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Transforming an Existing Scientific Sub-metric into a Universal Ecological Certificate for Automated Material Flow Exchanges

How to close the loop between earth's resources, industrial activity, personal consumption and planetary boundaries

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***Abstract*—Earth's Politicians have agreed a target to cap global warming to 1.5 degrees above pre-industrial levels. While the agreement of such a target is a laudable achievement, one has to be wondering how we will achieve this. What does sustainability actually mean and how do we measure it? And when will we know this goal has been achieved?**

Put more succinctly: what needs to happen in the economy to help us stay within the target? The promise of clever engineering to solve the problem was made many years ago but it hasn't materialized.

A key ingredient to the industrial success of our economy is the freedom that entrepreneurs and business owners have to create products that serve the wishes of society. No one wants this freedom of expression and access to such products to be curbed, but a brake of some sort may need to be applied.

This paper investigates the fundamental "missing link" that would enable people to understand the environmental impact of their economic/consumption activities. It posits that what is missing is an environmental accounting system that enables all economic actors to easily and therefore actively engage in a cogent sustainability solution. Such a solution would link economic activity to planetary boundaries.

Before any such global aspiration can be contemplated however, we would need a universally agreed metric, or system of metrics, in order to communicate effectively. A universally applicable ecological certificate is proposed. It is based on the existing scientific method of life cycle analysis; extending an existing sub metric with a vital missing component that could then behave like a global ecological "currency"

Keywords—resources economy; ecological economy; environment economy; accounting; planetary boundaries; ecocost; myecocost; automated material flow exchanges; ecoaccounting; sustainability; circular economy.

I. INTRODUCTION

A. An Economic Imperative

Although awareness and concern existed within the scientific community well before 1992, it is since that first Earth Summit at Rio de Janeiro in that year that the prospect of global warming has been growing in the wider public consciousness. Since then experts have been looking into how to curb carbon emissions in order to arrest the threat of global warming, by introducing ecological accounting.

The call for a more effective, in-house approach to ecological accounting has been in place since 2009 [1]. This paper describes how this can be achieved cost effectively with automation.

The Paris Agreement of December 2015 has thrown down the gauntlet. It declared the maximum figure of 1.5 degrees, in light of the fact that anything higher would result in the annihilation of hundreds of millions of people from low lying countries. The challenge of this target is that we have already reached 1.0 degree of the 1.5 and it is estimated that we could reach 1.5 degrees by 2026. Time is tight!

Sustainability and resilience will be achieved much faster if the majority of the Earth's population understand the value and needs of our increasingly fragile Earth. A shared understanding of the link between humanity and nature could induce a profound change that will allow all life to thrive in the Anthropocene. [2]

Understanding the value and needs of Earth requires an understanding of the link between humanity and nature. This statement addresses the "what needs to be done". In another statement from the same report, the World Wildlife Fund for Nature (WWF) provide a pithy "how" to the aforementioned "what":

We must adopt an entirely new perspective that will guide decision making at all levels.[2]

WWF's use of the term "perspective" is important. WWF is not arguing for a new technology, or for society to deprive itself… it is are arguing for a new way of viewing things - a new way of looking at the world. What view would we need to have to provide this new perspective? It needs to be scientific… it needs to be measurable.

Society already has a dominant perspective- that of finance. Money is currently the most influential global metric, affecting everyone:

- individuals have a sense of whether common items (milk, bread) are expensive or cheap.
- individuals have a sense of their monthly income and expenditure.
- individuals have a sense of their financial limits
- businesses have a source of income and costs involved in generating that income.
- businesses keep track of their financial situation using a financial accounting system.
- businesses use standard reports such as a profit and loss report to measure the success of the business
- the media use monetary metrics to report on the significance of events or situations.

Today's challenge, then, is to provide an environmental perspective on our day-to-day activities. If we did this we could develop a common sense of environmentally expensive products, and from that, environmentally affordable lifestyles. To do so would have to involve a common method of measuring and assessing the environmental impact of existing economic activity. Such a method would require, in the first instance, a common unit of measure.

B. *Economic Orientation*

The primary opportunity for a world that has a 1.5 degree constraint ahead of it is the ability to develop an environmental accounting system that can reflect the conditions leading up to the limit, one that works with the same efficiency as financial accounting systems.

The term "1.5 degree constraint" was chosen carefully. It is not just monetary constraints with ballooning debt mountains that are threatening to destabilize our familiar financial system, but economic constraints of a different kind - where there is *too much* resource than is healthy for us. Over past millennia as part of our economic evolution, we have conditioned ourselves into accumulating a scarce resource such as gold or silver. However this "old economic habit" has now been tipped on its head with *too much* resource (greenhouse gasses (GHGs)) in the atmosphere.

The idea of too much resource may seem peculiar because it is a novel constraint. It is not a constraint of "not enough" (the economic condition we are used to) but a constraint of "too much" - diametrically opposed to our conditioning. This is compounded by the fact that the resource is invisible because it is gaseous. To achieve our 1.5 degree target this needs to be monitored with just as much diligence as money.

The opportunity for society is the development of a standardized, computerized environmental accounting system. Such a system cannot be devised unless there is a numerical form that underpins it. This numerical form would be the equivalent of a "currency" for environmental accounting. Revealing such a unit of measure is the focus of this paper.

For ecological reporting to be substantive, it needs to be the output of an internal system of management control and reporting just as annual financial statements are the output of an internal system of management accounting and reporting [3]. A consistent unit of measure paves the way for ubiquitous reports based on environmental metrics.

C. *The Unspoken Challenge of 1.5 Degrees*

At the 1.5 Degrees Conference in Oxford in 2016 it was discussed that the deep challenge was getting a handle on the demand side of emissions - this means broad society as a whole, i.e. individuals are the foundation of all economic activity. This point was raised some three times within plenary sessions. The implied, singular, question raised was "how can we engage society as a whole to reduce its emissions in achieving the global 1.5 degree target?". Despite the numerous times it was raised, no one proffered an answer. It was the proverbial elephant head in the room that couldn't be talked about.

II. Financial Accounting as a Precedent

Financial accounting is already ubiquitous. Environmental accounting needs to become just as ubiquitous for any new perspective to emerge, capture the public imagination and ultimately influence our behaviour.

Two elements lie at the foundation of the financial accounting system:

- a unit of measure (money)
- a method of accounting for that unit of measure

The familiar financial accounting method used for the last 550 years is a standard technique of taking the unit of measure (money) and classifying it in such a way that the relevance (or value) of the unit of measure is recognised, and from that used to drive decision making towards some goal (e.g. the objectives of the organisation, or increase efficiency). Put simply, financial accounting is a sophisticated classification of money within an organisation. The basis of the classification system is a structure of ledgers, illustrated in Fig. 1.

- Each ledger stands alone, independent of other ledgers.
- The ledgers are each classified as being asset or liability ledgers.
- Each ledger has an opening balance, a debit side, a credit side and a closing balance.
- A ledger is open for a period of time and any number of debits or credits can be entered.
- Related ledgers are grouped together for reporting purposes, allowing us to summarize the figures into something meaningful.

- Reporting always declares a reporting date as the summarized accounts can change from day to day.
- A single accounting event will always update at least two ledgers with the total of credits matching the total of debits - this rule ensures balanced ledgers.

In addition to the balancing of ledgers, further checks are applied such as:

- an internal review of financial summaries (profit and loss, balance sheet) at the end of each accounting period
- an external review of accounts, known as an audit, performed by a skilled third party practitioner
- external reporting to authorities, creating a public record
- the submission of tax accounts (which feeds into national statistics)

This structure of checks and balances is what gives the financial system its rigor, its integrity, its credibility. This credibility and the flow of money into personal accounts as salaries (part of the above structure) is what binds each economic actor - governmental, corporate, organisational and personal - in the worlds economy.

We can use these attributes of financial accounting to set the precedent for a standardized method of environmental accounting. The legal entity has its own clearly defined boundary for its (financial) inputs and outputs, and every (financial) input and output is recorded. We just have to replicate this with an environmental equivalent to money..

III. Life Cycle Assessment as a Precedent

The current method of assessing environmental impact of products centres around the process oriented life cycle assessment, or LCA. LCA is a very detailed topic but its high level principles can be outlined [4].

Life cycle analysis examines the environmental impacts of a product by considering the major stages of a product's life, described in Table I.

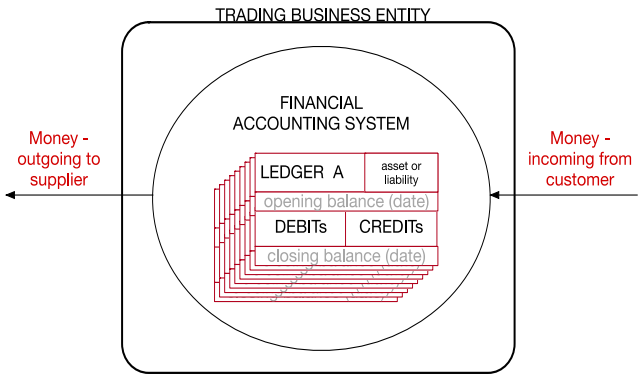

Fig. 1. Financial accounting is a sophisticated classification of money through a series of independent yet related ledgers.

Because tracing emissions data backward through a supply chain is difficult, each study must set its own boundaries and determine policies on extrapolations, absence of data etc, adding further complexity and margin for error within each study. Fig. 2 illustrates this challenge, highlighting the centralized focal point of the study in yellow. Compounding the difficulty is the prognostication of a product's use and end of life which can be uncertain.

The LCA technique can be narrowed down to four main steps [5] which address one or more of the product's life stages at a time:

1. The definition and scope is determined along with information needs, data specificity, collection methods and data presentation. In short, what is included in the study, represented as solid blue lines in Fig. 2.
2. The life cycle inventory (LCI) is completed through data collection and evaluation of the data. Process diagrams are used as an aid. Gathering the input (orange lines) and emissions figures (green lines) are shown in Fig. 3.

The life cycle impact assessment (LCIA) is determined with impact categories and their weights, as well as any subsequent results.

3. The final report should include significant data, data evaluation and interpretation, final conclusions and recommendations.

TABLE I. Major stages of a product's life

Stage	*Description*
Raw material acquisition	Which includes material harvesting and transportation to manufacturing sites
Processing	Which involves materials processing and transportation to production sites
Manufacturing	Which includes product manufacture and assembly, packaging, and transportation to final distribution
Product life	Which includes energy and emissions during normal product life, required maintenance, and product reuse (refurbishing, material reuse) and
Waste management / end of life	Which includes recycling, landfills, liquid waste, gas emissions, etc.

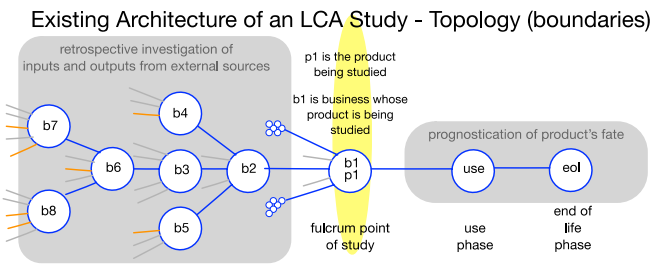

Fig. 2. LCA studies the entire impact of a product from a single point in the supply chain, invoking challenges in obtaining good quality data because suppliers do not have emissions data readily to hand. Some suppliers will be omitted from the study because they are service based, difficult or unwilling to provide data.

The fundamental unit of measure in developing an LCA is the Life Cycle Inventory, or LCI.

We make decisions concerning the environment every day, and many of these decisions are based on incomplete, inconsistent, and flawed information. Life cycle assessment (LCA) provides a holistic evaluation methodology and a consistent framework for making better informed decisions. Life cycle inventory (LCI) data are the primary inputs for conducting LCA studies [6].

It is the inventory that forms the evidence base for the assessment algorithms to work. The LCI is the foundation upon which all environmental assessment is made.

The latest categorization of environmental accounts by the international community include four types of accounts [7]:

- natural resource asset accounts,
- pollution and material physical flow accounts,
- monetary and hybrid accounts, and
- environmentally-adjusted macroeconomic aggregates

The Impact Assessment derived from LCIs is a comprehensive account of materials exploitation making many environmental indicators accessible. Table II shows the current suite of indicators available from an LCI.

In order to derive an impact from its source from nature all the way through use and end of life, the LCA will be a "cradle to grave" quantification.

IV. Other Developments in Life Cycle Analysis

A recent development in life cycle analysis is Hybrid LCA that combines the process driven data gathering described above with direct input-output details. The claim is that it will produce more accurate results. It has its challenges including terminology and ontology issues; extra work merging data from different formats and sources [8]. The results, and therefore opinions, are mixed with some claiming process driven LCA underestimates and adding input-output approaches results in overestimating [9].

Environmentally-extended input-output analysis (EEIOA) is another example of improving the accuracy of LCA. The advantage of EEIOA over process based LCA is that it can be used to calculate the hidden and indirect environmental, economic, and social impacts associated with downstream consumption (Baumann, 2013; Berners-Lee, Hoolohan, Cammack, & Hewitt, 2012; Duchin, 2005; Foran, Lenzen, & Dey, 2005; Kitzes, 2013; Roy et al., 2009) Unlike process based LCA there is no double counting of impacts in complex supply chains. Furthermore with EEIOA, complex problems - such as the altering of diets - can be modeled with greater ease than via process based LCA [10].

Despite these developments, process driven LCA remains the dominant method in use today and their existence highlights the need to improve the accuracy of process driven LCA. The question is, then, at what cost? A closing comment on these approaches is given later.

V. The Anatomy of a Life Cycle Inventory

Let us now examine the data structure of the fundamental data set underpinning environmental assessment today. Table III shows an excerpt of records from a sample LCI.

Each column is explained in Table IV so the reader can understand the content and the contribution each makes to impact assessment and recognize related columns.

Of the eight columns, there are some that overlap in scope so it is relevant to distil these. Related columns are combined to distinguish three fundamental attributes. This distillation is presented in Table V.

The category and sub-category within the vector attribute provides a detailed breakdown of where materials are sourced from or returned back to nature and Tables VI and VII illustrate this with a subset of each type.

The point being made is that the materials involved in the production of a product have a comprehensive catalogue of *historical* inputs and *historical* outputs - what it has taken in material terms to get the product to this point in the life cycle. It does not, however, reflect any content of what materials *make up the actual product itself*. The LCI of a product will typically be made up of thousands of records as illustrated in Table III. Numerous algorithms are then applied to the vector, material and quantity records to derive environmental indicator values.

TABLE II. The LCI provides a means to gain insight into a variety of environmental issues. These indicators could become available as business metrics.

Climate change	Ozone depletion	Human toxicity – cancer effects	Human toxicity – non cancer effects
Eco toxicity – freshwater aquatic	Particulate matter / Respiratory inorganic	Ionizing radiation	Photochemical ozone formation
Acidification	Eutrophication – terrestrial	Eutrophication – aquatic freshwater	Eutrophication – marine
Land use	Resource depletion – water	Resource depletion – mineral, fossil and renewable	

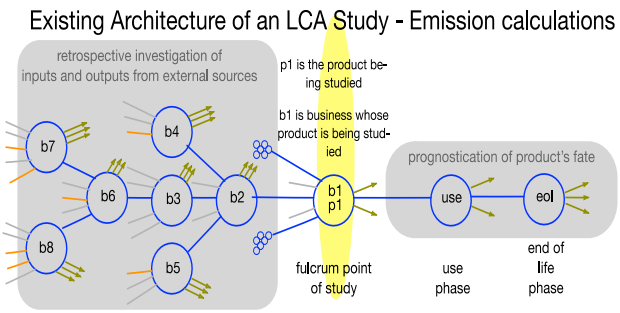

Fig. 3. Emissions are a key factor in an LCA and many of these are derived from earlier studies rather than taken from direct (primary) measurements.

TABLE III. A SUBSET OF A LIFE CYCLE INVENTORY (LCI) USED IN A LIFE CYCLE ANALYSIS.

Cat-egory	Sub-category	CAS number	Name	Unit	Mean value	Formula	Qty
Water	Fossil-		BOD5, Biological Oxygen Demand	Kg	1		4.182335E-02
Water	Ground-		BOD5, Biological Oxygen Demand	Kg	1		9.2637756E-03
Water	Ground-, long-term		BOD5, Biological Oxygen Demand	Kg	1		3.2676653E-02
Air	High population density	000 110-63-4	1,4-Butanediol	Kg	1	$C_4H_{10}O_2$	3.8618722E-05
Air	Low population density	000 110-63-4	1,4-Butanediol	Kg	1	$C_4H_{10}O_2$	1.0263356E-05

TABLE IV. A DESCRIPTION OF EACH OF THE PRIMARY COLUMNS INVOLVED IN AN LCI

Column	Description
Category	Where the material has been sourced or emitted
Sub-category	A refinement of where the material and has been sourced or emitted
CAS number	A code that represents a chemical compound
Name	A human readable description of the substance
Unit	Unit of measurement, predominantly mass (kg)
Mean value	Used to convert units from one unit to another e.g. pounds or grams to kilograms. (e.g. grams would have a value of 1000, relative to kg)
Formula	An alternative code to CAS number that represents a chemical compound; CAS number and formula are mutually redundant
Quantity	The amount, relative to Unit, of the substance involved.

TABLE V. THE ANATOMY OF AN LCI DISTILLED INTO THREE FUNDAMENTAL ATTRIBUTES.

Attribute	Columns involved	Comment
vector	Category & Sub-category	Where the substance has been sourced for an input or emitted as an output
material	CASnumber & Name & Formula	A specific chemical compound whenever possible, sometimes a textual description.
amount	Quantity & Unit & Mean value	Typically the physical mass although this may be expressed in other scientific dimensions.

LCI data sets can be extracted from databases with either a cradle to grave option (from natural source through use and end of life back to nature) for a full impact assessment of the product, or cradle to gate (from natural source through to leaving the factory being studied).

TABLE VI. SAMPLE OF INPUT CATEGORIES FOR LCI

Category	Sub category
Resources from air	Renewable element resources from air
Resources from air	Renewable material resources from air
Resources from biosphere	Renewable material resources from biosphere
Resources from ground	Non-renewable element resources from ground
Resources from water	Non-renewable material resources from water
Land use	Hemeroby
Energy resources	Non renewable energy resources
Material resources	Renewable resources
	About 30 category/sub categories in total

TABLE VII. SAMPLE OF OUTPUT CATEGORIES FOR LCI

Category	Sub category
Emissions to air	Emissions to air, indoor
Emissions to air	Emissions to urban air close to ground
Emissions to fresh water	Radioactive emissions to fresh water
Emissions to soil	Emissions to agricultural soil
Emissions to water	Emissions to fresh water
Emissions to water	Emissions to sea water
Heavy metals to industrial soil Organic emissions to air (group VOC) Radioactive emissions to air	Group NMVOC to air
	About 40 category/sub categories in total

VI. DEVISING A COMMON, INTERCHANGEABLE UNIT OF MEASURE FOR THE ENVIRONMENT

Environmental accounting works in a different dimension to finances. It is independent of value (represented by money) and is an enumeration of material flows. The description above shows how current life cycle analysis uses a life cycle inventory (LCI) as an enumeration of material flows.

Current environmental accounting has a focus on emissions. This focus is entirely appropriate but this paper posits that it would be possible to enhance environmental accounting: to make it more akin to financial accounting and in doing so, pave the way for an ecological cost to enter mainstream economics and ergo, mainstream consciousness.

Balanced ledgers are the fundamental rule of financial accounting. When money is received by a business for selling something, the money doesn't just show up in the bank. There will be a minimum of 3 entries made in the financial accounts:

- journal entry that identifies the event that occurred (invoice being paid)
- debit entry - amount of money arriving at bank

- credit entry - amount of money no longer owed by the customer

To mimic the financial accounting system further, an ecological accounting system must be able to apply the equivalent of balanced ledgers. The assertion in this paper is that an appropriate equivalent would be mass balance [11] calculations between inputs and outputs for the production point of each company in a supply chain (i.e. conservation of mass within physical systems). The precedent behind this is economy wide material flow accounting [12]. This paper claims it is now technologically possible to shift from a top down study of national statistics to a dynamically calculated, bottom up measurement at each stage in a supply chain and in doing so, make ecological metrics available to all economic actors.

In order to develop a unit of measure that parallels a financial accounting system we will have to enhance the LCI from historical inputs and historical outputs to one that can also represent current production flows *in the present*.

A. Current Architecture for Environmental Accounting

Current practice is based on an architecture of evaluating a product, built up from various life cycle stages, studied from a single point (Fig. 2). Put simply, a study of shampoo will consider all the inputs going into the manufacturing process plus all the inputs of the supplier products that went into the manufacturing plus the suppliers to the suppliers and so on until raw extraction from earth's natural resources. The company instructing the study has an interest in determining its impact but the suppliers may not share that interest, affecting the willingness to provide data. Boundaries are declared as to what is and is not included in the study. It then considers the use and the end of life stages of the shampoo, the clearing of the plastic bottle and effects on the sewerage system.

B. An Alternative Architecture for Environmental Accounting

An alternative architecture would be one that resembles the financial accounting model. Where each business involved at each life cycle stage accounts for the inputs and outputs of each product. Not just for a single product being studied at a point in time, but continuously for all products made, and calculates an ecological certificate which is passed on to the customer. The customer then uses this ecological certificate in their own ecological accounting system to do the same thing - account for inputs and outputs, calculating an ecological certificate for a product and passing it on to the next customer. Fig. 4 should be studied and compared to Fig. 2 to illustrate this point.

Distinct features:

- no focal point of study - every business (in Fig. 2 & 3) is a "b1"
- every business is an ecological certificate calculator
- every product is measured (no studies of selected products only) - p*
- every product has its own ecological certificate, re-calculated each time it is made, so changes in suppliers are reflected accurately
- every ecological certificate is passed from supplier to customer for subsequent re-use

Distinct advantages:

- all suppliers, including service providers, can be included in the calculation mix.
- far greater precision in calculating material flows can be achieved as each business in the value chain has a record of every (input) product purchased and every (output) product sold including the invisible substances taken from and returned to nature.
- a computer in each business (a computer that already exists) can carry out the calculation work with a high degree of precision very quickly
- as businesses eco innovate, their efficiencies are automatically communicated through the downstream supply chain.

One thing this alternative architecture does not provide, compared to current LCA practice, is a prognostication of what will happen at the end of life stage. *This is a feature, not a shortfall*. Resources and emissions of the use phase will not be included when the product is purchased, but when the product consumes additional resources while being used [13]. To establish a reliable and trusted figure, it only measures what has actually happened in the production of the product - up to the last point of sale. The end of life of a product is not ignored however. It will be dealt with when end of life processing actually happens… as materials are processed through recycling centres that can also implement this system. The impact of recycling services will be passed indirectly back to individuals through their council tax or similar.

We shall use the existing LCI structure as the basis of such a unit of measure. As established above, the fundamental components of an LCI are

- vector,
- material (substance) and
- amount.

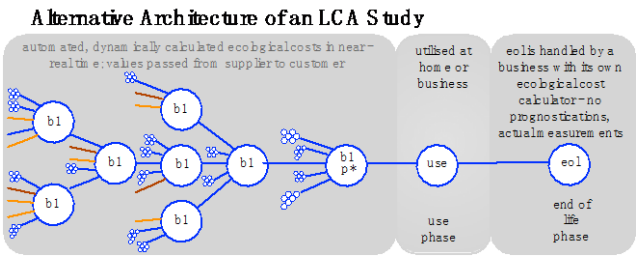

Fig. 4. With consistent environmental accounting, enabled with a universal measure for the environment, every business becomes a primary input gatherer. No boundaries have to be declared because every business could become an active environmental accounting point.

Broadly speaking the vector has classifications for inputs and outputs (emissions). The proposition being made is that the focus on aggregate inputs and aggregate outputs is inadequate for this alternative architecture. The current classification structure inhibits the alternative architecture above because it cannot be used in a calculation applying mass balance between inputs and outputs *of the current manufacturing process*. The inputs catalogued in an LCI are a sum total of all inputs to date. These cannot be applied to a mass balance calculation for the current business because they represent *historical* inputs, no longer in a form (e.g. raw ores taken from earth) that can be applied to what occurs at this point (this business) in the supply chain.

The outputs catalogued in an LCI are a sum total of all outputs to date. These cannot be applied to a mass balance calculation for the current business because they represent historical outputs. These historical output entries *can be added* to the outputs from a mass balance calculation determined at this point (this business) in the supply chain, maintaining an accurate history of outputs for the next actor in the ecological accounting (ecoAccounting) system.

C. Primary Requirement

Just as the unit of measure in a financial transaction (money) serves both the seller and buyer and just as the unit of measure is put through a financial accounting system comprising balanced ledgers by both parties, it is to be expected that an ecological unit of measure would also satisfy these two needs: mutually applicable to supplier and customer, and contributing to a framework of balanced figures.

In the new ecological accounting proposed here, the framework of balances is not ledgers but the scientific principle that "matter is neither created nor destroyed", i.e. that the mass of outputs must equal the mass of inputs. Inputs into the industrial process and outputs from the process must balance. The ecological "unit of measure" representing the trade, in physical terms the movement of goods leaving one business and arriving at another, must be able to reflect both inputs and outputs. Fig. 5 tries to illustrate this dual context. It must be capable of not just being applicable in the current transaction but in all subsequent transactions. The certificate would reflect a cradle to gate quantification at each step in the supply chain.

The ecological certificate must be able to authentically represent the seller's position on material flows, it must be able to provide utility for the next actor in the value chain when they calculate the ecological certificate of their product, and from that provide an updated, authentic position on material flows to be passed on to the next economic actor.

With the current classifications within LCIs, this cannot be done.

VII. What's Missing

An industrial process will typically take various materials, either purchased from a supplier or taken from nature, cut, crushed, mixed, heated, poured or manipulated in some way, possibly assembled, to create a new product. There could be chemical reactions involved that transform substances. There may be off cuts, burrs, dust, run off or some other waste left behind that is eliminated from the factory floor by moving it elsewhere, possibly by being hosed down a drain. It is also possible for an industrial process to produce by-product - a substance or material that is not the main product being made, but leaves the production line. The by-product can be put aside for either sale or use within another process.

The end result is a new, final product. It could be a circuit board, a nail, a bottle of shampoo.

Hence a comprehensive ecological certificate would need to be able to reflect all this, and this would behave like a "currency" for ecological accounting.

One critical factor of an effective ecological unit of measure is that it, like money, must be relevant to both the supplier and customer (Fig. 5). Please refer to Table VIII. By distinguishing **the text in bold** one will realize that this classification, while an output from the ecoAccounting system of the supplier, becomes the input values for the customer - the next step in the industrial sequence. In ecological accounting terms: one certificate, two different contexts (input/output), both parties satisfied. This has a corollary in financial terms: One currency, two different contexts (sale/purchase), both parties satisfied.

All that is required to define a universal ecological unit of measure is to extend the number of LCI classifications under vector so that a calculation incorporating mass balance between inputs and outputs can be applied. There are currently about 30 input categories and 40 output categories (Tables VI &VII) within life cycle inventories.

By adding one more classification to vector:

embedded (within the product)

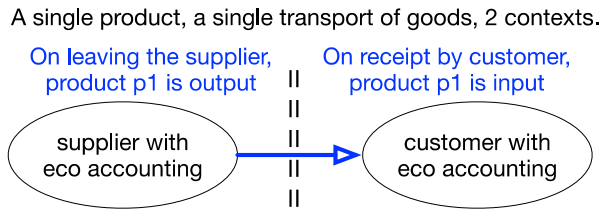

Fig. 5. The dual context of a single business transaction the output from the supplier becomes the input for the customer.

TABLE VIII. Summary of accountable materials within an organisation's ecological accounting system. Bold text highlights elements between each side of the input/output matrix calculated with mass balance.

INPUTs to industrial process	OUTPUTs from industrial process
Product or material obtained from a supplier	Emission to land
Material obtained from nature	Emission to water
	Emission to atmosphere
	Final product – materials embedded in the physical product provided to customer.

a comprehensive ecological unit of measure that has features similar to an ecological currency can be established and integrated into a dynamic calculation flow for material economics - the economics underlying the sustainability challenge. Table IX attempts to clarify the structural effect of this proposal.

The existing format of vector, material (substance) and amount does not change! The only modification is a single extension of categories that extends beyond the current catalogue of historical inputs and historical outputs.

VIII. THE MASS BALANCE CALCULATION

The products we buy can be described as an iterative flow of buy goods, make goods and sell goods. Each business in the supply chain does its incremental version of this until the final product is created and sold to the ultimate consumer. Each business in the sequence is a cog in a bigger wheel.

By creating an ecological certificate for a product that works within this iterative sequence we can produce a parallel flow of data that reflects and therefore communicates the resources involved in producing that product.

It was proposed above that a mass balance calculation would be the material flow equivalent of balanced ledgers in financial accounting. ecoAccounting needs this for credibility if it is going to be used to make business decisions. This means that the operational business process of producing a product would need to recognize all the inputs coming into this production event are accounted for and the mass of ensuing outputs would match the mass of all inputs. The fuel or content for this calculation would be the ecological certificate, or the ecoCost.

The historical inputs in an LCI do not need to be referred to. They would not form part of the mass balance calculation. They could be preserved in order to provide backward compatibility so updated ecoCost values can be used in external LCA calculations. What forms the inputs for the mass balance calculation are those materials classified "embedded (within the product)".

The new vector category of "embedded" is that part of the ecological certificate that is both output (for the company who made the product… the supplier) and input (for the customer who uses the product in the next iteration of manufacture), summarized in Table X. This is the portion of the certificate that is used in the mass balance calculation.

For the mass balance calculation to run, the business must create a calculation model that reflects the inputs and outputs of the production process for each product made. The purchased products may already be catalogued in a manufacturing system from the bill of materials so some of the information is already within the company. However the mass balance model must also include the materials taken from and returned to nature - both visible (e.g. soil from mining, crude oil from oil rigs) and invisible (e.g. oxygen from the atmosphere when burning gas, CO_2 emitted after burning, off gassing from drying paints). These materials would not exist in a conventional bill of materials.

TABLE IX. AN ADDITIONAL CLASSIFICATION TO VECTOR TRANSFORMS EXISTING LCI STRUCTURE FROM A STATICALLY DERIVED HISTORICAL CATALOGUE INTO A UNIVERSAL, DYNAMICALLY CALCULATED, FLUID ECOLOGICAL CERTIFICATE.

Vector group	Distinctions	Representing
Input categories	About 30	Catalogue of historical inputs
Embedded	Does not currently exist	Embedded materials in the current physical product; in-situ outputs (technosphere) from the company supplying; in-situ inputs (technosphere) to customer processes
Output categories	About 40	Catalogue of historical outputs

The operational event "make product" would be used to trigger the mass balance calculation method "using the inputs of this manufacturing operation (the materials embedded within the product), apply a mass balance calculation to reflect the outputs (vector, material, amount) within the ecoAccounting module. The outputs of the manufacturing process returning to nature are added to the historical outputs.

It is this embedded portion of the certificate that

- changes the way we can calculate an accurate ecoCost for a product at any stage
- enables a completely new architecture for measuring environmental impact of products
- allows us to think of ubiquitous ecological accounting as a real possibility
- would provide numerous ecological indicators to any business interested in them
- individuals being the final customer, provide a means to pass on ecoCosts to individuals that can then be aggregated to provide personal impact statements. This could be achieved by people swiping a "personal ecoCost ID card" at the point of sale, like we do now with loyalty cards (e.g. Nectar).

None of this is possible with LCIs in their current state. The vector classification "embedded" is the missing link.

IX. CLOSING THE LOOP: TOWARDS A CIRCULAR ECONOMY

Equipping individuals with the ecoCost of their purchases in an electronic format opens up a number of interesting possibilities. Many people have personal computers or some sort of mobile device connected to the internet. These devices could be used to receive the ecoCosts of purchases and then aggregate them into an impact assessment of an entire lifestyle.

The European average of household internet access is in excess of 85% [14]. See Fig. 6. This level of computer presence in households makes the provision of personal (or household) levels of sustainability highly relevant.

Recent work in determining planetary boundaries [15], scaling them down to the level of individuals, means a direct comparison between household consumption (using aggregate ecoCosts and extracting relevant indicator values) and planetary boundaries could be used to inform individuals on

the sustainability of their lifestyles. The planetary boundaries effectively act as a personal sustainability budget. Fig. 7 illustrates a realistic example, made more accessible with the use of smart phones.

The EU aspires to provide a "credible communication to consumers avoiding confusion and mistrust" regarding the impact of products [16] and as such has demonstrated its ambition to establish product environmental footprints [17] that is thwarted by data gathering challenges. The ecoCost certificate shows how this can be achieved in a very efficient manner. Substantiated green claims would also become a reality.

This ecological certificate (ecoCost) approach could represent the nucleus of a new era of eco-awareness in everyday life [18].

Bridging consumption with planetary limits means society can close the loop between Earth's resource use, industrial activity, personal consumption and planetary boundaries.

X. Closing Comments on Architecture

A. *Scientific Perspective: Hybrid LCA and Extended Environmental Input Output Analysis*

Both Hybrid LCA and EEIOA are attempting to improve the accuracy of process driven LCA. They both aim to improve data by accounting for actual inputs and outputs. The techniques vary considerably in how the input-output figures are gathered but its predominantly based on dissecting and merging international export and import statistics (e.g. wheat or iron) to apply real world data to enhance process models.

Introducing a universal ecological certificate as a unit of measure, derived from observing and measuring the actual inputs and outputs at each point in the economic value chain, delivers on the ambitions of these new approaches. Applying mass balance calculations at the factory floor level is a direct observation of inputs and outputs. These inputs and outputs are being derived from a calculation model that is based on the processes executed on the factory floor.

The method proposed in this paper is applying micro input-output data gathered at each step in the chain… i.e. at source. Each step in the value chain would be gathering primary input-output data directly correlated to the business processes being applied and modeled, using values received up-stream from the supplier and passing the values down-stream to the customer. And each step is automated. The ambition of Hybrid LCA and EEIOA is faithfully delivered with the method proposed in this paper.

B. *Commercial Perspective: Service Providers*

Service inputs would be included in this novel method. Although labor, both muscular and intellectual, does not have mass, the tools and energy required to provide the services do. The equipment behind service providers takes the form of computers, stationery, photocopiers, electricity, travel and heating. The ecoCost of these inputs would be accounted for as overheads within the ecoAccounting module, amortized over an expected life of the product and distributed to customers by apportioning the ecoCost through a common billing unit e.g. time.

TABLE X. How the additional category is used in an in-situ mass balance calculation when a batch of product is made.

Vector	What happens in mass balance calculation
Historical inputs	Not used in mass balance calculation. Inherited from existing LCIs. Carried forward for backward compatibility with existing impact assessment algorithms.
Embedded (within the product)	These materials are used as inputs into a mass balance calculation resulting in a final product that has its own embedded materials and a list of outputs.
Historical outputs	The outputs from the mass balance calculation are added to the historical outputs to produce an updated list of historical outputs.

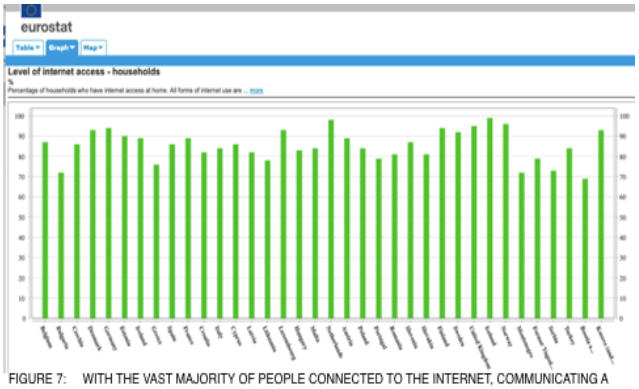

FIGURE 7: WITH THE VAST MAJORITY OF PEOPLE CONNECTED TO THE INTERNET, COMMUNICATING A SUSTAINABILITY FACTOR TO HOUSEHOLDS IS REALISTIC.

Fig. 6. With the vast majority of people connected to the internet, communicating a sustainability factor to households is realistic.

Fig. 7. Comparing aggregate ecoCost of a lifestyle with planetary boundaries brings the circular economy up close and personal.

C. Initial Calculations Using a "Primitive" EcoCost

Early adopters of this proposed architecture will be able to initiate calculations that can be sent to customers without suppliers providing ecoCost certificates first. This would be achieved by commissioning cradle-to-gate LCIs for their input products. The LCIs could be imported into the system and enhanced with materials classified as embedded, converting the LCI into a crude ecoCost. Calculations can then be performed.

D. Automation

By locating the ecological accounting software module with its own Application Programming Interface (API) within the network of the company, other corporate systems can be used to automate the calculation and sending of ecoCosts between suppliers and customers. An ecoCost would be imitated and sent when a financial invoice is generated. The calculation of an ecoCost could initiate when the manufacturing system logs the start of a production run. Fig. 8 illustrates how goods, money and ecoCost can flow through a company.

XI. Conclusion

Without altering the data structure of existing LCIs but simply extending its classifications, we could create the basis of a universal ecological certificate that flows through the economy like money does now. The ecological certificate is a unit of measure enumerating the materials involved to produce a product, from cradle to gate. The certificate represents an ecological cost - or ecoCost - of a product.

The ecological certificate in turn would be used by a computerized ecological accounting system to apply a mass balance method installed at each stage in a value chain that would establish a new environmental accounting method and architecture. This architecture would use dynamic calculations to produce near real time figures that adapt to changing supply chains automatically and are always current (a significant step forward from current practice). The ecological accounting method will employ a set of rules akin to financial accounting, with its own checks and balances to underpin its integrity.

Fig. 8. 21st Century economic practice - an API will allow financial and other intra-system events to automate the flow and calculation of ecoCosts.

The missing link to making all of this possible is an additional classification to the vector attribute of LCIs:

embedded (within the product)

This paper has identified the requirement of a new ecological unit of measure and describes how it can be achieved with an extra classification to LCIs. It is as simple as that. This additional classification transforms the historical account of inputs and outputs of LCI datasets into a current, balance based *ecological certificate* that could be backward compatible to provide continuing support for current impact assessment methods.

Although the ecoCost is based on the structure of LCIs, it cannot be derived using current impact analysis practice, but only with an automated sequence of computerized calculations at each stage in a product's lifecycle. This revised sub-metric will grant access to a series of well established indicators for each company and introduce a *new economic lens* for businesses to view their operations.

This dynamic accounting method mimics the architecture of financial practice, blending process modeling with direct input output calculations, and could fundamentally shift the ease with which that big externality - the environment - can be embedded into every day decision making.

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