, 2011), solar energy footprint (Brown, 2009), and others.

2.1.4. *Emission footprint (EMF)*

The EMF represents the quantity of product or service-created emissions into the air (e.g., SO_2, particles, CO, CO_2), water (e.g., chemical oxygen demand (COD), nitrogen and phosphorus), and soil (through spillage in the soil). EMFs are calculated on a per-area basis. The conversion of emissions is calculated according to the principle that anthropogenic mass flows must not alter the qualities of local compartments. Maximum flows are defined based on the naturally-existing qualities of the compartments and their replenishment rate per unit area. For emissions to soil, the replenishment rate is given by the decomposition of biomass to humus (measured by the production of compost by biomass). For ground water this is the seepage rate (given by local precipitation). For emissions into the air, the natural exchange of substances between forests and air per unit area is taken as a base of comparison between natural and anthropogenic flows. Different emissions to air are not weighted, as only the largest dissipation areas are to be considered. Lower area consumptions' emissions may be dissipated without violating the principle that anthropogenic mass flows must not alter the qualities of local compartments (Sandholzer and Narodoslawsky, 2007; De Benedetto and Klemeš, 2009a).

2.1.5. *Nitrogen footprint (NF)*

The NF is a measurement of the amount of reactive nitrogen (N_r – all of the nitrogen species except N_2) released into the environment as a result of human activities, expressed in total units of N_r (N-Print Team, 2011; Leach et al., 2012; Čuček et al., 2012a). The NF mainly covers the following N_r emissions: NO_x, N_2O, NO_3^-, and NH_3 and they can be rapidly interconverted from one N_r form to another (Galloway et al., 2003). The NF represents disruption of the regional to global N cycle and its consequences. The weakness of the NF is the lack of data and its uncertainty (Leach et al., 2012).

2.1.6. *Land footprint (LF)*

The LF includes sub-footprints, such as the forest footprint (FLF, the forest area required to produce the consumed forest products (WWF, 2002)); the agricultural land footprint (ALF, the agricultural land area used to grow biomass (Kissinger and Gottlieb, 2010)); the built-up land footprint (BLF, the land areas covered by human infrastructures (Chambers et al., 2004)); the grazing land footprint (GLF, the land used for livestock (WWF Japan and GFN, 2010)); and the crop land footprint (CLF, the land area required to produce those crops consumed by a population (Van Rooyen, 2005)).

2.1.7. *Biodiversity footprint (BF)*

The BF measures the biodiversity loss, the outcome of land conversion, land-usage changes, the unsustainable use of biological resources, the over-exploitation of marine ecosystem resources, and the invasion of alien species (Oteng-Yeboah, 2009). Some research has attempted to use the land area appropriated by human activity or the number of threatened species as an indicator for the BF (Burrows, 2011).

2.1.8. Other environmental footprints

The phosphorus footprint (PF) addresses the phosphorus imbalance within crops (Lott et al., 2009). The fishing-grounds footprint (FGF) represents the sustainable catches of a variety of fish species (WWF Japan and GFN, 2010). The FGF also represents the area needed to produce the fish and seafood products that human beings consume (Van Rooyen, 2005). The human footprint (HF) measures the energy quantities, resources, and products consumed by a human during his/her lifetime and includes, for example, the number of food “pieces”, the volumes of fuel and water, and the mass of waste (National Geographic Channel, 2011). The waste footprint (WSF) is the amount of waste produced by sourcing ingredients and materials, manufacturing and processing, and transportation (United Soybean Board – Thinking Ahead, 2011).

2.2. Social footprints

2.2.1. Social footprint (SF)

The SF is a measurement for quantifying the social sustainability performance of an organisation. The SF addresses the impacts on anthrocapital (human, social, and constructed) (Center for Sustainable Organizations, 2009).

2.2.2. Other social footprints

The human rights footprint (HRF) describes the potential of human rights practice for building towards political action and institutional change (Perelman and Young, 2010). However, it is difficult to assess the HRF in an unbiased fashion because evidence of rights violations is not readily available (Stamford and Azapagic, 2011).

The corruption footprint (COF) is an anti-corruption measurement that is still loosely defined. This footprint is based on the corruption perception index (Transparency International, 2010). As in the case of the HRF, it is difficult to assess the COF in an unbiased fashion because evidence of corruption is not readily available (Stamford and Azapagic, 2011).

The poverty footprint (POF) assesses and understands companies’ effects on society and on people living in poverty. The POF helps companies to comprehensively understand how they affect the people in their value-chains, and the communities and countries where they operate. Their operations are analysed in terms of the following critical factors: standard of living, health and well-being, diversity and gender equality, empowerment, and stability and security. The POF is formulated in both quantitative and qualitative terms (Oxfam International, 2009).

The online social footprint (OSF) represents the resulting combination of information revealed by multiple social-networking. A user’s online social footprint is the online information that is available about him/her by aggregating his/her social-networking profile sites (Irani et al., 2009).

The job footprint (JF) describes the entire scope and range of an employee’s duties and responsibilities within an organisation A JF indicates the employee’s level of responsibility. Consequently, the greater the JF, the more compensation the employee should receive (Investing answers, 2011; BusinessDictionary.com, 2011).

The work environmental footprint (WEF) represents the number of lost days at work per unit of product, but it can also represent the number of accidents per person (De Benedetto and Klemeš, 2009a).

The food-to-energy footprint (FEF) assesses possible competition between the food and energy sectors to favour the production of food, rather than bioenergy, from food-intended crops. The FEF is an uncommon social footprint; however it is included as a social one, since it deals with measuring the quality of life. The production of fuel from food crops threatens the safety of food supplies and increases the prices of food whilst insignificantly increasing the share of biofuel in the world’s total fuel consumption (Asch and Heuelsebusch, 2009; Peters, 2011). The FEF is defined as the mass flow-rate of food-intended crops converted to energy (Čuček et al., 2011, 2012b).

The health footprint (HLF) is the measurement of an individual’s health, and the effect that an individual’s health may have on those around that individual. The healthier the decisions that the individual makes, the higher the HLF becomes (Anthem Insurance Companies Inc., 2011).

2.3. Economic footprints

2.3.1. Financial footprint (FF)

A clear definition of the FF is as yet unavailable. The FF appears to represent the expenditures made by a human. The FF emphasises retirement, investments, insurance, tax, and estates (BMFG, 2008). The unit of the FF is as yet unclearly defined. Most likely, the FF will be defined in terms of the monetary units per person, company, country or time.

2.3.2. Economic footprint (ECF)

Likewise, no clear definition of the ECF is available. However, the ECF appears to represent the total direct and indirect economic impacts of specific processes, products, or activities, a region or an entire country. For the country, the ECF is the size of the economy relative to the country’s area (Holland et al., 2009).

It is agreed that the more likely definition of ECF is as a representation of the total direct and indirect (“net”) economic impacts. Some examples include the net ECF for universities, institutes, profitable organisations, and companies. E.g., in the case of companies, the indirect economic impact is even more important than the direct, for humans’ well-beings. An example of an economic activity is importing cheaper food into a given country. However, if fewer inhabitants in that country have work, less tax money flows into the exchequer, and more money is required for social transfers.

The unit of the ECF is unclearly defined. It is estimated that the most appropriate unit for ECF will be the monetary unit per person, company, institution, country or time.

2.4. Combined environmental, social and/or economic footprints

2.4.1. Exergy footprint (EXF)

The EXF includes resource consumption categories: materials, water, energy, and food, and with the additional research underway, human and monetary capital. By using exergy, the need to define, normalise and aggregate various impact categories is avoided. It uses national-level exergy consumption on a per capita basis as the normalisation factor and compares it to a national baseline value (Caudill et al., 2010; Exergy footprint, 2011).

2.4.2. Chemical footprint (CHF)

The CHF is an indication of potential risk posed by a product based on its chemical composition, the human and ecologically hazardous properties of the ingredients, and the exposure potential of the ingredients during its life cycle. Its analysis should include a comprehensive quantification of the chemicals used, consumed, produced or modified throughout the life cycle of the product of interest, and the risks posed (Panko and Hitchcock, 2011).

2.5. Composite footprints

A composite indicator combines two or more individual indicators or "sub-indicators" into one number. Composites have the advantage of expressing complex information within a single index and allowing companies or countries to be ranked in terms of their general sustainability. These simplified evaluations are media-friendly and are used somewhat similarly to an academic grade (OECD, 2008). The composite footprints are overviewed in the following sections.

2.5.1. Ecological footprint (EF)

The EF is a composite indicator that combines the BLF, CF (synonymous with the demand on carbon uptake land), FGF, FLF, GLF and CLF (Toderoiu, 2010; Galli et al., 2012). The EF has emerged as the world's primary measurement of humanity's demands on nature (Wackernagel and Rees, 1996) and is now widely used as an indicator for measuring environmental sustainability. The EF is defined as a measurement of the human demand for land and water areas, and compares the human consumption of resources and absorption of waste with the Earth's ecological capacity to regenerate (GFN, 2010). The EF provides an aggregated assessment of multiple anthropogenic pressures (Galli et al., 2012).

The main strength of the EF concept is that it is attractive and intuitive (Schaefer et al., 2006), and that its methodology is continuously improving. The EF helps in understanding the complex relationships between the many environmental problems by exposing humanity to a "peak-everything" situation (Galli et al., 2011). However, it should be noted that the EF measures only one major aspect of sustainability, namely, the environmental aspect, and not all environmental concerns (Galli et al., 2011, 2012). The EF excludes economic or social indicators. The EF is usually measured in global area units as the amount of bio-productive space (Hoekstra, 2008), and in global area units per person (Ewing et al., 2010). Each global hectare represents the same fraction of the Earth's total bio-productivity and is defined as 1 ha of land or water normalized to the world-averaged productivity from all of the biologically-productive land and water, within a given year. The total biologically-productive area available on the Earth is approximately 12,000 Mha (Galli et al., 2011). Biologically-productive areas include crop land, forests, and fishing-grounds but exclude deserts, glaciers, or the open ocean (Shanthini, 2010; Kitzes and Wackernagel, 2009). Converting the data to area units can be problematic. It also has limited data availability, uncertainty of data, and geographic specificity. The EF can be applied over scales ranging from single products to households, cities, regions, and countries or to humanity as a whole; however it is most effective, meaningful and robust at aggregate levels (Wackernagel et al., 2006; Galli et al., 2012).

2.5.2. Sustainable process index (SPI)

The SPI is based on the assumption that a sustainable economy relies only on solar radiation as natural income. The SPI is a member of the EF family (Kettl et al., 2011a) and measures the total area necessary to embed human activities sustainably within the biosphere. The total area is calculated as a sum of the area required to produce raw materials, the area needed to provide process energy, the area needed to provide installations for the process, the area required for the staff, and the area needed to accommodate products and by-products, and to allow for the dissipation of emissions and waste into the biosphere (Narodoslawsky and Krotscheck, 1995; Sandholzer and Narodoslawsky, 2007).

The areas are computed on the basis of mass and energy flows, and the infrastructural requirements for the referenced period, usually one year. Within this period, a number of system units will be supplied by the process in question. The specific area is defined as the total area divided by the system units. This specific area is a possible comparative measurement of sustainability and can be related to the area that is statistically-available to each person, and this defines the SPI. With a lower SPI, the impact of providing goods or services on the ecosphere is lower (Sandholzer and Narodoslawsky, 2007).

It should be noted that the same strengths and limitations relating to EF also relate to SPI. The advantages of the SPI are that material and energy flows are aggregated within one measurement, and are adaptable to individual processes, activities or regions, and are also adaptable for importing and exporting (Krotscheck and Narodoslawsky, 1996). The SPI, as well, only measures the environmental aspect. The SPI has limited data availability, uncertainty of data, time intensiveness when finding the appropriate regional data to perform a complete calculation (Hall, 2008), high possible error relating to the conversion of emissions to an area unit, geographical specificity, etc.

2.5.3. Sustainable Environmental Performance Indicator (SEPI)

The limited inclusion of cost and investment considerations significantly restricts the applicability of LCA as a source of input for strategic decision-making. Accordingly, the Environmental Performance Strategy Map (EPSM) was developed. The EPSM integrates financial, environmental, resource, and toxicological considerations into a single analysis. Environmental and social footprints are considered. Moreover, cost is considered as an additional category that relates to all of the other categories (De Benedetto and Klemeš, 2009a, b).

The objective of the EPSM is to provide a single indicator for each option. The best option from the environmental or social and financial perspectives can subsequently be selected based on this approach. A deviation-from-target methodology is used, in which a maximum target is defined for each of the footprints, and each value is expressed as a percentage of the distance to that target. The normalised values of the footprints are mapped on a spider diagram. The cost is considered as an additional dimension because it is not used for comparative reasons. The volume of each pyramid represents the overall environmental or social and financial impact of the option under consideration. This indicator is termed the SEPI. The EPSM enables the comparison of different footprints based on a single SEPI (De Benedetto and Klemeš, 2009a, b). The SEPI indicator was only recently suggested, and is designed to be composed of any combination of quantitative indicators, although it is currently depicted as a combination of the CF, WF, ENF, EMF and WEF. The SEPI indicator and an approach that complements environmental, financial and other considerations were described in detail by De Benedetto and Klemeš (2009a, b).

The advantage of using EPSM is that it combines the main indicators with the SEPI as a single measurement for the sustainability of a given option. However, the weaknesses are also, amongst others, the limited availability and uncertainty of data, time intensiveness to perform the study, and highly possible errors relating to the conversion of emissions to an area unit.

2.6. Note on the footprint definitions and measurement units

The foregoing overview of environmental, social, and economic footprints indicates that they are not yet standardised. A systematic approach to the evaluation of footprints was used. The definitions of environmental footprints often vary, as do the measurement units used for their evaluation (Table 1).

Table 1
Footprints and their corresponding measurement units.

	Measurement unit[a]											
Footprint	mu/fu	au/fu	mu/tu	mu/(au·tu)	eu/fu	eu/(au·tu)	vu/au	vu/fu	au	au·tu	mu	Other units
CF	**X**	X	x	X					x	x	x	
WF				X			x	**X**	x		x	
BWF								**X**				
WPF	**X**			X								
ENF		x			**X**	x			x			
EMF	**X**								x			
NF	**X**											
LF		**X**							x			au/(au·tu)
FLF		**X**							x			
ALF		**X**										au/(au·tu)
BLF		**X**							x			
GLF		**X**							x			
CLF		**X**							x			
BF		x							x			Number of threatened species **Biodiversity loss**
PF	**X**											
FGF		**X**							x			
HF	**X**							**X**				
EF		**X**							x			
WSF	**X**											
EXF					**X**							
CHF	**X**											**Risk**

[a] au – area unit, eu – energy or exergy unit, fu – functional unit, mu – mass unit, tu – time unit, vu – volume unit.

Various units of measurement can be found in the literature, especially for the CF (Table 1). Moreover, many different units are used for the WF and ENF. The land-based EF and other land sub-footprints are more standardised and are measured in global or local hectares or in global or local hectares per person or per functional unit.

The social and economic footprints are not shown in Table 1. Except for the WEF and FEF, the social footprints are more qualitative than quantitative. The WEF is used to define the number of accidents per person and the absence from work per person over a given amount of time (De Benedetto and Klemeš, 2009a). The FEF is used to calculate the mass flow-rate of food-intended crops converted to energy (Čuček et al., 2011, 2012b). The units of the economic footprints are unclearly expressed. It is probable that, in most cases, these footprints are defined in terms of monetary units per person, company, country, or time. This paper proposes that the measurement units marked with a bold **X** should be used. However, all of these units are also appropriate for using as per time units, as determined by the characteristics of the specific problem in question. Except for OSF and SF, all other footprints can be applied over scales ranging from single products to households, cities, regions, countries, and to humanity as a whole, and can be defined within their life cycles. OSF makes no sense when applied to products, whilst SF is only used for measuring organisations.

The definitions and measurement units for the CF both vary (Table 2). In particular, many definitions of CF exist despite the wide employment and acceptance of the concept. Moreover, the CF is often interchanged with the GWP. In this case, two completely different phrases are used to convey the same meaning.

The following questions need to be clarified (Wiedmann and Minx, 2008), due to the many different definitions of CF:

1. Should only the carbon present in gas emissions be included in the CF?
2. Should the CF only consider CO_2, which is the most abundant and potent GHG?
3. Should the CF be restricted to carbon-based gases?
4. Can the CF include substances whose molecules do not contain carbon (e.g., NO_x)?
5. Should the CF be measured in mass units of CO_2 equivalents, in mass units of CO_2, in mass units of C, per unit of area, or per unit of time?

This study proposes that the CF should represent the imbalance within the carbon cycle, should include only carbon, and should be measured in mass units of carbon per functional unit. Carbon is exchanged amongst the biosphere, pedosphere, lithosphere, hydrosphere, and atmosphere on the Earth, in various forms. Carbon can take different forms, from a simple element to its compounds (such as C, CO_2, carbohydrate, limestone, carbonate ions etc.) because it circulates throughout nature. The CF should be expressed in mass units because its conversion into area units would have to be based on a variety of different assumptions, and this conversion would increase the uncertainties and errors associated with a particular footprint estimate (Wiedmann and Minx, 2008).

3. Footprints and life cycle assessment

LCA is a structured, comprehensive, internationally-standardized tool (environmental management standards ISO 14040 and 14044,

Table 2
Various definitions and units for the CF.

Definition	Unit[a]	Reference
The CF stands for the amount of CO_2 and other GHGs, emitted over the full life cycle of a process or product	m.u.$_{CO2}$ eq./f.u.	UK POST, 2006
The CF is the result of life cycle thinking applied to global warming	m.u.$_{CO2}$ eq./f.u.	EC, 2007
The CF stands for the land area required for the sequestration of fossil-fuel CO_2 emissions from the atmosphere through afforestation	a.u.$_{CO2}$ eq./f.u.	De Benedetto and Klemeš, 2009a
The CF is a measurement of the exclusive direct and indirect CO_2 emissions over a life cycle	m.u.$_{CO2}$/f.u.	Wiedmann and Minx, 2008
The CF is a measurement of the imbalance within the carbon cycle	m.u.$_{C}$/f.u.	Suggested in this study

[a] a.u. – area unit, eq. – equivalent, f.u. – functional unit, m.u. – mass unit, SI and imperial units are used by different authors.

2006) for quantifying those emissions, resource consumption, environmental, and health impacts associated with processes, products or activities over their entire life cycles: from the extraction of resources (“cradle”) through materials production, manufacturing, use, maintenance, to the recycling, recovery and reuse (“cradle”) or disposal (“grave”), and includes all of the transportation steps (EC, 2010; Guinée et al., 2002). The comprehensive scope of LCA is useful in order to avoid problem-shifting, for example, from one phase of the life cycle to another, from one region to another, or from one environmental problem to another (Finnveden et al., 2009). An LCA is divided into four phases: Goal and scope definition, Inventory analysis, Life Cycle Impact Assessment (LCIA) and Interpretation. LCA is an adequate instrument for environmental decision support (Von Blottnitz and Curran, 2007) and has gained wider acceptance over recent years within both academia and industry (e.g., Grossmann and Guillén-Gosálbez, 2010).

Since sustainability assessment also includes social and economic performance, there is a pressure to develop this methodology for inclusion within both economic/cost impacts and social impacts in LCA to make LCA a sustainability assessment tool (Hauschild et al., 2005). Social LCA is under development and is intended to assess social implications or potential impacts (Jørgensen et al., 2008; Benoît et al., 2010). Currently LCA methodologies rarely include economic analysis. The economic method is usually LCCA and calculates the total costs of a product, process or an activity over its life span (Norris, 2001; Jeswani et al., 2010; Ahlroth et al., 2011).

However, despite the advantages of the LCA methodology, it still has major limitations that need to be overcome. A potential weakness of LCA is the tremendous amount of data involved, the availability of that data, and the resource and time intensities of LCA. The primary limitation is the high degree of uncertainty that arises from the Life Cycle Inventory (LCI) that causes the results to exhibit high variability (OECD Nuclear Energy Agency, 2001; Guinée et al., 2002; Curran, 2006; Finnveden et al., 2009). A further limitation is the lack of a systematic method for generating and identifying sustainable solutions (Grossmann and Guillén-Gosálbez, 2010; Gerber et al., 2011). In addition, conventional LCAs are for emerging technologies, such as e.g. production of biofuels, generally based on an average technology at lab- or pilot-scale that are extrapolated to large scale (Gerber et al., 2011).

Many different applications have been made for the assessments of different footprints as a life cycle perspective. In ScienceDirect 1341 articles and in Scopus 1538 articles can be found containing “footprint” and “life cycle assessment” or “LCA”, most of them over the last four years. Different studies have been performed using the life cycle approach for ecological footprint (e.g., Huijbregts et al., 2008; Stoeglehner and Narodoslawsky, 2009), water footprint (e.g., Berger and Finkbeiner, 2010; Jeswani and Azapagic, 2011), carbon footprint (e.g., Strohbach et al., 2012; Filimonau et al., 2011), energy footprint (e.g., Woolridge et al., 2006; Chowdhury et al., 2012), and nitrogen footprint (e.g., Xue and Landis, 2010; Čuček et al., 2012a). Only a few studies have been performed as yet on social footprints (e.g., Hutchins and Sutherland, 2008; Labuschagne and Brent, 2006).

4. Footprints and multi-objective optimisation

Different considerations, e.g., technical and economic factors, and environmental performance play an important roles in decision-making (Sowlati, 2007). Processes, technologies, products or activities should be economically-viable, environmentally-benign and socially-just to be the most sustainable. As these desired qualities often represent conflicting targets, simultaneous MOO must be performed to obtain compromise solutions (trade-offs) that reveal the possibilities for achieving improvements within the system (Azapagic and Clift, 1999).

MOO, also known as multi-criteria optimisation (MCO), is the process of simultaneously optimising two conflicting objectives (or more in many cases), that are subject to certain constraints. The use of MOO requires translating the environmental and/or social aspects of a problem into suitable environmental and/or social performance indicators, which should be optimized in conjunction with the traditional economic-based criteria (Grossmann and Guillén-Gosálbez, 2010).

Different methods can be applied to solve MOO problems. The simplest method is to transform the MOO problem into a single-objective optimisation (SOO) problem by applying weights to different kinds of criteria (the weighted objective method). Other widely used optimisation methods are the ε-constraint method, in which a sequence of constrained single-objective problems is solved; the goal-programming method, in which the solution is obtained by minimizing a weighted average deviation of the objective functions from the goal set by the decision maker, and evolutionary algorithms that involve random search techniques (Bhaskar et al., 2000). The solution for such problems is a set of “non-inferior” or Pareto points. The identification of the non-inferior solutions of an MOO problem using the ε-constraint method corresponds to a parametric programming problem.

Several applications of MOO have considered trade-offs between the economic and environmental, social or technical aspects of a problem. Many applications have been performed in the past that integrated LCA into synthesis problems, and several new methods for solving MOO problems have also been developed over recent years. However, only a few applications have been performed that integrate footprints into the MOO problems. MOO is becoming increasingly more and more important as in ScienceDirect 136 articles and in Scopus 51 articles can be found containing “footprint” and “multi-objective optimis(z)ation” OR “multi-criteria optimis(z)ation”, most of them from the last four years.

5. Tools for footprint evaluation

Many tools have been developed for footprint evaluation. A number of such tools focus on simple and rapid calculation (calculators), whereas other more sophisticated tools enable the calculation of various footprints and other indicators (e.g., the software Bottomline[3], ISA, 2008) or enable SOO or MOO (e.g., GAMS, Brooke et al., 2005). Some of these tools are overviewed in the following sub-chapters.

5.1. *Tools for footprint calculations, and suggested reduction tools*

5.1.1. *CF calculators*

CF calculators have become relatively common on the Internet. However, these calculators can generate varying results even for the same individual activity. Overall, these calculators lack consistency and furnish insufficient information about their methods and estimates. Nevertheless, CF calculators can promote public awareness of carbon emissions from individuals’ behaviour. Several of the CF calculators also promote methods for mitigating CO_2 emissions through offsets or investments in renewable energy technology (Padgett et al., 2008). The similarities and differences amongst ten US-based calculators were reviewed by Padgett et al. (2008). CF calculators are intended primarily for individuals and households but can also be applied to businesses. Table 3 contains a list of CF calculators selected from at least 80 currently available CF calculators (Squidoo, LLC, 2011).

Table 3
List of selected CF calculators.

Application	Unit	Developer	Website
Calculates the CF for different countries from mobility and from options for living with carbon offsets	t/y and €/y	Carbon Footprint Ltd	www.carbonfootprint.com
For the US, calculates the CF from transportation, housing and shopping with actions to reduce the CF, possibly to zero	$t_{CO2\ eq.}$/y	University of California, Berkeley	coolclimate.berkeley.edu
For the US, calculates the CF based on the state average and compares it with the US and global average CF per person	$t_{CO2\ eq.}$/y	The Nature Conservancy	www.nature.org
For the US, calculates the household CF and compares it to the average CF	lb_{CO2}/y	US EPA	www.epa.gov

See references: Carbon Footprint Ltd (2011); University of California (2010); The Nature Conservancy (2011); US EPA (2011).

5.1.2. *Calculators for other footprints*

Some online calculators for footprints have been developed, other than the CF. Such calculators allow individuals to calculate their EF, WF, NF, and HLF. However, calculators for other footprints than CF are uncommon. Several footprint calculators other than CF calculators are shown in Table 4.

5.2. *SPIonExcel*

SPIonExcel, introduced by Sandholzer and Narodoslawsky (2007), is a software product that allows for the easy and rapid EF calculation of processes and products. This program is based on the SPI. The identification of ecological "hot-spots" regarding processes is the prime goal of the SPIonExcel software. These analyses allow for the ecological optimisation of processes. The software is downloadable for free from the SPIonExcel homepage <spionexcel.tugraz.at> (Institute for Resource Efficient and Sustainable Systems, 2007).

5.3. *RegiOpt*

The RegiOpt (Regional Optimiser) software tool was introduced by Kettl et al. (2011b). The Process Network Synthesis (PNS) (Friedler et al., 1995) and SPI methodologies are combined in RegiOpt to enable the creation of economically-optimal regional energy technology networks that are subject to the consideration of environmental impacts (EF). The EF provides insights into possible "hot-spots" within the system and also furnishes information on the benefits of a system. The program is provided in two versions: the "Conceptual Planner" for rapid and simple analysis and the "Advanced Designer" for a more detailed energy network scenario (Kettl et al., 2011b).

5.4. *Bottomline^3 (BL^3)*

BottomLine^3 is a software package developed by Dipolar Pty Limited and ISA (ISA, 2008). This software enables the production of robust, reliable, and repeatable sustainability reports for companies and organisations. A wide-range of environmental, social, and economic indicators can be calculated. This software performs a complete LCA of all of the direct and indirect impacts associated with the organisations. The program features a number of economic, social, and environmental indicators, including the EF, CF, GHGs, energy and resource usages, air pollutants, and material flows. In total, the database includes well over 100 indicators. The required minimal data input only consists of the company's or organisation's financial data. The outputs of the software include aggregate figures, detailed breakdowns and rankings of the indicators into supply chain contributions (Wiedmann et al., 2007).

5.5. *PNS solution*

The graph-based tool PNS Solution is a software package for solving PNS problems based on the P-graph approach (Friedler et al., 1992; Sűle et al., 2011). The aim of the PNS framework is to examine the feasible structures and select their optimum. An advanced branch-and-bound (ABB) algorithm is used to determine the optimal structure without generating all of the solutions (Friedler, 2010). The optimal structure can be assessed in terms of the cost, profit, or footprint (Lam et al., 2011). PNS Solution enables the optimisation of footprints and economics at scales from a single product or process, to e.g., optimal energy networks, or to the whole supply chain.

5.6. *Mathematical programming tools*

MP (also called mathematical optimisation, MO) is a powerful mathematical technique that can also be used for LCA and during sustainability analyses. The goal of MO is the maximisation or minimisation of an objective function, subject to certain constraints. The system can be optimised on different footprints, impacts or performances separately by using SOO (e.g., maximising the profit or

Table 4
List of selected calculators for footprints other than CF.

Footprint	Application	Unit	Developer	Website
EF	For 15 countries, calculates how many planets and how much land area is required to support a human's lifestyle, including food, shelter, mobility, goods, and services	$N_{Planet\ Earths}$ and global hectares	Global Footprint Network	www.footprintnetwork.org
EF	Calculates how many planets are required to support a human's lifestyle, including food, travel, home and staff	$N_{Planet\ Earths}$	WWF	footprint.wwf.org.uk
WF	For different countries, calculates the water required to produce the goods and services consumed by humans compared with the per capita US average	m^3/y	Hoekstra, Chapagain, Mekonnen	www.waterfootprint.org
WF	For different countries, calculates the water required to produce the goods and services consumed by humans	L/d, gal/d	Kemira	www.waterfootprintkemira.com
NF	For the US, Netherlands and Germany, calculates the amount of N_r released	m.u./y	N-PRINT Team	www.n-print.org
HLF	For US residents, calculates the overall score out of a maximum score, with recommendations for improving the HLF	–/–	Anthem Insurance Companies, Inc.	connects.anthem.com

See references: GFN (2011); WWF (2011); Hoekstra et al. (2005); Kemira (2011); N-Print team (2011); and Anthem Insurance Companies Inc. (2011).

minimising the operating cost or the CF) or simultaneously using MOO (e.g., maximising the profit and simultaneously minimising the CF).

The optimisation problems are categorised by the structure of the objective function and the constraints. MP tools use mathematical methods in the forms of linear (LP), non-linear (NLP), or mixed-integer non-linear programming (MINLP), or other approaches, to numerically solving a certain optimisation problem. Amongst the widely and less-widely used tools for performing SOO or MOO are the General Algebraic Modelling System (GAMS) (Brooke et al., 2005), A Mathematical Programming Language (AMPL) (AMPL, 2011), Advanced Interactive Multidimensional Modelling System (AIMMS) (Roelofs and Bisschop, 2011), the Mixed-Integer Process SYNthesizer (MIPSYN) (Kravanja, 2010; Lam et al., 2011) and others. They support a range of different types of solvers for different types of models, such as BARON, CONOPT, CPLEX, DICOPT, MINOS, OQNLP, etc.

6. Conclusions

Moving towards sustainability requires the redesigning of production, consumption, and waste management. Reliable definitions and measurements are necessary for achieving these goals. Several tools for measuring sustainability have been developed to evaluate the (un)sustainability of humans, nations, processes, products or activities. Nevertheless, the definition of a suitable environmental and/or sustainability metric for supporting objective environmental and/or sustainability assessments is still an open issue within the literature. This paper provides overviews and a literature review for the definitions of various footprints. The usage of environmental footprints is particularly widespread and therefore, such footprints are being defined more frequently and their units clearly expressed. In contrast, social and economic footprints are still rarely used. This study shows that CF, ENF, and economic footprints are not yet standardised and are still an open issue. The units of the economic footprints are unclearly expressed. This paper, therefore, represents a step towards better systemisation of footprints, their definitions and units, and provides a framework for discussing footprint definitions and measurements, thus allowing the science regarding footprints' measurements of sustainability and SD to be further advanced. The indicators measuring sustainability and SD should be useful for decision-making. Substantial work will be necessary to achieve the systematic standardisation of footprint definitions and units of measurement. Further work will be required to achieve this goal for social and economic footprints.

The tools for footprint evaluation were further explored in this paper. CF calculators are the principal tools. However these calculators reportedly lack consistency and calculate different results. In order to achieve SD, all of the necessary components including economic prosperity, environmental protection, and social responsibility, should be integrated into producing harmonious solutions. This goal requires the quantification of a system's sustainability impact(s) throughout its life cycle. This integrated consideration involves an MCO and the use of MP tools, which represent a powerful framework for designing sustainability systems. However, few such sustainable applications have been developed to date. These perspectives on the footprints, SD, and extended LCA indicate that substantial work remains in order to properly integrate economic, environmental, and social considerations during decision-making.

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Abbreviations

ABB	advanced branch-and-bound algorithm
AIMMS	Advanced Interactive Multidimensional Modelling System
ALF	agricultural land footprint
AMPL	A Mathematical Programming Language
BF	biodiversity footprint
BLF	built-up land footprint
BWF	Blue Footprint™
CF	carbon footprint
CHF	chemical footprint
CLF	crop land footprint
COD	chemical oxygen demand
COF	corruption footprint
ECF	economic footprint
EF	ecological footprint
EMF	emission footprint
ENF	energy footprint
EPSM	Environmental Performance Strategy Map
EXF	exergy footprint
FEF	food-to-energy footprint
FF	financial footprint
FGF	fishing-ground footprint
FLF	forest footprint
GAMS	General Algebraic Modelling System
GHG	greenhouse gas
GLF	grazing land footprint
GWP	global warming potential
HF	human footprint
HLF	health footprint
HRF	human rights footprint
JF	job footprint
LCA	Life Cycle Assessment
LCCA	Life Cycle Cost Analysis
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LF	land footprint
LP	linear programming
MCO	multi-criteria optimisation
MINLP	mixed-integer non-linear programming
MIPSYN	Mixed-Integer Process SYNthesizer
MO	mathematical optimisation
MOO	multi-objective optimisation
MP	mathematical programming
NF	nitrogen footprint
NLP	non-linear programming
OSF	online social footprint
PF	phosphorus footprint
PNS	Process Network Synthesis
POF	poverty footprint
SD	sustainable development
SEPI	Sustainable Environmental Performance Indicator
SF	social footprint
SLCA	Social Life Cycle Assessment
SOO	single-objective optimisation
SPI	Sustainable Process Index
WEF	work environment footprint

WF	water footprint
WPF	water pollution footprint
WSF	waste footprint

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