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3-Levers of Emission Control-Modeling Framework: Modeling GHG Emissions When Direct Measurement is not Possible

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Abstract. The Corporate Sustainability Reporting Directive (CSRD) requires the measurement and reporting of the greenhouse gas (GHG) emissions of companies and products in CO2-equivalent, considering all stages of their Life Cycle Assessment (LCA) where scopes 1, 2, and 3 emission categories are included. The GHG Protocol Product Life Cycle Accounting and Reporting Standard distinguishes between the “direct measurement” and ”indirect measurement”, i.e. activity-based measurement. The most accurate method would be to directly measure the GHG emissions. However, in many companies, this is not possible due to the unavailability of adequate measurement sensorics. For the activity-based LCA, the ISO14000 family of standards constructs an environmental management system by using a “technical” terminology. In contrast to that, the “E-Liability Accounting System” from Kaplan/Ramanna is casted in the language of financial and cost accounting. Accordingly, it presents the LCA of products GHG emission in a well-established and familiar theoretical foundation. The E-Liability Accounting System is constructed mainly at the conceptual level, as the activity-based GHG measurement and the distinction of scopes 1, 2, and 3 are not really operationalized. In this paper, these limitations are addressed by operationalizing the E-Liability Accounting System within the “3 Levers of Emission Control (3-LoEC)-modeling framework”. This framework allows the explicit specification of activity-based GHG measurement metrics all over the product’s life cycle. Due to the CSRD compliance, the 3-LoEC-modeling framework possesses practical validity. This carries over to its derived metrics. The applicability of the 3-LoEC-metrics is demonstrated in a use case, where a “food-bowl” is produced via injection molding technology.

Keywords: CSRD Requirements, Life Cycle Assessment, GHG Emissions Indirect Measurement, E-Liability Accounting System, 3-LoEC-Modeling Framework, Activity-Based Energy Consumption, Activity-Based E-Liability Allocation.

1. Introduction

The Corporate Sustainability Reporting Directive (CSRD) requires companies to report and control their Greenhouse gas (GHG) emissions for the Life Cycle Assessment (LCA): “*Users are also interested to know the efforts made by companies to effectively reduce absolute GHG emissions as part of their climate mitigation and adaptation strategies, including scope 1, scope 2 and, where relevant, scope 3 emissions*” [1, rec.47]. In this context, the GHG Protocol Product Life Cycle Accounting and Reporting Standard serves as a guiding instrument to account for such emissions: “*The Product Standard accounts for the GHG emissions and removals that occur during a product’s life cycle*” [2, p. 7]. This standard underscores the importance of identifying data types needed for GHG measurement, distinguishing between ‘direct measurement’ and 'indirect measurement', i.e. activity-based measurement. "*Identifying data types – Identifying the data types used in an inventory will provide companies with a better understanding of the data and their quality. Typically, data can be gathered in one of two ways: 1. Directly measuring or modeling the emissions released from a process. 2. Collecting activity data and emission factors for a process and multiplying the activity data by the emission factor.*" [2, p. 51].

Ideally, the most accurate approach would involve "direct measurement" of GHG emissions. However, in real use cases, many companies face a challenge due to the unavailability of adequate measurement sensorics. Consequently, they often resort to employing "indirect measurement", i.e. activity-based measurement. The activity-based approach involves collecting detailed activity data and emission factors within the production activities, followed by the multiplication of activity data by the corresponding emission factor. However, while this indirect measurement offers an alternative to direct measurement, it requires data collection and suitable measurement metrics. Hence, its effectiveness is based on the reliability and accuracy of the data gathered and the selected metrics. Therefore, the construction of suitable measurement metrics becomes crucial, requiring a careful examination of the various parameters influencing emissions during production activities.

A "technical" specification of the LCA is suggested by ISO 14000 family of standards. Emblemsvåg/Bras criticize ISO's technical representation and the promote an Activity-Based Life Cycle Assessment (AB-LCA) [3] with an explicit energy consumption focus. The idea of an activity-based LCA is taken over by Kaplan/Ramanna in the conceptualization of their E-Liability Accounting System, where measurement metrics for GHG emissions are promoted. "*We propose that companies tackle ESG reporting in a more targeted and auditable way. They should first develop specific and objective metrics for the most important and immediate ESG problems, rather than produce catchall reports that are often made up of inaccurate, unverifiable, and contradictory data. GHG emissions are the ideal starting point for such an approach. They represent the most immediate danger to the planet, and they are among the easiest of ESG items to reliably measure and interpret.*" [4, p. 3].

Kaplan/Ramann deeply discuss the measurement problems related to the scope 3 emissions over the company's up- and downstream supply chain. But they are not providing explicit definitions of measurement metrics for the scope 1, 2, and 3 emission categories. The primary research objective of this paper is the explicit operationalization of the E-Liability Accounting System within the 3 Levers of Emission Control (3-LoEC)-modeling framework. This modeling framework traces back to Baumüller/Schwaiger [5]. They established a generic 3-LoEC-model that allows the derivation of activity-based and energy consumption related measurement metrics that are CSRD compliant and that can be flexibly aligned to different contexts. For achieving this paper's primary research objective, Baumüller/Schwaiger's generic 3-LoEC-model is enhanced for including activity-based allocations of E-liabilities incorporated in the production resources, i.e. material and equipment resources. As such, the 3-LoEC-modeling framework allows the operationalization of the E-Liability Accounting System that aligns the reporting requirements from the Corporate Sustainability Reporting Directive (CSRD) and the European Sustainability Reporting Standard (ESRS) E1 [6] with the activity data available in Resource Consumption Driven (RCD)-ABC as well as in Time Driven (TD)-ABC [7] accounting systems.

The flexibility of the 3-LoEC-modeling framework allows the development of different GHG emission measurement metrics for covering a wide range of use cases, allowing efficient measurement of the activity-based unit carbon footprint (AB-uCFP) with activity-based (AB)-Energy Consumption focus. In the simplest case the power coefficient of the AB-Energy Consumption-metrics is constant over the activity's production time, i.e. the production coefficient. In this case the activity's energy consumption is just the mathematical product of the production and the power coefficient. Multiplying the activity's energy consumption by the emission coefficient gives the activity's GHG emission in form of the primary unit carbon footprint (upCFP).

In the more realistic use case, the power coefficient is fluctuating over the activity's production time, so that the mathematical product of the production and the power coefficient would not correctly specify the activity's energy consumption. In this case the mathematical product has to be replaced by an integral calculation where the fluctuated power coefficient is integrated over the activity's production time. Furthermore, the 3-LoEC-framework is addressing the scope 3 emission category where the Activity-Based emission (AB-E)-Liability Allocation focus of the consumed material and the used capacity equipment are allocated to the finished good based on activities as unit E-liability of material (uELiabMAT) and unit E-liability of equipment (uELiabEQIP).

From a methodological view, the design and specification problem that underlies this paper is solved with the Design Science Research (DSR) methodology [8]. The development of 3-LoEC-modeling framework at the conceptual and operational level corresponds to the artefact that is designed to operationalize the E-Liability Accounting System. The validity of the designed artefact stems from its compliance to the GHG reporting requirements specified in the CSRD and its related ESRS E1, and its practical applicability is demonstrated by a use case, where "food-bowls" are produced with the injection molding technology.

The structure of this paper is as follows: After this introduction, important concepts concerning the activity-based GHG measurement are investigated, i.e. the GHG Protocol product life cycle assessment of the GHG emission of products (finished goods), the ISO's environmental management system and its accompanying critics from Emblemsvåg/Bras and Kaplan/Ramanna's E-Liability Accounting System. Next, the 3-LoEC-modeling framework is built on top of these activity-based GHG measurement concepts by designing it at the conceptual as well as at the operational level. Of special importance are the framework's three pivotal coefficients, i.e. production, power, and emission coefficients and the distinction of the Resource Consumption-Driven Activity-Based (RCD-AB) measurement from the Time-Driven Activity-Based (TD-AB) measurement. Furthermore, the scope 3 emission components in form of the (E)-liability with respect to finished good's consumed materials and used equipment that enhance Baumüller/Schwaiger's generic 3-LoEC-model are elaborated. After the design of the 3-LoEC-modeling framework its validation is addressed and its applicability is demonstrated with the food-bowl production use case. Finally, the paper is concluded.

2. 3-LoEC-Modeling Framework: Relationships to GHG related Concepts

According to CSRD, companies shall report and control their GHG emissions within the measurement and management directions specified in the European Sustainability Reporting Standard (ESRS)-E1 [6] using the GHG Protocol Product Life Cycle Accounting and Reporting Standard where a structured accounting methodology, yet generic, is specified for the LCA. To fulfil these requirements, different solutions were suggested, among which: ISO 14000 family of standards' environmental management system [9] on which the GHG Protocol product's standard was build, and recently, Kaplan/Ramanna's E-liability Accounting System.

Despite of the foundational structure provided by these approaches in assessing the environmental impact, they present certain limitations in terms of specifying the correct metrics for the GHG emissions indirect measurement for scope 1, 2, and 3 emissions categories. Therefore, the 3-LoEC-modeling framework comes to turn these limitations into opportunities to fulfil the measurement and reporting requirements.

2.1 Product GHG Emission: Life Cycle Assessment (LCA)

The GHG Protocol Product Life Cycle Accounting and Reporting Standard provide a structured approach for GHG emissions accounting throughout the product's life cycle for each of the five pivotal stages comprising a product's life cycle: "material acquisition & pre-processing", "production", "distribution & storage", "use", and "end-of-life". To facilitate a comprehensive understanding of the information flow within these stages, a conceptualization [10] of the Product's AB-uCFP Life Cycle Assessment (LCA) has been modeled using a Unified Modeling Language (UML) activity diagram (https://www.omg.org/spec/UML/).

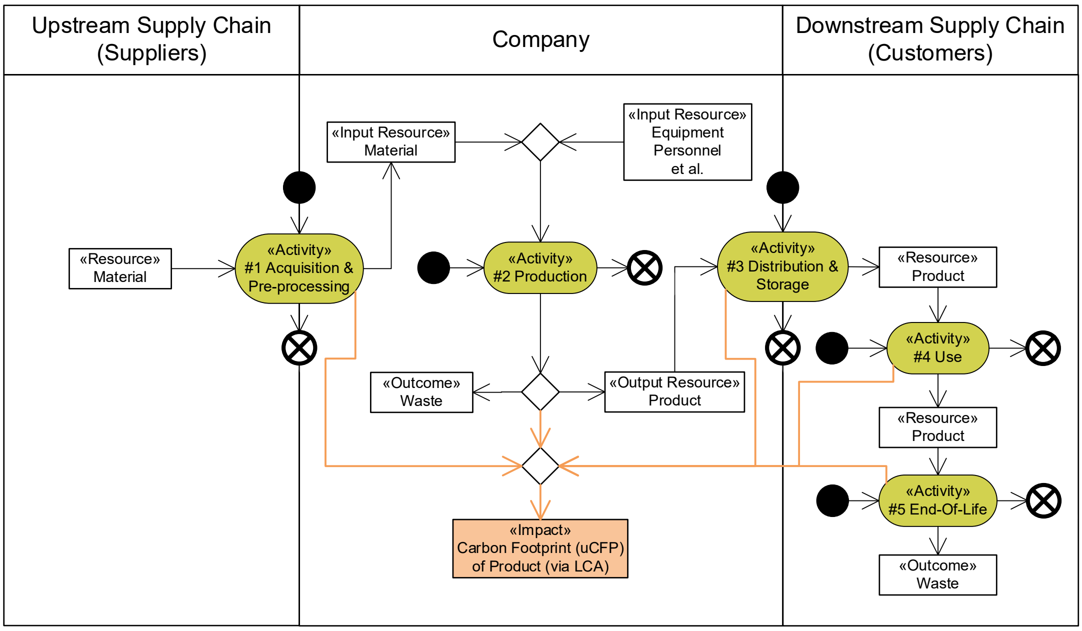

Figure 1. *Product's AB-uCFP Life Cycle Assessment (LCA)*

In Figure 1, the five product life cycle's stages are described using rounded rectangles and the stereotype «Activity». The black circles show the start, and the crossed circle show the end of each activity, and the input-output information flow within these activities are specified through rectangles. The «Resource» stereotype represents the resource information related to each activity. As for the «Input-Resource», «Output-Resources», «Impact», and «Output-Resources» stereotypes, these are I/O economics' semantics, where the impact shows the uCFP related to each activity in the product's life cycle, i.e. AB-uCFP.

While companies shall conduct emission calculations for all the five stages of the product's life cycle, the focus in this paper is the AB-uCFP measurement of the 'Acquisition & Pre-Processing' (#1) and 'Production' (#2) activities including the company level as well as the product's 'upstream scope 3' emissions related to the consumed material and the used equipment.

The GHG Protocol product's standard provides guidance in the application of the GHG emissions indirect measurement. "*The following equations illustrate how to calculate CO2e for an input, output, or process based on activity data, emission factors, and GWP*" [2, p. 88].

(1) $$kgCO_2e = \underset{[unit]}{Activity\ Data} * \underset{[kg\ GHG/unit]}{Emission\ Factor} * \underset{[kgCO_2e/kg\ GHG]}{GWP} = \underbrace{uCFP_{acty,fG}}_{[kgCO_2e]}$$

where

[UOM] …	Unit Of Measure
Emission Factor …	GHG emissions per unit of activity data
GWP …	Global Warming Potentials relative to CO_2
acty …	activity
fG …	product (finished good)

In formula (1) articulates that the quantification of GHG emissions measured as CO_2 equivalent (CO_2e) involves a straightforward multiplication process, where the Activity Data is multiplied successively by the Emission Factor and the Global Warming Potential (*GWP*). This lead to calculate the unit carbon footprint (*uCFP*) of a specific product (*fG*) based on the activity data. In this formula, the "Activity Data" lacks the specification of energy consumption, which is the core of AB-uCFP measurement.

2.2 Technical Approach: ISO's Environmental Management System

In their book Emblemsvåg/Bras state that "*In the last decade of the 20th century, the International Standards Organization (ISO) has thrown its hat into the environmental ring by producing the ISO 14000 environmental management standards. The aim is to provide clarity and uniformity, but many agree that it still leaves a lot to be desired*" [3].

To guide companies towards a structured approach to life cycle assessment (LCA), ISO 14000 family of standards have come up with a technical approach relying on 'Inventory Analysis' to quantify inputs and outputs of a product system. However, ISO's Life-Cycle Inventory (LCI) analysis was seen as a complicated practice for companies rather than being an opportunity for them to integrating and managing their environmental impact [3, p. 32]. Therefore, Emblemsvåg/Bras suggested a different environmental management approach based on activity-based costing (ABC) to simplify the allocation of mass and energy to the finished goods, in order to enhance the clarity and applicability of the LCI for companies, i.e. Activity-Based Life Cycle Assessment (AB-LCA) method. This method suggested the activity's energy consumption quantification to define a more operational specification of the Activity Data from the GHG protocol's standard.

However, while Emblemsvåg/Bras advance the integration of cost accounting with environmental management and suggest more operational approach to activity data collection, their method does not extend to a complete LCA that encapsulates all stages of a product's life. Kaplan/Ramanna came after 24 years to fill this gap by considering the holistic view of GHG emissions via suggesting the E-Liability Accounting System including scope 3 emissions, and integrating them into a comprehensive environmental liability accounting system.

2.3 Accounting Approach: Kaplan/Ramanna's E-Liability Accounting System

In their paper "Accounting for Climate Change", Kaplan/Ramanna accentuate the necessity to specify tangible metrics to measure the companies' environmental impact. Their aim is to mitigate the risk of measurement error and manipulation by eliminating duplicative counting of emissions, and aligning environmental reporting with financial accounting standards. Their suggestion emphasizes the need for accuracy in environmental data reporting to be more compliant with the CSRD standard.

In their contribution, Kaplan/Ramanna explain the E-Liability Accounting System as: "*This new accounting system requires two basic steps: (1) Calculate the net E-liabilities the company creates and eliminates each period, adding them to the E-liabilities it acquires and has accumulated, and (2) allocate some or all of the total E-liabilities to the units of output produced by the company during the reporting period. For the first step, environmental engineers can estimate the quantity of GHG emissions from a company's primary-source activities, such as burning hydrocarbons for electricity, heat, and transport; producing metals, cement, glass, and chemicals; agriculture involving livestock emissions and deforestation or reforestation; and waste management. The second step is identical to activity-based costing (ABC) for assigning overhead and other costs to the multiple products and services produced in a given period.*" [4, p. 10].

This statement implicitly emphasizes the utility of the Activity-Based Costing (ABC) approach to account for the company's environmental impact. However, this E-Liability Accounting System doesn't focus on the measurement of GHG emissions in a holistic way within the activity-based measurement, and no measurement metrics specification was detected. Furthermore, Kaplan/Ramann are not discussing the usage of the Time-Driven ABC (TD-ABC) aspect, which was promoted by Kaplan/Anderson [7] as an efficient extension of the traditional ABC accounting system. All these limitations open a room for enhancement, which is are subsequently explicitly addressed via the 3-LoEC-modeling framework.

3. 3-LoEC-Modeling Framework: Conceptual & Operational Design

The 3-LoEC-modeling framework constitutes a flexible framework that covers the activity-based GHG measurement within scope 1, 2, and 3 emission categories. To identify the information needed for the activity-based measurement of GHG emissions, a conceptual model is designed as a first step to capture the GHG emission measurement information. Then, the operational model of the 3-LoEC-modeling framework is constructed used different 3-LoEC-metrics, based on the conceptualized information, for both the activity-based (AB)-Energy consumption metrics and the activity-based (AB)-E-Liability allocation metrics.

3.1 3-LoEC-Modeling Framework: Conceptual Design

To elaborate a comprehensive approach of the 3-LoEC's information, a conceptual model of the ERP-control system is designed to align the 3-LoEC-modeling framework semantics with the ERP-control semantics [11] using the Unified Modeling Language (UML) class diagram. This alignment is highly needed for management and control requirements.

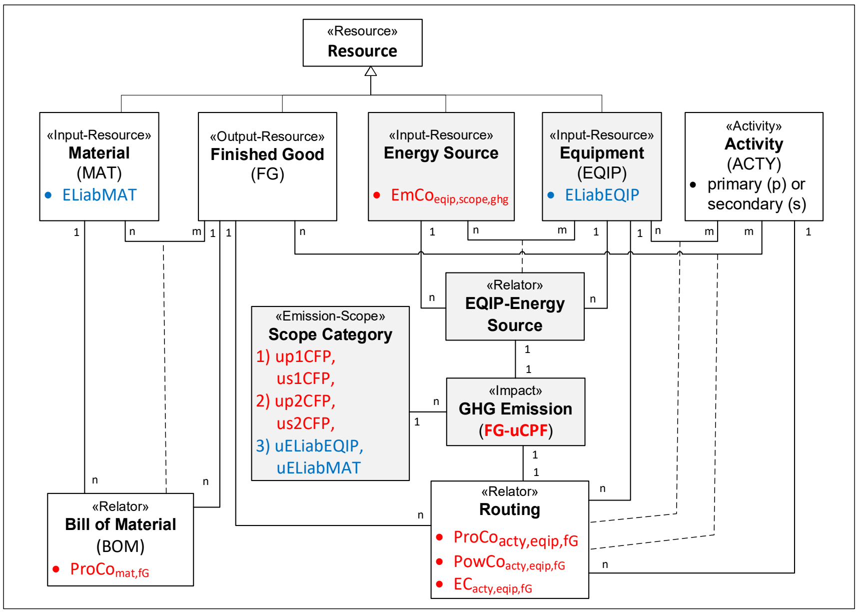

Figure 2. *'ERP-Control' system – Conceptual model including 3-LoEC's information*

The conceptual model in Figure 2 represents Leontief's I/O-economics [12] where input and output resources are related to each other and the 3-LoEC's information are included at the conceptual level as:

- GHG emission impact: The conceptual model's lower middle part includes two entities, i.e. Scope Category and GHG Emission, for capturing the 3-LoEC information as the results for scope 1, 2, and 3 emission categories.

- Energy consumption focus: The model's Routing relator is including the AB-energy consumption's information, i.e. the activity's production coefficient (ProCo) and the equipment's power coefficient (PowCo), so that the energy consumption (EC) can be identified by using these coefficients, i.e. information ProCo and PowCo.
- Emission coefficient: The model's Energy Source entity includes the emission coefficient (EmCo), so the activity's consumed energy can be transformed into its corresponding GHG emission, i.e. primary uCFP (upCFP) and secondary uCFP (usCFP).
- E-Liability: The model's Material as well as Equipment entities include their related E-liabilities, i.e. E-LiabMAT and E-LiabEQIP. Those are captured and allocated to the finished good to identify the uELiabMAT and uELiabEQIP.

Building upon this conceptual model, the operationalization of the 3-LoEC-modeling framework is constructed in the following sections. The AB-uCFP-metrics related to AB-energy consumption focus and E-Liability allocation are discussed in more actionable methodology, where formulas are implemented to allow quantification of the GHG emissions within the indirect measurement method using 3-LoEC-modeling framework-metrics.

3.2 Activity-Based (AB)-Energy Consumption Metrics

As a refinement of the generic GHG Protocol's formula (1), the 3-LoEC-modeling framework suggest the quantification of AB-uCFP based on the activity's energy consumption focus as the core of GHG emission calculation related to scope 1 and 2 emission categories, which aligns with Emblemsvåg/Bras approach.

(2)
$$\underbrace{uCFP_{acty,res,fG}}_{[kg\ CO_2e]} = \underbrace{ec_{acty,res,fG}}_{[kWh/unit]} * \underbrace{e_{res,scope,ghg}}_{[kgCO_2e/kWh]}$$

where

uCPF …	activity's unit (u) carbon footprint (CFP)
acty …	activity
ec …	activity's unit-energy consumption [kWh/unit]
e …	activity's emission coefficient [kgCO_2e/kWh]
fG …	product (finished good)
ghg …	greenhouse gas
scope …	scope of GHG emission (measured in CO_2e)

The formula (2) for calculating the unit carbon footprint (uCFP) involves multiplying the activity's unit-energy consumption (*ec*) by the emission coefficient (*e*) to derive the GHG emissions in kg CO_2e. This formula is the starting point for calculating the AB-uCFP. The AB-energy consumption-metrics, i.e. production coefficient and power coefficient are required, using both time-driven (TD) and resource consumption-driven (RCD) variants to ensure AB-energy consumption accurate calculation. This process involves construction of measurement metrics to prepare the stage for calibration and validating their applicability within the upcoming demonstration.

3.2.1 Manufacturing Activity: TD-AB-Energy Consumption-Metrics

Time-Driven Activity-Based Costing (TD-ABC) approach is "*An alternative approach for estimating an ABC model, which we call "time-driven activity-based costing," addresses all the above limitations. It is simpler, less costly, and faster to implement, and allows cost driver rates to be based on the practical capacity of the resources supplied.*" [7, p. 5]. By using this approach, where the unit-time is the cost driver, the AB-energy consumption is calculated using TD-variant of the 3-LoEC measurement metrics, i.e. the activity's production coefficient (*d*) and equipment's power coefficient (*p*).

(3)
$$\underbrace{ec_{acty,res,fG}}_{[kWh/unit]} = \underbrace{d_{acty,res,fG}}_{[time/unit]} \cdot \underbrace{p_{acty,res,fG}}_{[kW]}$$

where
ec … energy consumption (measured in kWh)
d … unit-time duration driver (production coefficient)
p … power coefficient
res … capacity resource employed in activity

In formula (3), the energy consumption is not always the product of a simple multiplication (*). The usage of the dot-operator (·) indicates the possibility of using an integral multiplication when the power coefficient (*p*) is a fluctuating variable, which is the case of many realistic manufacturing scenarios when the equipment's power profile is varying over the activity duration.

3.2.2 Transportation Activity: RCD-AB-Energy Consumption-Metrics

Kaplan/Anderson's [7] TD-variant is a special case where the cost driver is the unit-time. However, in many cases, the unit-time is not the only cost driver. Therefore, the Resource Consumption-Driven (RCD)-variant is considered as unit-resource input as for the case of transportation activity where the ton-km related fuel consumption is the driver. Accordingly, new RCD-AB-energy consumption measurement metrics are used.

(4)
$$\underbrace{ec_{acty,res,fG}}_{[kWh/unit]} = \underbrace{a_{acty,res,fG}}_{[res.input/unit]} \cdot \underbrace{q_{acty,res,fG}}_{[kWh/res.input]}$$

where
a … unit-resource input (production coefficient)
q … energy per unit of resource input (power coefficient)

In formula (4) the AB-energy consumption is calculated via multiplication of RCD-AB-energy consumption measurement metrics, i.e. production coefficient (*a*) that is replacing the TD-ABC model's unit-time (*d*), and the power coefficient's labelled now (*q*) instead of its (*p*). Here again the usage of dot-operator (·) indicates the integral multiplication when the power profile is fluctuating.

3.3 Activity-Based (AB)-E-Liability Allocation Metrics

Kaplan/Ramanna emphasize the necessity of accounting not only for scope 1 and 2 emissions but also to include the scope 3 emissions transferred by material or equipment providers. They introduce the Environmental (E)-Liability as non-monetarized providers' debts that should be accounted for and transferred to the manufacturer's balance sheet at the acquisition of materials and equipment capacity resources. These E-Liabilities, related to the consumed material and used equipment, should be allocated to the "unit of output produced", i.e. the finished goods.

But the question is how to allocate these E-Liabilities to the finished goods? According to Kaplan/Ramanna, the ABC method can be used to allocate these emissions to the finished good in the same way overhead costs are allocated [4, p.10]. However, no activity-based (AB)-allocation metrics were specified. The 3-LoEC-modeling framework is then used to model this allocation within the activity-based method.

3.3.1 Materials' GHG Allocation: AB-uELiabMAT-Metrics

The activity-based (AB)-allocation of the consumed material is quite easy. On the acquisition of the material, the GHG emission of this material is transferred from the provider to the production company. This transferred emission is referred to as Emission (E)-Liability of material (*ELiabMAT*).

(5) $$\underbrace{uELiabMAT_{acty,mat,fG}}_{[kgCO_2e]} = \underbrace{a_{acty,mat,fG}}_{[res.input/unit]} * \underbrace{ELiabMAT_{mat,3,ghg}}_{[kgCO_2e/res.input]}$$

where
ELiabMAT ... material's emission liability per unit of material (MAT)
mat ... material
a_{mat} ... material's production coefficient (unit-res.input)
3 ... scope 3 GHG emission

In formula (5) the unit E-liability of material (*uELiabMAT*) represents the AB-allocation metric of the material consumed for the production of one unit of finished good. It's calculated by multiplying two metrics, i.e. the material's production coefficient (*a*) and the *ELiabMAT* using the RCD variant.

The accurate specification of these AB-uELiabMAT-metrics is a very important step to measure the environmental impact associated with the consumption of material during the production activity, which contributes to the overall GHG emission of each of finished good.

3.3.2 Equipment's GHG Allocation: AB-uELiabEQIP-Metrics

As for the activity-based (AB)-allocation of the used capacity resources such as equipment, the depreciation method should be used. "*The units-of-production method allocates a varying amount of depreciation each year based on an asset's usage. Units-of-production depreciates by units rather than by years. As we noted earlier, a unit of output can be miles, units, hours, or output, depending on which unit type best defines the asset's use. When a plant asset's usage varies every year, the units-of-production method does a better job of matching expenses with revenues.*" [13].

By depreciating the equipment, the environmental impact of the used equipment is meticulously defined and related to its actual lifetime usage. The AB-allocation of equipment E-liability to the unit of produced finished good is calculated within two steps. Firstly, by calculating the equipment's E-liability for one capacity-unit (*cuELiabEQIP*) via depreciating of the equipment E-Liability (*E-LiabEQIP*) over its lifetime capacity, as shown in formula (6).

(6) $$\underbrace{cuELiabEQIP_{eqip,scope,fG}}_{[kgCO_2e/unit]} = \underbrace{ELiabEQIP_{eqip,3,ghg}}_{[kgCO_2e]} / \underbrace{LifetimeCapacity_{eqip,fG}}_{[time/unit]}$$

where
cuELiabEQIP … equipment's capacity-unit (cu) emission liability
ELiabEQIP … equipment's transferred emission liability
LifetimeCapacity … equipment's lifetime capacity
3… scope 3 GHG emission

And secondly, by allocating the *cuELiabEQIP* to the finished good based on the activity by multiplying it by the activity's production coefficient (*d*) using the TD variant as shown in formula (7).

(7) $$\underbrace{uELiabEQIP_{acty,eqip,fG}}_{[kgCO_2e]} = \underbrace{d_{acty,eqip,fG}}_{[time/unit]} * \underbrace{cuELiabEQIP_{eqip,3,fG}}_{[kgCO_2e/unit]}$$

where
uELiabEQIP ... equipment's unit emission liability

4. 3-LoEC-Modeling Framework: Validation and Demonstration

The conceptual and operational modeling of the 3-LoEC-modeling framework in the previous section provides the vocabulary and the operational GHG measurement metrics. The framework's CSRD compliance assures its practical validity that carries over to its derived 3-LoEC-metrics. All of these GHG measurement metrics are activity-based and they are applicable to all levels within the product's life cycle where all GHG emissions of the finished goods. For demonstrating the 3-LoEC-metrics' applicability the production of a "food-bowl" via injection molding technology serves as use case.

The food-bowl's unit-carbon footprint (uCFP) relates firstly, to its manufacturing activity and the material transportation activities, and secondly, the allocation of the GHG emission liabilities of the material consumed and the equipment used in the manufacturing activity. The information needed for the GHG measurement metrics that were specified in the 3-LoEC-modeling framework are as follows:

- Food-bowl consists of PLA (polylactic acid) plastic with the weight of 0.32 kg/unit.
- PLA plastic's emission liability (ELiabMAT) is 0.5 $kgCO_2e$ per kg of plastic.
- Per lot 100 pieces of the food-bowl are produced so that the lot weight is 32 kg.
- Injection molding equipment (IME) is "Arburg Allrounder 370H": 59 kW nominal power; operating for the food-bowl production half time at 90 % as well as 60 % of nominal power; 6,530 $kgCO_2e$ emission liability (ELiabEQIP); 19,590 machine hours lifetime capacity.
- Production time for one lot is 3 hours 20 minutes.
- Emission coefficient is the grid emission factor based on the Austrian energy mix (78 % renewable energy) for scope 2 emission and the year 2022 amounting to 0.127 $kgCO_2e$/kWh.
- PLA is transported 500 km via ship (ship transport) and 100 km via truck (truck transport), which gives 16 ton-kilometres (t-km) for the ship transport and 3.2 t-km for the truck transport.
- Both transportation vehicles are operated with diesel.
- The diesel consumption of ship freight is 0.09 litres per 100 t-km (l per 100t-km) and of road freight 1.81 l per 100 t-km.
- Diesel has energy of 9.94 kWh/litre and an emission coefficient of 0.27 $kgCO_2e$/kWh.

4.1 Activity-Based (AB)-Energy Consumption Metrics

The unit carbon footprint (upCFP) is measured via the AB-Energy Consumption-metrics for primary activities, i.e. the manufacturing and transportation activity. In the case of the manufacturing activity the dot-operator (·) integral multiplication is used to reflect the activity's fluctuating power profile specified. For the transportation activity the simple case is assumed, where the star-operator (*) is used to handle an activity's constant power profile.

4.1.1 Manufacturing Activity: TD-AB-uCFP-Metrics

The 3-LoEC's measurement metrics are constructed using TD variant and TD-AB-Energy consumption metrics are constructed in the same way as formula (3).

In the simple case, the AB-energy consumption (*ec*) the production is calculated by multiplying the activity's production coefficient (*d*) by the injection molding equipment (*IME*)'s power coefficient (*p*) where the nominal power of 59 kW is used as the measurement metric. The result is shown in formula (8).

(8) $$\underbrace{ec_{acty,IME,fG(lot)}}_{\left[\frac{kWh}{lot}\right]} = \underbrace{d_{acty,IME,fG(lot)}}_{\left[\frac{time}{lot}(h)\right]} * \underbrace{p_{acty,IME(nom),fG}}_{[kW]} = \underbrace{3.33}_{\left[\frac{time}{lot}(h)\right]} * \underbrace{59}_{[kW]} = \underbrace{196.65}_{\left[\frac{kWh}{lot}\right]}$$

where

IME ... Injection Molding Equipment
fG(lot) ... lot size of finished good (food-bowl lot size)
$p_{IME(nom)}$ ... equipment's nominal power level

In more realistic cases, the power profile is fluctuating over the activity time. Therefore, a calibration of the AB-energy consumption's measurement metrics is needed, where the usage of the dot-operator (·) for calculating based on integral multiplication using different power levels for each activity's sequence as shown in formula (9). In this case, the energy consumption value is different, i.e. 145.5 kWh/lot instead of 196.65 kWh/lot.

(9) $$\underbrace{ec_{acty,IME,fG(lot)}}_{\left[\frac{kWh}{lot}\right]} = \underbrace{d_{acty,IME,fG(lot)}}_{\left[\frac{time}{lot}(h)\right]} \cdot \underbrace{p_{acty,IME,fG}}_{[kW]}$$

$$= \sum_i \underbrace{d_{acty(i),IME,fG(lot)}}_{\left[\frac{time}{lot}(h)\right]} * \underbrace{p_{acty(i),IME,fG}}_{[kW]}$$

$$= (\underbrace{1.66}_{\left[\frac{time}{lot}(h)\right]} * \underbrace{53.1}_{[kW]}) + (\underbrace{1.66}_{\left[\frac{time}{lot}(h)\right]} * \underbrace{35.4}_{[kW]}) = \underbrace{147.5}_{\left[\frac{kWh}{lot}\right]}$$

where

$d_{acty(i)}$ ... *i*-th sub-activity's *EQIP* production coefficient
$p_{acty(i)}$ ... *i*-th sub-activity's power coefficient

If the activity's average power coefficient ($p_{acty(avg),IME,fG}$) value of 44.25 kW is known, the usage of the simple multiplication using a star-operator (*), as shown in formula (10) could be justified and the result is exactly the same as when the AB-energy consumption metrics are calibrated, i.e. 147.5 kWh/lot. But this information can't be certainly available. Therefore, the calibration of the AB-Energy Consumption's measurement metrics is needed.

(10) $$\underbrace{ec_{acty,IME,fG(lot)}}_{\left[\frac{kWh}{lot}\right]} = \underbrace{d_{acty,IME,fG(lot)}}_{\left[\frac{time}{lot}(h)\right]} * \underbrace{p_{acty(avg),IME,fG}}_{[kW]} = 3.33 * 44.25 = 147.50$$

where

$p_{acty(avg)}$ ... activity's average power level

The manufacturing activity is a primary activity within scope 2 emissions. To calculated the uCFP related to this activity (*up2CFP*), the correct metrics of the TD-AB-uCFP measurement, i.e. TD-AB-Energy Consumption (*ec*) and the scope 2 emission coefficient (*e*), should be specified and multiplied as shown in formula (11).

(11) $$\underbrace{up2CFP_{\ act,IME,fG(lot)}}_{\left[\frac{kgCO_2e}{lot}\right]} = \underbrace{ec_{act,IME,fG(lot)}}_{\left[\frac{kWh}{lot}\right]} * \underbrace{e_{IME,2,ghg}}_{\left[\frac{kgCO_2e}{kWh}\right]} = \underbrace{147.50}_{\left[\frac{kWh}{lot}\right]} * \underbrace{0.127}_{\left[\frac{kgCO_2e}{kWh}\right]} = \underbrace{18.73}_{\left[\frac{kgCO_2e}{lot}\right]}$$

where

up2CFP ... primary (p) scope 2 unit (u) carbon footprint
2 ... scope 2 GHG emission (electricity)

4.1.2 Transportation Activity: RCD-AB-uCFP-Metrics

The transportation activity is also a primary activity but within scope 1 emissions. To calculate the related uCFP, called *up1CFP,* unit-time is not applicable as the activity's energy consumption is driven by driven by the unit-resource input. Therefore, the RCD-AB-uCFP is calculated, firstly, via integral calculation by using the dot-operator (·) with the RCD-AB-Energy Consumption metrics, i.e. production coefficient (*a*), for 2 different transportation activities using a truck and a ship, and the constant power coefficient (*q*) representing the diesel's energy value of 9.94 kWh/litre as shown in formulas (4) and (12).

(12)
$$\underbrace{ec_{acty,TE,fG(lot)}}_{\left[\frac{kWh}{lot}\right]} = \underbrace{a_{acty,TE,fG(lot)}}_{\left[\frac{res.input}{lot}(litre)\right]} \cdot \underbrace{q_{acty,TE,fG}}_{\left[\frac{kWh}{litre}\right]}$$
$$= \sum_i \underbrace{a_{acty(i),TE(i),fG(lot)}}_{\left[\frac{res.input}{lot}(litre)\right]} * \underbrace{q_{acty(i),TE(i),fG}}_{\left[\frac{kWh}{litre}\right]}$$
$$= \left(\underbrace{0.014}_{\left[\frac{res.input}{lot}(litre)\right]} * \underbrace{9.94}_{\left[\frac{kWh}{litre}\right]}\right) + \left(\underbrace{0.058}_{\left[\frac{res.input}{lot}(litre)\right]} * \underbrace{9.94}_{\left[\frac{kWh}{litre}\right]}\right) = \underbrace{0.719}_{\left[\frac{kWh}{lot}\right]}$$

where
TE ... Transportation Equipment (ship and road transportation)

Secondly, the *up1CFP* is calculated by multiplying this RCD-AB-Energy Consumption (*ec*) by the emission coefficient (*e*) related to fuel as energy source as shown in formula (13). This measurement metrics specification allows more accurate GHG emissions measurement.

(13)
$$\underbrace{up1CFP_{\,acty,TE,fG(lot)}}_{\left[\frac{kg\,CO_2e}{lot}\right]} = \underbrace{ec_{acty,TE,fG(lot)}}_{\left[\frac{kWh}{lot}\right]} * \underbrace{e_{TE,1,ghg}}_{\left[\frac{kgCO_2e}{kWh}\right]} = \underbrace{0.719}_{\left[\frac{kWh}{lot}\right]} * \underbrace{0.271}_{\left[\frac{kgCO_2e}{kWh}\right]} = \underbrace{0.194}_{[kgCO_2e]}$$

where
up1CFP ... primary (p) scope 1 unit (u) carbon footprint (CFP)
acty ... transportation activity
1 ... Scope 1 of GHG emissions (fuel)

4.2 Activity-Based (AB)-E-Liability Allocation Metrics

In this section, the finished goods (food-bowls) E-Liabilities related to scope 3 emissions are demonstrated using the 3-LoEC-modeling framework, where practical allocation of the consumed material's E-Liability (uELiabMAT)-metrics and used equipment's E-Liability (uELiabE-QIP)-metrics are calibrated and validated using activity-based information, i.e. activity's production coefficients of material resource (MAT) and equipment resource (EQIP).

4.2.1 Material Allocation: AB-uELiabMAT-Metrics

In the manufacturing activity of injection molding, PLA plastic is used as a raw material, which becomes an integral part of the produced food-bowls. The E-liability associated with the PLA material, based on its consumption per lot, is fully allocated to the finished good. This allocation is calculated by using the AB-uELiabMAT allocation metrics constructed in formula (5) with the RCD variant. This is done by multiplying the lot's weight, i.e. 32 kg as material's production coefficient (*a*) by the consumed material's E-liability *ELiabMAT*, resulting in the unit E-liability attributed to a lot of food-bowls as shown in formula (14).

(14) $$\underbrace{uELiabMAT_{acty,PLA,fG(lot)}}_{\left[\frac{kgCO_2e}{lot}\right]} = \underbrace{a_{acty,PLA,fG(lot)}}_{\left[\frac{unit}{lot}(kg)\right]} * \underbrace{ELiabMAT_{PLA,3,ghg}}_{\left[\frac{kgCO_2e}{kg}\right]}$$

$$= \underbrace{32}_{\left[\frac{unit}{lot}(kg)\right]} * \underbrace{0.50}_{\left[\frac{kgCO_2e}{kg}\right]} = \underbrace{16}_{\left[\frac{kgCO_2e}{lot}\right]}$$

where

uELiabMAT ...	material's unit emission liability
ELiabMAT ...	material's emission liability
PLA ...	*PLA* material (input-resource)
3 ...	scope 3 GHG emissions

This activity-based AB-allocation of material's E-Liability is crucial for ensuring that the environmental impact of material consumption is accurately reflected in the uCFP of the finished good.

4.2.2 Equipment Allocation: AB-uELiabEQIP-Metrics

To allocate the E-Liability associated with the equipment's usage within the manufacturing activity, the AB-uELiabEQIP metrics are specified, firstly, using the depreciation method to calculate the equipment's E-Liability capacity-unit (*cuELiabEQIP*), then by calculating the activity-based unit E-Liability of equipment (AB-uELiabEQIP) via multiplication of this *cuELiabEQIP* by the manufacturing activity's production coefficient (*d*) using TD variant as constructed in formulas (6) and (7) that are referring to the formulas (15) and (16).

(15) $$\underbrace{cuELiabEQIP_{IME,3,fG}}_{\left[\frac{kgCO_2e}{h}\right]} = \underbrace{ELiabEQIP_{IME,3,ghg}}_{[kgCO_2e]} / \underbrace{LifetimeCapacity_{IME,fG}}_{[h]}$$

$$= \underbrace{6{,}530}_{[kgCO_2e]} / \underbrace{19{,}590}_{[h]} = \underbrace{0.33}_{\left[\frac{kgCO_2e}{h}\right]}$$

where

cuEliabEQIP ...	equipment's capacity-unit (cu) emission liability
ELiabEQIP ...	equipment's Emission Liability
3 ...	scope 3 of GHG emission

(16) $$\underbrace{uELiabEQIP_{act,IME,fG(lot)}}_{\left[\frac{kgCO_2e}{lot}\right]} = \underbrace{d_{act,IME,fG(lot)}}_{\left[\frac{time}{unit}(h)\right]} * \underbrace{cuELiabEQIP_{IME,3,fG}}_{\left[\frac{kgCO_2e}{h}\right]}$$

$$= \underbrace{3.33}_{\left[\frac{time}{unit}(h)\right]} * \underbrace{0.33}_{\left[\frac{kgCO_2e}{h}\right]} = \underbrace{1.1}_{\left[\frac{kgCO_2e}{lot}\right]}$$

5. Conclusion

The primary research objective of this paper was the explicit operationalization of the E-Liability Accounting System within the 3-LoEC-modeling framework. To achieve this objective, the 3-LoEC-modeling framework had to be established first. For this purpose, the generic activity-based 3-LoEC-model developed by Baumüller/Schwaiger [5] was enhanced for additionally including activity-based allocations of E-liabilities incorporated in the production resources, i.e. material and equipment resources. As such, the conceptualized and operationalized 3-LoEC-modeling framework allows the operationalization of the E-Liability Accounting System. The operationalized E-Liability Accounting System now aligns the GHG reporting requirements from CSRD and ESRS E1 with the activity data available in Resource Consumption Driven (RCD)-ABC as well as in Time Driven (TD)-ABC accounting systems.

Although the demonstration case was restricted to manufacturing and transportation activities, the applicability of the 3-LoEC-modeling framework is not restricted to the product's production stage within the product's life cycle. The reason is that the activity-based measurements can be applied to any LCA-stage. The 3-LoEC-metrics can be applied to the production company's upstream LCA stages as well as to its downstream LCA stages. E.g. the consumer who uses the finished product performs a "consumption" activity where the owned/leased/rented product is used. By using the finished product, the consumer generates energy consumption related GHG emissions as well as allocated E-liability emissions that result from the resources applied in the consumption activity, i.e. especially from the E-Liability incorporated in the used product.

By applying the 3-LoEC-modeling framework for operationalizing Kaplan/Ramanna's E-Liability Accounting System the primary research objective was achieved. The objective's achievement was demonstrated for the case, where a "food-bowl" is produced via injection molding technology. Due to the extendibility of the 3-LoEC-metrics to all stages in the product's life cycle, the 3-LoEC-modeling framework is suitable framework for the product's LCA. Due to its CSRD compliance, the 3-LoEC-modeling framework possesses practical validity. This means that a company that measures the GHG emissions of its finished goods with the 3-LoEC-metrics can used the measured emissions not only for internal purposes, but also for the external legally required GHG reporting. Furthermore, the framework's 3-LoEC-metrics also are useful for consumers who want to assess the GHG emission that is caused when bought products are consumed.

Data availability statement

This study employs a constructed case study for demonstration and validation of the 3-LoEC-modeling framework. No external datasets were used, and the case serves as a hypothetical scenario to illustrate the application of the framework.

Underlying and related material

No underlying or related material is associated with this article.

Author contributions

- Author 1 (Lalla Hasnae Alaoui): Main contribution to paper writing.
- Author 2 (Josef Baumüller): Main contribution to legal requirement analysis.
- Author 3 (Walter S.A. Schwaiger): Main contribution to the conceptualization and operationalization of the 3-LoEC-modeling framework.

Competing interests

The authors declare that they have no competing interests.

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