OPTIMIZING INDUSTRIAL OPERATIONS: BALANCING ECONOMIC AND ENVIRONMENTAL KPIs FOR A CIRCULAR ECONOMY

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Abstract

To transition to a circular economy, businesses require a holistic understanding and optimization of economic and environmental key performance indicators (KPIs) across their value chain. From industry practitioners we learned that operational decisions today are typically optimized for economic benefits (revenue, profit, cost reduction), whereas environmental considerations are an afterthought, to comply with regulations, or to show progress towards high level corporate targets (such as achieving carbon neutrality by 2050).

Switching to more sustainable operations (e.g., using renewable energy or recycled inputs) is perceived to incur a cost, and assessing the tradeoffs between the environmental benefit and impact on economic performance is challenging. Business decision makers require a clear understanding of such tradeoffs. For example, an OEM was considering switching from natural gas ovens to electric ovens but needed a quantitative assessment of the environmental value versus capital and operating expenses. As another example, a consumer goods company was considering switching from their current process utilizing virgin materials to one using recycled feedstocks and needed to weigh the environmental benefit against the financial implications, such as costs and impact on revenue and profits.

We are working on a novel systems approach to comprehensively measure and integrate these often-conflicting KPIs, enabling businesses to make informed decisions that drive both profitability and sustainability.

Our approach consists of: (a) defining and measuring a set of economic KPIs (including costs and profits) and environmental KPIs (going beyond traditional energy consumption and GHG emissions to include resource usage and waste) relevant for industrial operations in a circular economy; (b) developing a utility function to capture the interdependencies between these KPIs; (c) using the utility function to jointly optimize these KPIs to maximize profitability and sustainability. We consider KPIs that span the entire value chain, from raw material procurement to production and sales to product use, end-of-life, and recovery. We describe a system to connect the stakeholders in the industrial value-chain, enable collection of data, and compute and optimize the KPIs.

To illustrate our approach, we present a case study from the industrial process manufacturing sector. We develop optimized digital sales and operations plans that minimize environmental impact while maximizing economic performance. This is achieved through simulation and joint optimization of relevant KPIs, such as greenhouse gas emissions, energy consumption, water consumption, recovered material use, production costs, and revenue. The optimization space covers multiple scenarios for example, different mix of virgin and recovered materials, production processes, energy sources, consumption of resources, and generation of waste and effluents.

1. Introduction

The transition to a circular economy (CE) is critical to address pressing environmental challenges and ensure long-term sustainability. CE aims to minimize waste and maximize resource utilization through reuse, remanufacturing, and recycling. While CE offers significant potential benefits, including reduced environmental impact, improved resource security, and enables new economic opportunities, achieving true circularity requires a fundamental shift in how businesses operate and make decisions. This shift necessitates a comprehensive assessment and optimization of both economic and environmental performance across the entire value chain, from raw material extraction to product end-of-life and recovery.

From practitioners across various industry sectors, we learned that businesses currently optimize for economic key performance indicators (KPIs) such as revenue, profit, and cost reduction, and relegate environmental considerations to an afterthought, primarily to comply with regulations or demonstrate progress towards high-level corporate sustainability targets, such as achieving carbon neutrality by a certain year. This siloed approach fails to capture the interplay between economic and environmental factors and leads to suboptimal outcomes. Businesses need to systematically quantify the benefits of circularity, such as reduced material consumption, lower emissions, and less waste, so that they can be directly compared to traditional financial metrics. This requires a systems approach to data collection and analysis, and a framework for defining, measuring and optimizing a comprehensive set of economic and environmental KPIs.

In this paper, we present our approach to address this challenge. Section 2 reviews related work. Section 3 examines the problem in detail and presents our four-step approach to address it. Section 4 discusses real-world application results. Section 4 concludes and proposes future research directions.

2. Review of Related Work

Integration of sustainability into business operations management has gained attention in recent years. Various approaches to incorporate environmental factors into decision-making processes or to provide metrics to inform decision making are being explored. However, often the focus is on specific environmental aspects, such as energy consumption or carbon emissions. The broader context of circular economy and a comprehensive multi-dimensional view is not considered.

Existing research areas, frameworks and approaches include:

- Circular Economy Frameworks: Several frameworks have been proposed to guide the transition to a circular economy, including the Ellen MacArthur Foundation's ReSOLVE framework and the 9R framework, which provide high-level strategies for resource efficiency [1][2][3].
- Life Cycle Assessment (LCA): LCA is a widely used methodology for assessing the environmental impacts of products and processes throughout their life cycle. However, traditional LCA often focuses on single environmental impacts and may not adequately capture the complexities of circular systems [4][5][4][6].
- Material Flow Analysis (MFA): MFA tracks the flow of materials within a system which provides insights into resource use and waste generation. While MFA is valuable for understanding material circularity, it often lacks integration with economic considerations [7].
- Techno-Economic Assessment (TEA): TEA evaluates the economic feasibility of new technologies, including those relevant to the circular economy. However, traditional TEA often overlooks environmental impacts beyond basic cost considerations [8].
- Greenhouse Gas Protocol (GHG Protocol): GHG Protocol provides a standardized framework for measuring and managing greenhouse gas emissions. Its scope is restricted to emissions and doesn't extend to other environmental and economic KPIs [9].
- Corporate Sustainability Reporting Directive (CSRD): CSRD directive adopted by EU mandates detailed disclosures on environmental, social, and governance (ESG) matters, including climate change, resource use, and circular economy initiatives. However, it is focused on assessment of KPIs separately and doesn't provide integration or tradeoff assessment with economic considerations [10].
- Multi Objective Optimization and Decision Analysis: Such methods can be used to evaluate alternatives based on multiple criteria, including economic and environmental factors. Multi-objective optimization is increasingly used in supply chain and manufacturing (e.g., arc welding) for balancing conflicting KPIs, though its application to circular economy transitions is still limited [11][12].

3. Technology Approach

We are working on a systems approach to comprehensively measure and jointly optimize economic and environmental KPIs, enabling businesses to make informed decisions that drive both profitability and sustainability. Our approach comprises four key aspects:

A. ENCORE TRACE

In our prior work, we highlighted the criticality of emerging digital technologies in enabling the transition to a Circular Economy [13]. Subsequently, we presented a systems approach, 'ENCORE,' to transform businesses to a circular economy, establish efficient closed loops and RE-X pathways, and address specific challenges [14][15]. Now we are extending ENCORE to add a sustainability and circularity KPIs measurement and optimization framework – ENCORE TRACE (Figure 1).

ENCORE TRACE connects the stakeholders in the industrial value-chain (suppliers, manufacturers, logistics providers, customers, and recyclers), enables collection of the necessary data from these stakeholders, and computes and optimizes the KPIs. The system includes a trusted platform for secure and transparent data sharing, AI/Analytics for measurement, optimization, and generation of insights for decision support.

B. Defining and Measuring KPIs

We have developed a comprehensive framework to define KPIs that are relevant for industrial operations in a circular economy. These KPIs span economic and environmental dimensions (in the future, we will include social dimensions as well). Effectively computing such KPIs requires data from the entire value-chain from raw material procurement

to production, distribution, product use, end-of-life, and recovery. While the decisions that the KPIs will influence may be limited to a stakeholder, their impact can potentially span the entire value chain.

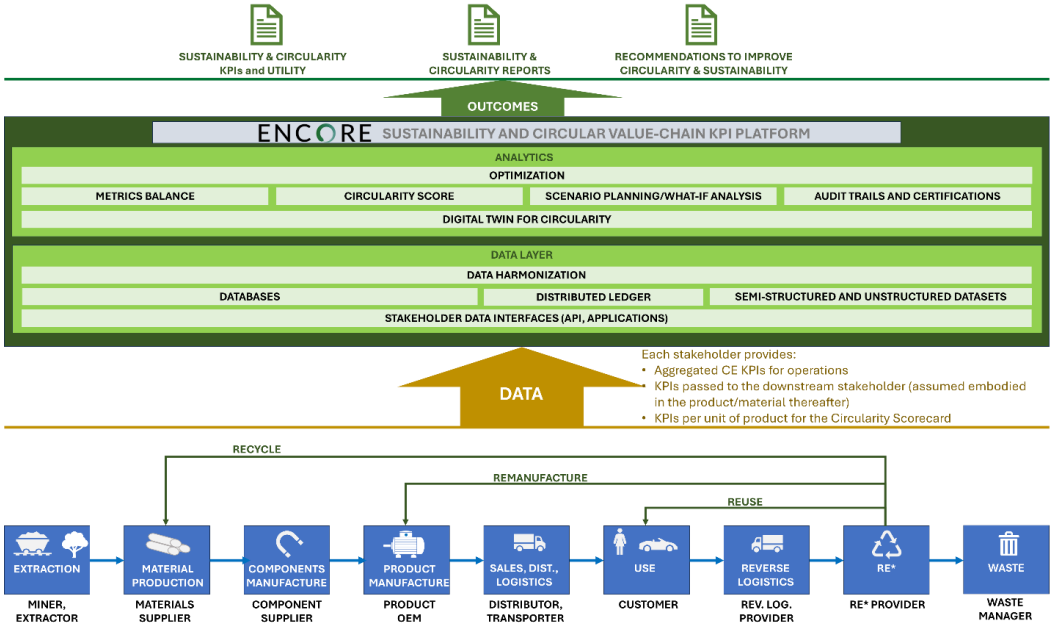

Figure 1: ENCORE TRACE system

The exact set of KPIs will depend on several factors, such as the specific industry sector, operational processes and regulatory and business environment. However, a few widely applicable KPIs include:

- **Economic KPIs:**
  - Revenues: Sales revenue from primary products and recovered materials.
  - Costs: Raw material costs (including recycled materials); production costs including indirect costs; labor costs; logistics costs; waste management costs; capital expenses; operating expenses; cost of energy
  - Penalties: Associated with environmental impact such as emissions, effluents.
  - Carbon credits and other instruments: Cost of purchasing such instruments to offset environmental impact.
  - Profits: Overall profitability considering all costs and revenues.
- **Environmental KPIs:**
  - Greenhouse Gas (GHG) Emissions: Scope 1, 2, and 3 emissions.
  - Energy Consumption: Total energy used, including electricity and fuels; energy mix including proportion of renewable energy and non-renewable energy.
  - Water Consumption: Total water used in operations; wastewater discharged.
  - Recovered Material Use: Percentage of recycled or remanufactured materials used in production.
  - Recovery rate: Amount of material recovered at end of use.
  - Waste Generation: Amount of waste generated (e.g., hazardous, non-hazardous); amount of waste processed.
  - Effluents: Volume and composition of liquid waste discharged.

These KPIs can be measured comprehensively using a framework like ENCORE TRACE. In the initial phase, data can also be collected from company's internal systems, reports, and industrial standards. For some KPIs, proxies may be used until an automated data capture process is established.

C. Joint Optimization Formulation

Once the set of economic and environment KPIs are identified, we jointly optimize them to maximize profit, factoring in the costs and constraints of the environment KPIs. The goal is to balance profitability, which is what the businesses care about the most, with sustainability, which is a key goal.

We formulate the joint optimization problem on a select set of KPIs and assuming production of a single product p. The approach can be extended to a broader set of KPIs and to multiple products.

Table 1 presents the notation and definitions used in the formulation and Table 2 provides the constraints.

Table 1: Notations and Definitions

Notation	Definition
Sets	
$\boldsymbol{T}$	Set of time periods (e.g., months, quarters)
$\boldsymbol{R}$	Set of raw materials including recycled materials
$\boldsymbol{J}$	Set of energy types (e.g., electrical, thermal)
$\boldsymbol{E}$	Set of energy sources. Different sources may provide same type of energy (e.g., solar and wind will be considered different sources electricity)
$\boldsymbol{M}$	Set of production processes for producing p. Each process may have a different input, production process, consumption and output profile, but will produce an equivalent unit of product p.
$\boldsymbol{W}$	Set of waste types
$\boldsymbol{N}$	Set of methods for treating waste
$\boldsymbol{L}$	Set of regulations for different aspects. For example, it may include following subsets: $\boldsymbol{L^{Emissions}}$: Penalty or taxation rate for emissions $\boldsymbol{L^{Toxic}}$: Penalty or taxation rate for releasing toxic air pollutants $\boldsymbol{L^{Effluents}}$: Penalty or taxation rate for wastewater discharge $\boldsymbol{L^{Waste}}$: Penalty or taxation rate for waste, by waste type
Decision Variables	
$X_{m,t}$	Quantity of product p produced using method m in period t with $m \in \boldsymbol{M}$ and $t \in \boldsymbol{T}$
S_t	Quantity of product p sold in period t with $t \in \boldsymbol{T}$
$I_{r,t}$	Quantity of raw material r consumed in period t with $r \in \boldsymbol{R}$ and $t \in \boldsymbol{T}$
H_t	Amount of labor needed in period t with $t \in \boldsymbol{T}$
$Y_{j,e,t}$	Quantity of energy of type j from source e consumed in period t with j $\in \boldsymbol{J}$, $e \in \boldsymbol{E}$ and $t \in \boldsymbol{T}$
U_t	Quantity of water consumed in period t with $t \in \boldsymbol{T}$
Q_t	Quantity of treated water discharged in period t with $t \in \boldsymbol{T}$
V_t	Quantity of wastewater (i.e., untreated water) discharged in period t with $t \in \boldsymbol{T}$
$G_{w,t}$	Quantity of waste of type w generated in period t with $w \in \boldsymbol{W}$ and $t \in \boldsymbol{T}$
$Z_{w,n,t}$	Quantity of waste of type w treated with method n in period t with $w \in \boldsymbol{W}$, $n \in \boldsymbol{N}$ and $t \in \boldsymbol{T}$
K_t	Quantity of toxic pollutants released in period t with $t \in \boldsymbol{T}$
A_t	Number of carbon credits bought in period t with $t \in \boldsymbol{T}$
Parameters	
D_t	Demand for product p in period t with $t \in \boldsymbol{T}$
P_t	Selling price for product p in period t with $t \in \boldsymbol{T}$
$C_{r,t}^{material}$	Unit cost of raw material r in period t with $r \in \boldsymbol{R}$ and $t \in \boldsymbol{T}$
C_t^{labor}	Unit cost of labor in period t with $t \in \boldsymbol{T}$
$C_t^{indirect}$	Total indirect cost associated with total production of product p in period t with $t \in \boldsymbol{T}$
C_t^{carbon}	Cost of unit of carbon credit in period t with $t \in \boldsymbol{T}$
Cap_t	Production capacity for product p in period t with $t \in \boldsymbol{T}$ The formulation can be extended to distinguish production capacity by manufacturing method
$\alpha_{m,j}$	Quantity of energy of type j required to produce one unit of product p using process m with $j \in \boldsymbol{J}$ and $m \in \boldsymbol{M}$
$\beta_{m,r}$	Quantity of raw material r required to produce one unit of product p produced using process m with $r \in \boldsymbol{R}$ and $m \in \boldsymbol{M}$
λ_m	Quantity of labor required to produce one unit of product p produced using process m with $m \in \boldsymbol{M}$
δ_m	Water usage for producing one unit of product p produced using process m with $m \in \boldsymbol{M}$
$\gamma_{m,w}$	Quantity of waste of type w generated from producing one unit of product p using process m with $w \in \boldsymbol{W}$ and $m \in \boldsymbol{M}$
η_m	Quantity waste water discharge per unit of product p produced using process m with $m \in \boldsymbol{M}$
κ_m	Quantity of toxic air pollutants discharged per unit of product p produced using process m with $m \in \boldsymbol{M}$
$\rho_{j,e,t}$	Unit cost of energy of type j from source e in period t with $j \in \boldsymbol{J}$, $e \in \boldsymbol{E}$ and $t \in \boldsymbol{T}$

Notation	Definition
υ_t	Unit cost of water in period t with $t \in \boldsymbol{T}$
$\tau_{w,n,t}$	Cost of treating one unit of waste of type w with method n in period t with $w \in \boldsymbol{W}$, $n \in \boldsymbol{N}$ and $t \in \boldsymbol{T}$
ω_t	Cost of treating one unit of wastewater in period t with $t \in \boldsymbol{T}$
$\mu_{l,t}$	Penalty of taxation rate associated with regulation l in period t with $l \in \boldsymbol{L}$ and $t \in \boldsymbol{T}$
$\varepsilon_{j,e,t}$	GHG emissions per unit of energy of type j consumed from source e in period t with j $\in \boldsymbol{J}$, $e \in \boldsymbol{E}$ and $t \in \boldsymbol{T}$
ϕ_r	Emission factor for raw material r with $r \in \boldsymbol{R}$
ψ_w	Emission factor for waste type w with $w \in \boldsymbol{W}$
$\sigma_{w,n}$	Emission factor for treatment method n when treating waste type w with $n \in \boldsymbol{N}$ and $w \in \boldsymbol{W}$
θ	Emission factor for water treatment method

Table 2: Constraints

Type	Constraint
Demand Satisfaction	$S_t \leq D_t \; \forall \, t \in \boldsymbol{T}$ Assumption is there is no inventory or buffer stock
Labor	$\sum_m (X_{m,t} * \lambda_m) = H_t \; \forall \, m \in \boldsymbol{M}, t \in \boldsymbol{T}$
Production Capacity	$\sum_m X_{m,t} \leq Cap_t \; \forall \, m \in \boldsymbol{M}, t \in \boldsymbol{T}$
Raw Material Balance	$\sum_m (X_{m,t} * \beta_{m,r}) = I_{r,t} \; \forall \, m \in \boldsymbol{M}, r \in \boldsymbol{R}, t \in \boldsymbol{T}$
Energy Consumption	$\sum_m (X_{m,t} * \alpha_{m,j}) = \sum_e Y_{j,e,t} \, I_{r,t} \; \forall \, m \in \boldsymbol{M}, j \in \boldsymbol{J}, e \in \boldsymbol{E}, t \in \boldsymbol{T}$
Water Usage	$\sum_m (X_{m,t} * \delta_m) = U_t \; \forall \, m \in \boldsymbol{M}, t \in \boldsymbol{T}$
Toxic Pollutants Discharged	$\sum_m (X_{m,t} * \kappa_m) = K_t \; \forall \, m \in \boldsymbol{M}, t \in \boldsymbol{T}$
Wastewater Discharged	$\sum_m (X_{m,t} * \eta_m) = V_t \; \forall \, m \in \boldsymbol{M}, t \in \boldsymbol{T}$
Waste	$\sum_m (X_{m,t} * \gamma_{m,w}) = G_{w,t} \; \forall \, w \in \boldsymbol{W}, m \in \boldsymbol{M}, t \in \boldsymbol{T}$
Waste Treatment	$\sum_n Z_{w,n,t} * \leq G_{w,t} \; \forall \, w \in \boldsymbol{W}, n \in \boldsymbol{N}, t \in \boldsymbol{T}$
Wastewater Treatment	$Q_t + V_t \leq U_t \; \forall \, t \in \boldsymbol{T}$
Non-Negativity	$S_t, \; D_t, \; X_{m,t}, \; I_{r,t}, \; Q_t, \; U_t, \; V_t, \; Y_{j,e,t}, \; G_{w,t}, \; Z_{w,n,t} \geq 0$

Next, we define an objective function for profit. It includes sales revenue, costs associated with production and operation, penalties or taxation related to the environmental footprint of operation (such as emissions or effluents or toxic pollutants or waste). If a particular aspect is not applicable to a use-case, it can be set as zero. The components of the objective function are defined in (Table 3)

Table 3: Components of the Profit objective

Component		Notation	Formula
Sales Revenue		$\mathcal{S}$	$\sum_t (P_t * S_t)$
Costs	Indirect	$\mathcal{I}$	$\sum_t C_t^{indirect}$
	Raw Material	$\mathcal{R}$	$\sum_{r,t} (C_{r,t}^{material} * I_{r,t})$
	Labor	$\mathcal{H}$	$\sum_t (C_t^{labor} * H_t)$
	Energy	$\mathcal{Y}$	$\sum_{j,e,t} (\rho_{j,e,t} * Y_{j,e,t})$
	Water intake	$\mathcal{W}$	$\sum_t (U_t * \upsilon_t)$
	Water Treatment	$\mathcal{Q}$	$\sum_t (Q_t * \omega_t)$
	Waste Treatment	$\mathcal{Z}$	$\sum_{w,n,t} (\tau_{w,n,t} * Z_{w,n,t})$
	Carbon Credits	$\mathcal{C}$	$\sum_t (C_t^{carbon} * A_t)$
Penalties	Emissions	$\mathcal{D}$	$\sum_t \mu_{l,t} * \left(\sum_r (\phi_r * I_{r,t}) + \sum_{j,e} (\varepsilon_{j,e,t} * Y_{j,e,t}) + \sum_{w,n} (\psi_w * (G_{w,t} - Z_{w,n,t})) + \sum_{w,n} (\sigma_{w,n} * Z_{w,n,t}) + \theta * Q_t\right) \forall \, l \in \boldsymbol{L^{Emissions}}$
	Wastewater	$\mathcal{V}$	$\sum_t (\mu_{l,t} * V_t) \; \forall \, l \in \boldsymbol{L^{Effluents}}$

Component		Notation	Formula
	Toxic Air Pollutants	K	$\sum_t(\mu_{l,t} * K_t)\ \forall\ l\ \in \boldsymbol{L^{Toxic}}$
	Waste	$\mathcal{G}$	$\sum_{w,n,t}\left(\mu_{l,t} * (G_{w,t} - Z_{w,n,t})\right)\ \forall\ l\ \in \boldsymbol{L^{Waste}}$

The objective is to maximize the profit while meeting the regulatory requirements and corporate targets:

$\boldsymbol{Profit\ Objective} = Maximize(\mathcal{S} - (\mathcal{I} + \mathcal{R} + \mathcal{H} + \mathcal{Y} + \mathcal{W} + \mathcal{Q} + \mathcal{Z} + \mathcal{C}) - (\mathcal{D} + \mathcal{V} + \mathrm{K} + \mathcal{G}))$, that is

$$\boldsymbol{Profit\ Objective} = Maximize\Big(\sum_t(P_t * S_t) - \Big(\sum_t C_t^{indirect} + \sum_{r,t}(C_{r,t}^{material} * I_{r,t}) + \sum_t(C_t^{labor} * H_t) + \sum_{j,e,t}(\rho_{j,e,t} * Y_{j,e,t}) + \sum_t(U_t * \upsilon_t) + \sum_t(Q_t * \omega_t) + \sum_{w,n,t}(\tau_{w,n,t} * Z_{w,n,t}) + \sum_t(C_t^{carbon} * A_t)\Big) - \Big(\sum_{l,t}\mu_{l,t} * \Big(\sum_r\left(\phi_r * I_{r,t}\right) + \sum_{j,e}\left(\varepsilon_{j,e,t} * Y_{j,e,t}\right) + \sum_{w,n}\left(\psi_w * (G_{w,t} - Z_{w,n,t})\right) + \sum_{w,n}\left(\sigma_{w,n} * Z_{w,n,t}\right) + \theta * Q_t\Big) + \sum_{l,t}(\mu_{l,t} * V_t) + \sum_t(\mu_{l,t} * K_t) + \sum_{l,w,n,t}\left(\mu_{l,t} * (G_{w,t} - Z_{w,n,t})\right)\Big)\Big)$$

The above objective function can then be optimized using a multi-objective optimization model or MIP approach to optimize both discrete and continuous variables. By considering factors such as production quantity, energy mix, waste processing, and water treatment, the model identifies optimal operating points that balance economic returns with environmental impact. The optimization process may generate multiple solutions, from which the Top-K Pareto optimal strategies are selected for further analysis.

For each of the Top-K strategies, specific KPIs are computed (as presented in Table 4). This allows for a comprehensive and deeper evaluation of the economic and environmental performance of each strategy.

Table 4: KPI Computation

KPI	Formulation
Profit	Handled by the objective function
GHG Emissions	$\sum_r\left(\phi_r * I_{r,t}\right) + \sum_{j,e}\left(\varepsilon_{j,e,t} * Y_{j,e,t}\right) + \sum_{w,n}\left(\psi_w * (G_{w,t} - Z_{w,n,t})\right) + \sum_{w,n}\left(\sigma_{w,n} * Z_{w,n,t}\right) + \theta * Q_t$
Renewable Energy Percentage	$\frac{\left(\sum_{e\ \in Renewables} Y_{j,e,t}\right) * 100}{\sum_e Y_{j,e,t}}$
Recycled Material Percentage	$\frac{\left(\sum_{r\ \in Recycled} I_{r,t}\right) * 100}{\sum_r I_{r,t}}$
Water Usage	U_t
Wastewater discharge	V_t
Toxic Air Pollutants	K_t
Waste Generation	$\sum_{w,n,t}\left(G_{w,t} - Z_{w,n,t}\right)$
Waste Recycling Percentage	$\frac{\left(\sum_{w,n\ \in Recycle} Z_{w,n,t}\right) * 100}{\sum_w G_{w,t}}$

Illustrative example:
Consider a manufacturer aiming to maximize profit while evaluating various operational changes: recycled input percentages, production processes, energy sources, and waste management. Applying our joint optimization approach, they identified three top-performing scenarios (i.e. Top 3 pareto optimal strategies). These are illustrated in Table 5. Scenario A leverages process A, reliant on natural gas. Scenario B shifts to process B, using renewable electricity (at a higher cost but lower emissions) and generating less waste. Scenario C entails a third process C with a mixed energy source and higher-quality more expensive feedstock but resulting in reduced waste and wastewater.

Table 5: Illustrative example – top-3 highest profit options after joint optimization of the KPIs

	Profit ($)	GHG Emissions (tons-CO_2)	Waste Generation(tons)	Wastewater (m^3)
Scenario A	1,000,000	550	150	3,500
Scenario B	970,000	200	110	3,500
Scenario C	965,000	450	60	2,800

The optimal scenario is selected based on the decision-maker's priorities. For example, if minimizing GHG emissions is paramount, Scenario B (and process B) becomes the preferred choice, despite a potential reduction in profit, due to its significant CO2 reduction. We will outline a systematic approach to facilitate this selection process next.

D. Developing a Utility Representing Social Responsibility Score

To facilitate decision-making among the top optimal strategies and capture the interdependence and tradeoffs between KPIs, we develop a utility function representing Social Responsibility Score (SRS). This function represents the overall performance of the system as a function of the individual KPIs. The utility function represents the preferences of the decision-maker and can be used to capture the trade-offs between economic and environmental KPIs.
We calculate SRS using a weighted sum of the KPIs, where the weights represent the relative importance of each KPI.

$$U_{SRS} = w_1 * KPI_1 + w_2 * KPI_2 + \cdots w_n * KPI_n$$

where: U_{SRS} is the overall utility (social responsibility score), w_i is the weight assigned to the i^{th} KPI, and KPI_i is the value of the i^{th} KPI.

This approach allows for a flexible and customizable evaluation framework that aligns with the specific priorities and values of the decision-maker. These priorities and values may be derived from multiple factors including regulations, company targets, industry directives, customer expectations, or value-chain constraints.
For instance, let's consider the manufacturer from the illustrative example in the previous section. The manufacturer is focused on the KPIs: Profit (P), Emissions (E), Waste (W) and Water Usage (H). The utility score is represented as:

$$U_{SRS} = w_p * P + w_e * \mathrm{E} + w_w * P + w_h * \mathrm{H}$$

The manufacturer picked weights as follows (with negative weights representing costs):
Weight for profit, w_p= 1
Weight for emissions, w_e= -\$50 per Ton-CO_2 (approximated from Social Cost of Carbon)
Weight for waste, w_w= -\$300 per Ton (approximated from waste cleaning expenses)
Weight for water usage, w_h= -\$5 per Ton (approximated from wastewater treatment costs)
Applying these weights to the example scenarios in Table 5, we compute utilities for each scenario (Table 6).

Table 6: Illustrative example – computation of utility from KPIs

	Profit ($)	GHG Emissions (tons-CO_2)	Waste Generation (tons)	Wastewater (m^3)	**Utility U_{SRS} ($)**
Scenario A	1 x 1,000,000	-\$50 x 550	-\$300 x 150	-\$5 x 3,500	**910,000**
Scenario B	1 x 970,000	-\$50 x 200	-\$300 x 110	-\$5 x 3,500	**909,500**
Scenario C	1 x 965,000	-\$50 x 450	-\$300 x 60	-\$5 x 2,800	**910,500**

In this simplified example, though Scenario A maximizes profit, Scenarios B and C, based on the manufacturer's weighted KPIs utility ($\boldsymbol{U_{SRS}}$), are comparable, with C marginally better. The manufacturer should choose Scenario B for GHG reduction or Scenario C for waste and water minimization.

Table 7 demonstrates the sensitivity of the utility score U_{SRS} to weights. For instance, a 10% change in a weight can alter the optimal scenario. Therefore, it is crucial to assign weights that accurately reflect the decision-maker's priorities and requirements. Standardizing weights through government or industry consortia would set benchmarks and enable objective comparisons.

Table 7: Impact of changing weights on utility, $\boldsymbol{U_{SRS}}$ (optimal scenario in **bold**)

		10% Decrease in (Absolute) Weight Value				10% Increase in (Absolute) Weight Value			
Weight	Original Weight	New Weight	Scenario A	Scenario B	Scenario C	New Weight	Scenario A	Scenario B	Scenario C
$\boldsymbol{w_e}$	-50	-45	**912,750**	910,500	**912,750**	-55	907,250	**908,500**	908,250
$\boldsymbol{w_w}$	-300	-270	**914,500**	912,800	912,300	-330	905,500	906,200	**908,700**
$\boldsymbol{w_h}$	-5	-4.5	911,750	911,250	**911,900**	-5.5	908,250	907,750	**909,100**

4. Discussion

As a real-world application of our approach, we present a case study from the industrial process manufacturing sector. In this scenario, an industrial chemical manufacturer wants to evaluate different options for optimizing its sales and operations plans to enhance both economic and environmental performance.

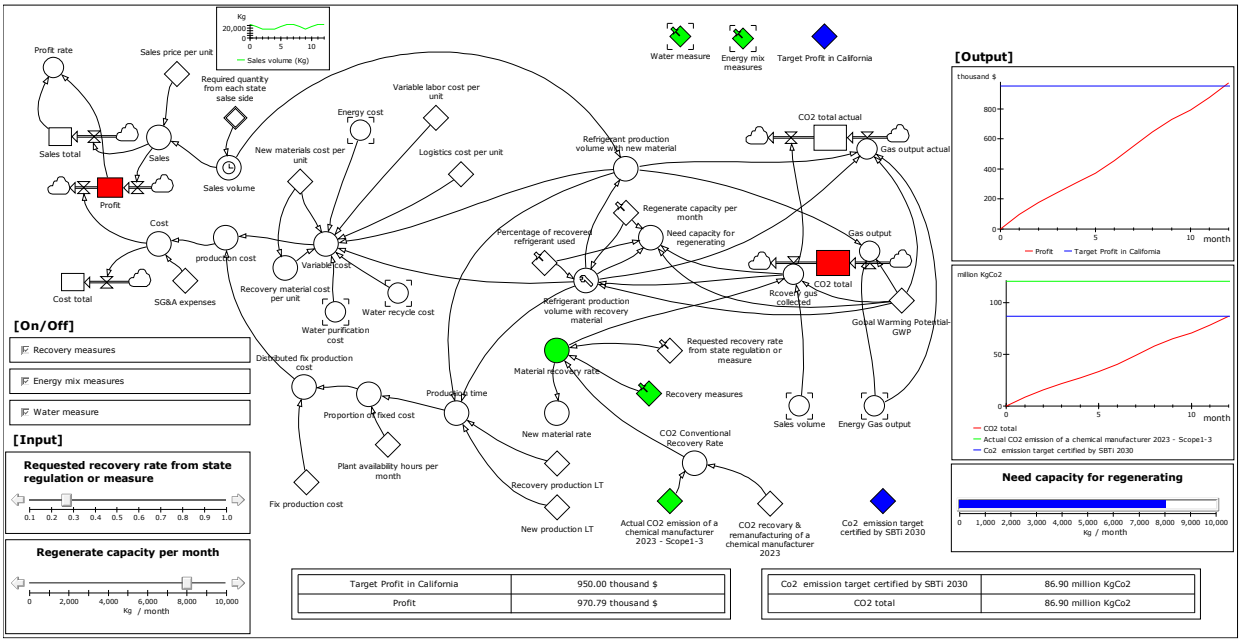

Figure 2: Simulation Setup

Scenario

The manufacturer produces a range of industrial chemicals using various raw materials, including both virgin and recovered materials. It operates multiple production lines with varying energy sources and resource consumption profiles (e.g., water). Its current sales and operations planning system is based on simulation and generates plans that optimize profit. It takes customer demand, supply availability, production capacity, costs, and profit targets as inputs; simulates different scenarios; and generates a plan indicating demand that can be met, the potential profit and production lines that need to be engaged. However, the manufacturer is facing regulations mandating minimum recycled raw material use. In addition, it has set corporate targets for reducing emissions and reducing water use. The manufacturer needs sales and operations plans that maximize profit, while meeting and exceeding the environmental targets.

KPI Definition and Measurement

Following the approach outlined above, we first identified the following key metrics and KPIs of relevance to the manufacturer:

- **Economic KPIs:** Revenue, production costs (broken down by material, labor, energy), profit.
- **Environmental KPIs**: GHG emissions, energy consumption by source, water consumption, and recovered material use.

For these KPIs, the data and targets were collected from the regulatory requirements, manufacturer's reports, operational systems, and industry benchmarks.

Simulation Setup and Optimization

We setup a simulation to model the operations and relationship between the KPIs (Figure 2). For example, the model captures how increasing the proportion of recovered materials as inputs, affects production costs and GHG emissions, and which production lines can be engaged. It also models the trade-offs between using different energy sources (e.g., renewable vs. fossil fuels) in terms of costs and emissions. Further, it models the water usage efficiency, wastewater treated, water recycled and associated costs of treating the water. The simulation allows setting targets according to manufacturer’s strategic priorities and regulatory requirements. Within the simulation, the energy mix, percentage of

recycled material, and wastewater discharge were the controls to balance profits, emissions and material circularity targets, given the constraints on demand and production line capacity (Figure 3).

The simulation identifies optimal sales and operations plans that maximize profits while meeting the emissions and water use reduction targets. The optimization space covers multiple scenarios, including:

- Different mixes of virgin and recovered materials
- Different mixes of renewable and non-renewable energy sources
- Varying levels of water consumption and wastewater treatment

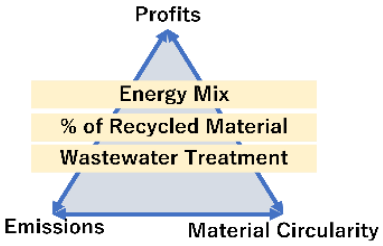

Figure 3: KPIs to balance and the controls

In an example scenario, the manufacturer wanted to fulfill the demand, meet the revenue targets, achieve the state mandated recycled material requirement (of minimum 20%), reduce GHG Emissions in line with SBTi (Science Based Targets initiative) for chemical manufacturers, and reduce freshwater consumption by 2500 m^3. Using the simulator the manufacturer was able to arrive at a viable plan, which met or exceeded most of the objectives with only a 5% impact on profits. Table 8 summarizes objectives, tradeoffs and simulation results.

Table 8: Objectives, Tradeoffs and Simulation Results

KPIs	**Tradeoffs**	**Impact of tradeoff**
Objective 1: Reduce annual water consumption by 2500 m^3	+ Treat wastewater and recycle a percentage of it to reduce intake. - But Treating wastewater adds cost. *Simulation Recommendation*: Water recycling rate 18% (previously 0%)	• Achieved annual water intake reduction target 2524 m^3 • Annual cost increase of $361
Objective 2: Reduce CO_2 emissions to meet the SBTi reduction targets specified for chemical manufacturers by 2030.	+Reduce CO_2 emissions by RE-X (recovery and recycling of materials). - Recovery and recycling add to cost. *Simulation Recommendation*: Increase recovery rate 27% (previously 12%)	• Achieved annual CO_2 emissions reduction of 79 tons-CO_2 • Annual cost increase of $70,913
	+Reduce CO_2 emissions by increasing renewable energy use. - Renewable energy is more expensive than non-renewable energy. *Simulation Recommendation*: Renewable electricity use rate 34%. (previously 17%)	• Achieved annual CO_2 emissions reduction of 160 tons-CO_2 • Annual cost increase of $598
Final results	• Achieved a reduction of 18% in water intake; reduction volume is 2524 m^3. • Achieved the CO_2 emissions target. Reduction volume is 239 tons-CO_2. • Improved recovered material usage (18%); improved renewable energy use (by 17%) • The revenue target was achieved, but the profit reduced by about 5%.	

5. Conclusions and Recommendations

The transition to a circular economy requires a fundamental shift in how businesses measure and manage their performance. Our proposed systems approach provides a practical framework for integrating economic and environmental KPIs into operational decision-making which enables businesses to optimize for both profitability and sustainability. By defining comprehensive KPIs along economic and environmental dimensions, formulating their interdependencies as a joint-optimization problem, simulating scenarios, assessing the utility and impact of the optimum solutions, manufacturers can make their operations more sustainable in a measurable way without losing the sight of profitability. The case study provides an example of how this approach can be applied in a real-world setting.

To extend and enhance our approach, future research can focus on the following directions:

- **Refining the utility function:** extending the model to include more resource types and multiple product types; incorporating more elaborate models of KPI interdependencies, and stakeholder targets and objectives.
- **Expanding the scope of KPIs:** Including a broader set of KPI along the economic and environmental dimension; incorporating social KPIs to capture the societal impact of circular economy initiatives such as green job creation, DEIA, safety incidents.
- **Improving the optimization approach:** Combining simulation approach with constrained multi-objective optimization solvers.
- **Further validation:** Engage with industrial OEMs to further validate and enhance the approach by applying it to use-cases in diverse industry sectors and geographies.

Ultimately, we plan to turn this approach into a practical system for businesses to optimize their circular economy transition, creating business value for themselves, and benefiting society and the planet.

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