Resources, Conservation & Recycling 192 (2023) 106919

Contents lists available at ScienceDirect

Resources, Conservation & Recycling

journal homepage: www.elsevier.com/locate/resconrec

Full length article

Lessons from the biosphere for the anthroposphere: Analysis of recycling structures of conservational measures

M. Varga[a,*], B. Csukas[b], S. Khanal[c], B.R. Bakshi[d]

[a] Hungarian University of Agriculture and Life Sciences, Inst. of Animal Sciences, 40 Guba, 7400, Kaposvar, Hungary
[b] Hungarian University of Agriculture and Life Sciences, 1 Pater, 2100, Godollo, Hungary
[c] Dept. of Food, Agricultural and Biological Engineering, The Ohio State University, Columbus, OH, 43210, United States
[d] Dept. of Chemical and Biomolecular Engineering, The Ohio State University, Columbus, Ohio 43210, United State

ARTICLE INFO

Keywords:
Circularity
Process net structure
Maximal pathways
Recycling
Conservational measures
Assembly and disassembly

ABSTRACT

This paper analyzes cyclic and transferring maximal pathways in some natural and human-built process structures to show how the essential features of recycling based conservation are embedded in natural systems, and how these lessons can be implemented in human-built systems, consciously. Having studied an example biosystem and ecosystem, it was found that i) local open transferring routes result in cycles at the system level; ii) the diversified species are built from a restricted pool of fundamental components; iii) assembly and disassembly are coordinated by symmetrical structural patterns; iv) recycling is supported by storage, resulting in average composition. Conscious applications of these features are discussed for the carbon emission-free hydrogen energy cycle; for a published case study on grocery bag recycling and for possible assembly-disassembly logistics of electronic waste reprocessing. The household waste-related example also illustrates how process net structure can be applied for the generation of the respective dynamic model.

1. Introduction

Considering the global challenges of depleting resources and accumulating waste reservoirs, Bio-based Circular Economy has gained high interest in the past years (BioFuture Platform, 2018; Ellen MacArthur Foundation, 2019). In the analysis of the lessons from biosphere for anthroposphere, we may start from the big picture of the main interacting sub-systems in Fig. 1.

To manage the various risks and threats, ***humanity needs to learn useful principles from recycle structures of biosphere to generate new practical solutions***.

Effective interventions, inspired and supported by nature, have to manage recent challenges to conserve and recirculate materials with the possible minimum waste generation (Debele et al., 2019; European Commission, 2021). This endeavor has already appeared in several fields, referred with various terminologies with slightly different focus, such as

- Nature-based solutions (e.g. Kumar et al., 2021; Langemeyer et al., 2021) that mainly refer to solutions that use ecosystem as infrastructure, e.g. for coastal protection against climate change related hazards (US Army Corps of Engineers, 2013; Hynes et al., 2022), for water pollution control (Liquete et al., 2016), or for land and landscape management strategies (Keesstra et al., 2018).
- Nature-inspired solutions, where terminology refers to innovative design and production methods to create materials, structures or systems (e.g., biomimicry in Venkata Mohan et al., 2019 or in Tate et al., 2019; inspiration from nature for the economy from firm to global level in van den Bergh, 2020; bio-inspired nested architectures for industrial symbiosis in Chatterjee et al., 2021). Van den Bergh (2020) point out also the adaptation difficulties and drew attention to the fact that even in the case of adaptation, humanity can expect to reach only a "semi-circular" economy.

An interesting circularity-related analysis of complex issues for policy design is discussed by Sterner et al. (2019). Zeng and Li (2021) reviewed the emergence of anthropogenic circularity science and proposed three laws of circularity chemistry for the basic principles of circularity science. Referring also to these three laws, anthropogenic circularity, as a new interdisciplinary science is emphasized by Zeng (2023). In this paper, authors focus on anthropogenic circularity in the context of metal criticality and carbon neutrality.

* Corresponding author.
E-mail address: varga.monika@uni-mate.hu (M. Varga).

https://doi.org/10.1016/j.resconrec.2023.106919
Received 26 October 2022; Received in revised form 12 January 2023; Accepted 7 February 2023
Available online 11 February 2023

To demonstrate and promote favorable solutions, the engineering analysis, planning and operation of complex man-made systems require appropriate models for the underlying large-scale, long-term transdisciplinary processes. The main types of modeling approaches, supporting problem-solving for the emerging systems of (optionally Bio-based) Circular Economy are the following:

- There are ***discipline-specific process modeling frameworks and tools*** for the detailed analysis, ***planning and design of the various local sub-systems of circular processes,*** for example: in chemical engineering: (gPROMS, 1997–2020); in civil and environmental engineering: Activated Sludge Model (Henze et al., 1987) and Anaerobic Digestion Model (Batstone et al., 2002); in soil-related and hydrological processes Soil & Water Assessment Tool (Gassman et al., 2007); in agriculture Agricultural Production Systems Simulator (Holzworth et al., 2014) or STICS (Brisson et al., 2009); in fisheries Ecopath with Ecosim (Christensen and Walters, 2004); etc.
- The ***control and operation of well outlined complex systems***, is supported by the new generations of ***sensors, Internet of Things and data analytics based methods*** of Information Technology and Artificial Intelligence also in agriculture (e.g. Kamilaris et al., 2017); and in environmental engineering (e.g. Izquierdo et al., 2018).
- For the ***upper level, optionally multi-criteria (economic, ecologic, etc.) evaluation*** of the complex processes, the applied approach usually embeds a ***simplified model into the exact optimization of the whole system***. For example, the Mixed Integer Linear or Non-linear Programming (MILP or MINLP) based optimization is used for Water-Food-Energy-Ecosystem processes (Veintimilla-Reyes et al., 2019; Namany et al., 2020). Recently, the techno-ecological approach also considers the ecosystem in the multi-objective optimization of sustainable industrial process systems (Hanes et al., 2018).

However, obvious gaps appear in the integration of the above models, especially at the following points:

- ***Between the discipline-specific models:*** Several efforts were made to couple various sub-models (e.g., biogeochemical and hydrological processes in Cipolla et al. (2021); or hydrologic model with an agronomic model in Deng et al., 2021, etc.). Besides case-specific solutions, model integration approaches also appeared (e.g. OpenMI by Open Geospatial Consortium, FMI by Modelica Association, etc.). In spite of these efforts, model integration is still a challenging task (Huynh, 2016; Deng et al., 2021).
- ***Between the sophisticated discipline-specific models and the lower-level data analytics based models:*** Regardless to applications from manufacturing industry to economics (e.g. Johnson et al., 2016; Feldkamp et al., 2017; Greasley, 2018; Sharif et al., 2018; Shao et al., 2020; etc.), new frameworks are needed, where data analytics based models support the fast refinement of dynamic model parameters, while dynamic models uncover hidden causal relationships behind data analytic models.
- ***Between the sophisticated discipline-specific models and the upper level evaluation/optimization of complex, trans-sectorial systems:*** Hybrid LCA (Suh, 2004) and Process-to-Planet (Hanes and Bakshi, 2015) frameworks links multiple scales for the sustainability related evaluation and for process design. Various other case specific solutions are also reported (e.g. Bisinella de Faria et al., 2015; Lan and Yao, 2019; Marvuglia et al., 2022), however, there is not a generally usable bi-directional feedback.

We assume that there is a common reason for the above gaps, namely, the existing methodologies do not support the unified combination of the explicit structural characteristics with the causally established dynamic balances. ***Programmable Process Structures (PPS) proved to be an effective framework for modeling and simulation-based analysis, design and planning in several former tasks*** (e.g. Varga and Csukas, 2022, 2017; Varga et al., 2017; Audino et al., 2020; Yang et al., 2019).

The further development needs to learn more about the recycling structures of conservational processes. Accordingly, the ***objectives*** of this paper are to:

- analyze some interesting recycle structures of natural processes in the biosphere;

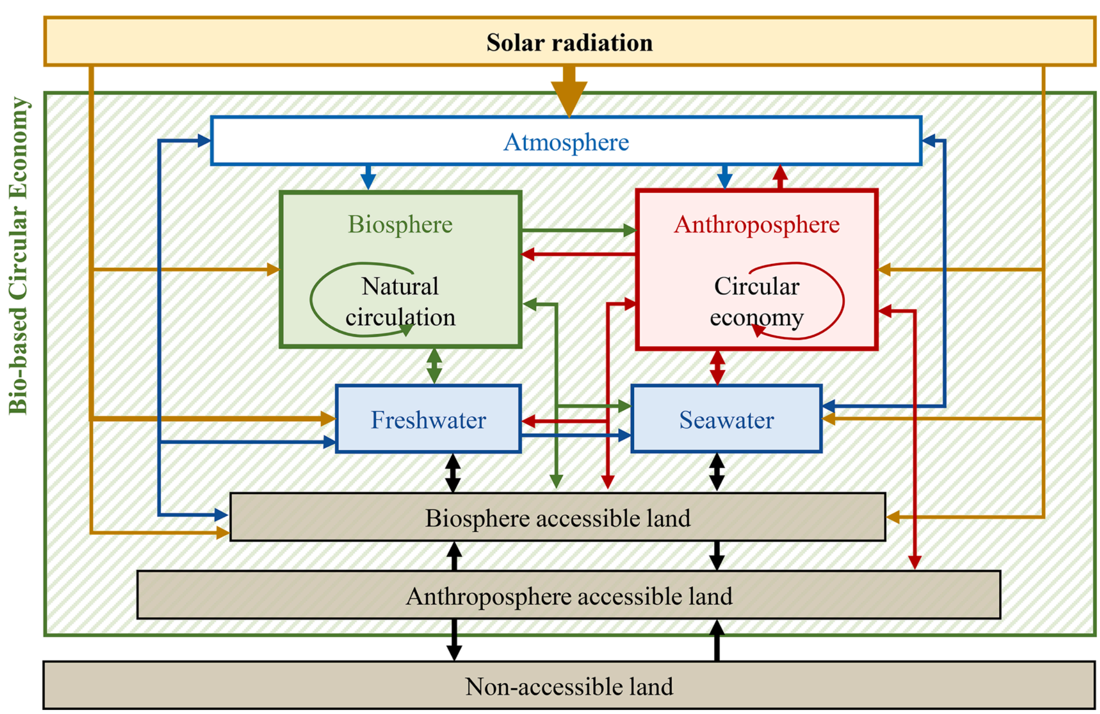

Fig. 1. Big picture of Bio-based Circular Economy.

- derive recycling-based and conservation related principles from these structures;
- illustrate the application of these principles in recycle structures of human-built processes in anthroposphere; as well as
- show a simple example about how PPS of dynamic simulation can be generated from the applied process net structures.

The ***novelty*** of our recent work is threefold: i) it explains how the structural analysis of maximal (transferring and cyclic) pathways in natural systems can be applied to derive recycling-related, conservation-based principles; (ii) it shows how these nature-inspired principles do appear and can be embedded in man-made circular processes, consciously; iii) furthermore, it illustrates how the simple state-transition nets can be transformed into a unified Programmable Process Structure for the more detailed dynamic simulation based analysis and planning.

2. Studied example recycle systems and applied methods

2.1. Examples for recycling processes in biosphere

To study the structural characteristics and to illustrate the embedded recycling loops in nature, we utilize two different examples, as follows:

The ***biosystem*** example focuses on some core functionalities of chloroplast and mitochondria. They have key role in energy and material supply chains of cellular biosystems. The related well-known architectures can be studied as sub-systems of biochemical pathways (Michal, 1999 and 2014). This example is the further development of the analysis of these cellular organs in an early paper (Varga, 2007).

The ***ecosystem*** example analyzes a typical natural land patch (without human intervention) where trees, plants and optionally animals coexist. The main driver of the long-term sustainable survival of this ecosystem is the solar radiation, captured by plants and trees. In addition, solar energy promotes evapotranspiration and precipitation via the meteorological system. In previous works on various ecosystem involving agroforestry (Varga et al., 2021) and pond aquaculture (Varga et al., 2020) systems, we investigated the related processes in a deeper level by developing simplified but dynamic and causally right first principles-based models of the respective systems. This paper focuses on the recycling related example features of the formerly built models.

2.2. Examples for recycling processes in anthroposphere

In the first example, the ***perspective use of solar radiation based hydrogen energy*** (Miranda, 2018) ***through electrical energy and electrolysis*** is analyzed. Actually, photovoltaic systems, hydro-power and wind energy are fluctuating and limited resources, while the artificial chloroplast (e.g. Barras, 2020) develops slowly. Burning of fossil resources or freshly produced biomass result in carbon-dioxide emission. Accordingly, regardless of safety concerns, humanity produces surplus electrical energy also in nuclear reactors, temporarily. However, the limited storage of electrical energy is to be considered, especially in context of seasonal and fluctuating changes of sustainable resources. This is the very point where hydrogen energy (produced by electrolysis) gives a feasible solution. Here we also considered the experiences from our previous works related to hydrogen supply chain modeling (Varga and Csukas, 2018; Varga et al., 2019).

In the second illustrative example, the structure of ***household-used plastic and paper carrier bags*** is discussed, as an interesting case of recycling of municipal waste. Carrier bags form a large component of discarded and mismanaged plastic waste whose value can be retained through a sustainable and circular economy (Thakker and Bakshi, 2021a). A novel design framework (Thakker and Bakshi, 2021b) was applied to design optimal value chains based on a superstructure network containing cradle-to-cradle life cycles of some currently available carrier bag alternatives. The applied metrics constituted the objectives of the framework, and Pareto optimal solutions were found. The paper versus plastic dilemma was quantified and the prospects of bio-based poly-(lactic acid) bags were also studied.

In the third example, we study the structure for recycling based conservation of typical ***inorganic resources***. Considering the traditionally mining-based raw materials, the increasing production of electronic goods has caused serious crisis in the market of some ***rare*** **(e.g.** ***rare earth) elements*** (e.g., Yao et al., 2021). This is another case, where mankind ought to utilize the principles of recycling based conservation, learnt from natural processes.

2.3. Methods for structure representation of process systems

In the graph representation of ***general nets*** (Petri, 1980), the state and transition nodes are distinguished by dots and bars, respectively, as it is illustrated in Fig. 2a. This structure describes the flux structure of various transformation or transportation networks, correctly. Here the state → transition and transition → state edges correspond to the respective decreasing and increasing quantities, but the causalities are not visible. However, in the state / transition nets of signals and rules, the state → transition and transition → state edges follow the causalities, determined by antecedent and consequent signals. Fluxes and causalities can be represented together (Varga et al., 2017) in a ***special process net structure*** (see in Fig. 2b) that distinguishes the causally determining signaling connections (dotted lines), as well as the increasing or rewriting (solid lines) and decreasing (dashed lines) connections.

More details to Section 2.3 are in the Part S1 of Supplementary materials.

The constant and conservational measures can only be defined axiomatically. Accordingly, a measure C is ***model-specific conservation-law-based constant measure*** if and only if (IFF): any ΔC change of the measure C in any finite spatial region V, during any time interval is always accompanied by the identical change of the same measure in the universal complement U/V, with an opposite sign. The ***model-specific conservation-law-based stoichiometric measures (shortly conservational measures)*** can be derived from the model-specific constant measures according to a homogeneous linear relationship, defined by the model-specific stoichiometric coefficients (see Part S1 of Supplementary materials).

Based on the special process net structure and on the notion of conservational measures, in PPS (Varga and Csukas, 2022) the state elements (symbolized by ellipses) and transition elements (symbolized by rectangles) contain input and output connectors for the "conservational" and signaling connections, separately (see in Fig. 2c). PPS can be generated from the special process net structure, using one state and one transition meta-prototypes, resulting in a unified, extensible and connectible model for integrated, but distinguished consideration of conservational and informational (signaling) processes.

In the systemic view of circularity, the process nets can be characterized by the so-called ***maximal routes*** (Arva and Csukas, 1988 and 1989; Csukas et al., 1989). A route is a ***complete transferring route***, if and only if (IFF) its first element is an input element, while its last element is an output element. A route is a ***complete cycle***, IFF its first element and its last element are identical. For example in the process structure of Fig. 2 maximal transferring routes are

$$\{s_1 \rightarrow t_1 \rightarrow, s_3 \rightarrow t_2 \rightarrow s_5\}$$

$$\{s_2 \rightarrow t_1 \rightarrow, s_3 \rightarrow t_2 \rightarrow s_5\}$$

$$\{s_4 \rightarrow t_2 \rightarrow s_5\}$$

while a complete cycle is

$$\{s_2 \rightarrow t_1 \rightarrow, s_3 \rightarrow t_2 \rightarrow s_2\}$$

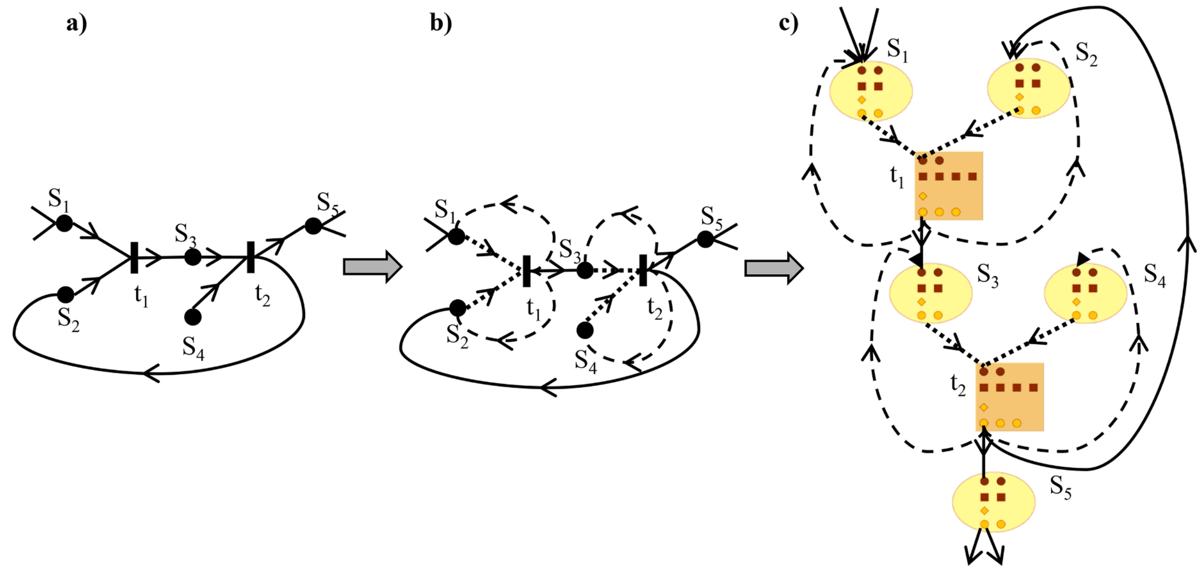

Fig. 2. From process nets to Programmable Process Structures.

3. Results and discussion

The examples for the analysis of structural features in recycling-based conservation processes are illustrated mainly by the conventional process net representation, according to Fig. 2a and to Eqs. (S1.1), (S1.2) in Part S1 of Supplementary material. However, in the example of Section 3.3.2, also the causality-expressing extended structure (Fig. 2b) based generation and simulation of a PPS (Fig. 2c), will be explained.

3.1. Analysis of recycling-based conservation in natural process structures

In the following sections, the natural example systems, introduced in Section 2.1, will be analyzed.

3.1.1. Cellular energy and material supply structures

Extracted from the biochemical pathways (Michal, 1999 and 2014) and from KEGG database (http://www.kegg.jp), in Fig. 3 the simplified essential structure of chloroplast (shown in regular fonts) and mitochondria (shown in italics) are illustrated. It is to be noted that Fig. 3 does not include all of the components and reactions, but displays only the simplified main pathways to highlight the essential maximal routes. In Fig. 3, state elements (dots) refer to components, while transition elements (bars) refer to actual transportations and transformations. The comprehensive lists of state and transition elements, as well as of the maximal transferring and cyclic pathways are listed in Part S2 of Supplementary material.

Chloroplast utilizes solar radiation to split water into oxygen, protons and electrons. Mitochondria produces heat energy by oxidation of hydrogen (protons and electrons) to water, utilizing externally supplied oxygen.

In chloroplast, protons and electrons supply hydrogen for the synthesis of metabolites (in the Calvin cycle), with an accompanying external carbon-dioxide usage. In mitochondria, the protons and electrons for H_2O production come from the Szentgyörgyi-Krebs (TCA) cycle, where a given part of metabolites is decomposed with external carbon-dioxide emission.

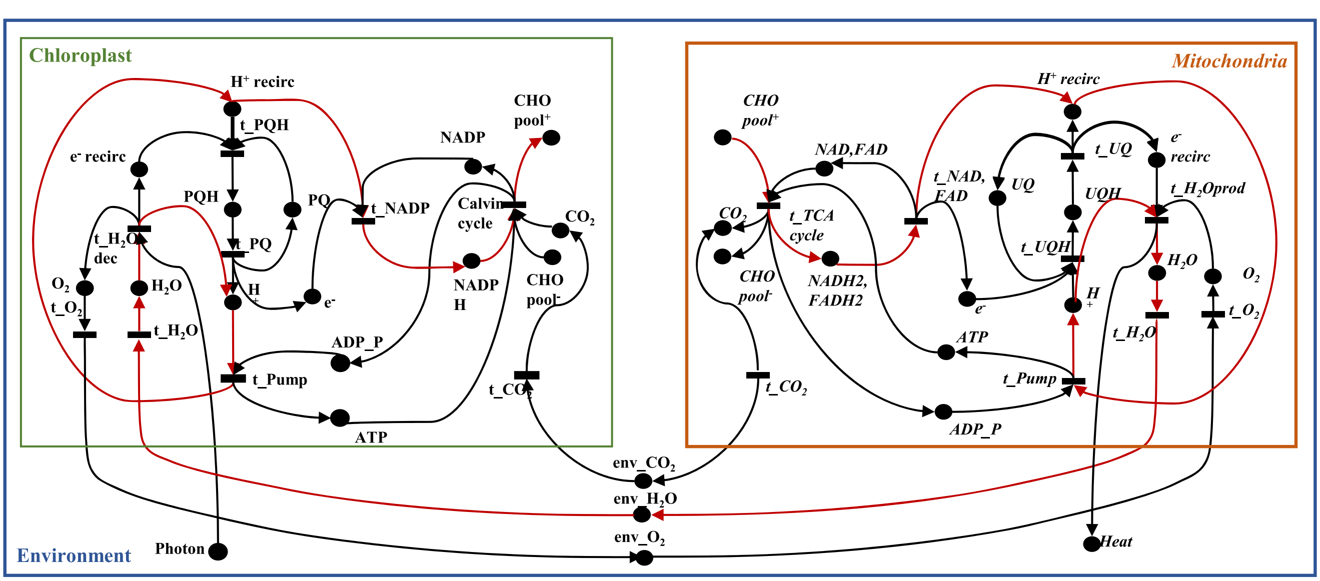

Fig. 3. Essential symmetrical transferring routes and complete cycles in chloroplast (normal fonts) and mitochondria (italics), transitions' names start with "t_" prefix.

Chloroplast and mitochondria are well known systems in literature, so they exemplify well the usability of maximal pathway analysis. In this case, structural analysis draws the attention to the interesting point that all connections have reversed direction in chloroplast and in mitochondria, except of ADP+*P* and ATP flows, because ATP pump produces chemical energy in both systems. It is worth mentioning that all of local recycle loops are organized symmetrically.

Both chloroplast and mitochondria realize the inside conservation of atoms, except the environmentally imported or exported H_2O, O_2 and CO_2. However, having connected the sub-systems, the whole virtual system has also the capability to maintain the conservation for these environmental components. Accordingly, the overall process utilizes only photons (from the unlimited outer resource) and produces heat and chemical energy (ATP → ADP+*P*) for continuous composition and decomposition (i.e., for continuous recycling) of the underlying stoichiometric compounds of biosphere.

Main transferring route (as alternating series of state and transition elements) in the virtually connected hypothetical system of chloroplast and mitochondria (conversion of solar energy to heat energy with intermediate CHO storage) is as follows:

{*Photon*→t_H2Odec→E-_recirc→t_PQH→PQH→t_PQ→E-→t_NADP→NADPH→t_Calvin_cyle→CHOpool+}→{*CHOpool+*→t_*TCA_cycle*→*NADH2_FADH2*→t_*NAD_FAD*→*E-*→t_*UQH*→*UQ*→t_*UQ*→*E*-recirc→t_*H2Oprod*→*Heat*}

The main cycles in the virtually connected hypothetical system of chloroplast and mitochondria are not connected in individual living systems, but only in ecosystem level, as follows:

- Overall water decomposition and composition based hydrogen cycle of photosynthesis and respiration (highlighted by red arrows in Fig. 3):

{env_H2O→t_H2O→H2O→t_H2Odec→*H+*→t_*Pump*→*_H*+recirc→t_NADP→NADPH→t_Calvin_cyle→CHOpool+}→{CHOpool+→t_TCA_cycle→NADH2_FADH2→t_NADH_FAD→*H*+recirc→t_*Pump*→*H+*→t_H2Oprod→H2O→t_H2O→env_H2O}

- Overall oxygen cycle:

{env_O2→t_O2→O2→t_H2Oprod→H2O→t_H2O→env_H2O}→{*env_H2O*→t_*H2O*→*H2O*→t_*H2Odec*→*O2*→t_*O2*→*env_O2*}

- Overall carbon-dioxide cycle:

{env_CO2→t_CO2→CO2→t_Calvin_cycle→CHOpool+}→{*CHOpool+*→t_*TCA_cycle*→*CO2*→t_*CO2*→*env_CO2*}

- CHO pool composition and decomposition:

{CHOpool-→t_Calvin_cycle→CHOpool+}→{*CHOpool+*→t_*TCA_cycle*→*CHOpool-*}

Summarizing the structural analysis, chloroplast, mitochondria, and especially their integrated system demonstrate the dominance of cyclic conservational pathways, related to the complete transferring routes, resulting in an "almost closed" system with solar radiation, as a single resource from outside. There are limited number of the same fundamental components in both subsystems of different (actually reversed) functionality. The invariant components and reversed connections result in the coordinated structural organization of composition and decomposition processes. The [CHO] pool, processed by the Calvin and TCA cycles, gives a dynamic storage for the whole system.

3.1.2. Material supply structure of a simplified ecosystem

The simplified process structure of coupled tree and plant ecosystems is illustrated in Fig.S2. This and the hypotheses and assumptions of the simplified conceptual model are explained in Part S3 of the Supplementary material.

All of the tree and plant related state elements (dots in Fig.S3) are characterized by species-specific (and optionally time-varying) stoichiometric composition of the respective [C, H, O, N, P,…] atoms. Solar radiation provides photons for the photosynthesis and heat energy for evapotranspiration. Atmosphere (and the optional air compartments) represent the actual or forecasted meteorological conditions, as well as contain H_2O, O_2, CO_2 and N_2 components. Upper soil layer compartments contain residue, humus, solution and inorganic phases, containing [C, H, O, N, P,…] pools, as well as H_2O, N, P, O_2, CO_2 N_2 components.

The functionalities are calculated by the transition elements (bars in Fig. S3), according to the stoichiometric changes of above components within and between the phases and compartments.

The tree and plant related main dynamic down-flow and up-flow fluxes are basically determined:

- by push logistics of the photosynthesis driven utilization of H_2O from xylem (and CO_2 from air) to produce O_2 into air and [C,H,O,N,P] pool into phloem (representing a logistical storage), as well as
- by the pull logistics of evaporation- (evapotranspiration-) driven emission of H_2O and CO_2 into the air from the xylem, accompanied with the uptake of components from soil to the xylem (representing a logistical storage).

Trees and plants (as self-controlled living systems) tend toward rational behavior (Schmid, 2016). Accordingly, the photosynthesized biomass is distributed from the phloem amongst the compartments by the process of "growth", considering the stoichiometric composition of the respective compartments. Analogously, the xylem (considering the availability limits of the soil) is filled with the necessary amount of water and soluble components from the upper (in case of plants, trees) and from the lower (in case of trees) soil compartments via the transition "uptake".

There are many symmetrical maximal transferring routes and cycles in the two sub-systems. In addition, there are interesting cooperative routes between tree and plant sides, namely:

- Plant related nitrogen fixation based N supply for trees:

  {Atmosphere→t_Air/land-interaction→Uppersoilunderplants→t_Seepage→Lowersoilunderplants-→t_Side-flow→Lowersoilundertrees→t_Uptake→Xylemoftrees→t_Photosynthesis};

- Phosphorous, mined by the trees from the deeper soil layers for plants (a phosphorus pathway is highlighted by red arrows in Fig. S2):

  {Lowersoilundertrees→t_Uptake→Xylemoftrees→t_Photosynthesis→Phloemoftrees-→t_Growth→Leavesoftrees→t_Littering→Uppersoilundertrees→t_Side-flow-→Uppersoilunderplants→t_Uptake→Xylemofplants→t_Photosynthesis→Phloemofplants→t_-Growth→Leavesofplants→t_Decay→Uppersoilunderplants→t_Seepage→Lowersoilunderplants→t_Sideflow→Lowersoilundertrees].

Structural analysis shows that the trees and plants are characterized by similar dominant cyclic conservational pathways besides the complete transferring routes, while all of them are driven by the solar radiation. The synthesis produces the plant and tree compartment-specific [C,H,O,N,P,…] pools from a limited number of environmental components, while the respiration and decay recycles the same environmental components from these [C,H,O,N,P,…] pools. This results in the coordinated organization of synthesis and respiration/decay processes. The dynamic storage in xylem and phloem supports the short-term push logistics of photosynthesis and the pull logistic of respiration. The long-term (seasonal or multiple year) resilience is ensured by the storage of specific [C,H,O,N,P,…] pools in bole (for trees), as well as and in roots and "products" (in case of plants and trees).

3.2. Some recycling-based conservation principles in natural process structures

The lessons, learnt from the structural analysis of recycling-based conservation as illustrated above and some other natural process systems, can be summarized as follows:

- **Local transferring pathways result in system level cycles**: The sustainability of biosystems and ecosystems is ensured by the dominance of complete cycling pathways, related to all of maximal (transferring and cyclic) pathways in the process structure. The sustainable structures are characterized by the (optionally coupled) recycling routes (cyclic pathways) of the conservational measures. The conservational measures are the stoichiometric combinations of the constant measures. For example, the biological components (i.e., the "conservational measures") are built from the atoms (i.e., from the "constant measures"). The energy, utilized for the recycling-based conservation by the continuous composition (photosynthesis) and decomposition (respiration and decay) of the biological components within the system's contour is supplied by the single unlimited outer resource of solar radiation.
- **Limited pool of fundamental components**: The recycling-based robust reusability of the cycling material is supported by the strictly limited pool for the fundamental components of primary processes in the highly diversified set of species. Behind the adaptation supporting, evolution-driven biodiversity, the same ADP / ATP cycle produces energy, the same NADH, FADH2 and NADPH components transport the hydrogen, there are the same 12 precursor metabolites and 20 amino-acids, etc. in the quite different living systems. Biosystems and ecosystems do not utilize the combinatorial possibilities of organic chemistry at all. This limitation contributes to the recycling- based conservation of the more and more diversified higher level biological materials, obviously. Human-designed systems should also follow this approach, however, especially in developed countries, there are still many counter argument toward the effective operationalization of these insight.
- **Coordinated structural organization of assembly and disassembly**: There are coordinated (symmetrically reversible) structural patterns of the assembly (composition) and the disassembly (decomposition) related processes. This feature contributes to the effective organization of recycling based conservation within the system's contour. In the cellular biosystem, the [C,H,O] pool is synthesized from H_2O and CO_2, while the [C,H,O] pool decomposing respiration and decay result in the same components. Analogously, in the ecosystems, the specific parts of the [C,H,O,N,P,…] biomass are produced from the atmospheric and soil based components via photosynthesis, while the solar energy driven evapotranspiration and decay result in the same components, vice versa.
- **Resilience supporting averaged storage of recycling resources**: The natural supply/demand logistics of stoichiometric assembly/ disassembly processes is controlled by the necessary and sufficient storage capacity according to the various shorter and longer time horizons. The appropriate capacity of intermediate storage also controls the average composition of the supply of suddenly changing or slowly (daily, seasonally, etc.) fluctuating resources to prepare them for resilient dynamic balance of productions and consumptions in the usually applied processing. In cellular biosystem the inner storage is given by the [C,H,O] pool, processed in the Calvin and TCA cycles. In the ecosystem example, the short term storage is solved by the logistical units of xylem and phloem, while the long term storage is given by the product (or root) in the plant for one season, as well as by the bole and root of trees for multiple years. The outer storage in both cases is ensured by the relatively higher capacities of atmosphere and soil.

These practice-oriented principles are in accordance with the theoretical establishments of circulation and circularity in the evolution of science. This historical way drives from the pioneering analysis of circulation and conservation in the book of "Elements of Physical Biology" (Lotka, 1925), to the up-to-date circularity science (Zeng and Li, 2021), including the three laws of circulation chemistry (Law #1: relative contents of chemical elements in the universe are constant; Law #2: all the elements are moving along cyclical routes; Law #3: chemical reactions should be designed to tentatively achieve zero emission of waste.)

Considering the emerging knowledge of circularity science and the increasingly growing global problems, the above derived principles aim to motivate practical engineering solutions, focusing on the knowledge transfer of maximal process net pathways from the natural processes to the human-built ones. In addition, we show, how these net structures can help to generate dynamic process models in the sense of Programmable Process Structures to propose an adequate simulation-based design- and control- supporting framework for circularity science.

3.3. Examples for these recycling-based conservation principles in human-built process structures

3.3.1. Emission-free storable hydrogen energy through the electrolysis of water

It is a simple example to illustrate the evidence of the studied recycling-based conservation principles. In the utilization of solar radiation, the photosynthesized biomass should be used for feed, food and recyclable material production as much as possible. Burning of biomass or production of secondary fuels from biomass decrease the food and easier recyclable organic material supply, as well as increase the direct return of the metabolized CO_2 to the atmosphere. Accordingly, the production of electrical energy from solar radiation (by photovoltaic system directly, or by hydro-power and wind power, etc., indirectly) can be supplied by nuclear energy, temporarily. Perhaps better photovoltaic and brand-new other solutions, like synthetic chloroplast (Barras, 2020) will appear that may decrease the necessity of the nuclear power, in a longer time horizon.

The operation of hydropower, wind-power and photovoltaic systems depend on the daily, seasonal and abrupt change of meteorological and hydrological conditions. In addition, the extensive storage of electrical energy is still unsolved. Lack of effective storage causes difficulties also for the conventional electric energy supply chains. Considering the need for transportable and storable fuel energy (e.g., for air, sea and road traffic), hydrogen may be a feasible solution (see in Fig. 4).

Hydrogen can be produced by electrolysis of water (with useful concentrated oxygen by-product), while burning of hydrogen produces only water. Looking at the basic structure in Fig. 4, the respective cycle of

$$\{H_2O \rightarrow t\_Electrolysis \rightarrow H_2 \rightarrow t\_Burning \rightarrow H_2O\}$$

is similar to the full cycle, resulting from chloroplast and mitochondria related functionalities. This cyclic pathway supports the sustainable and resilient energy production according to the complete transferring pathway of

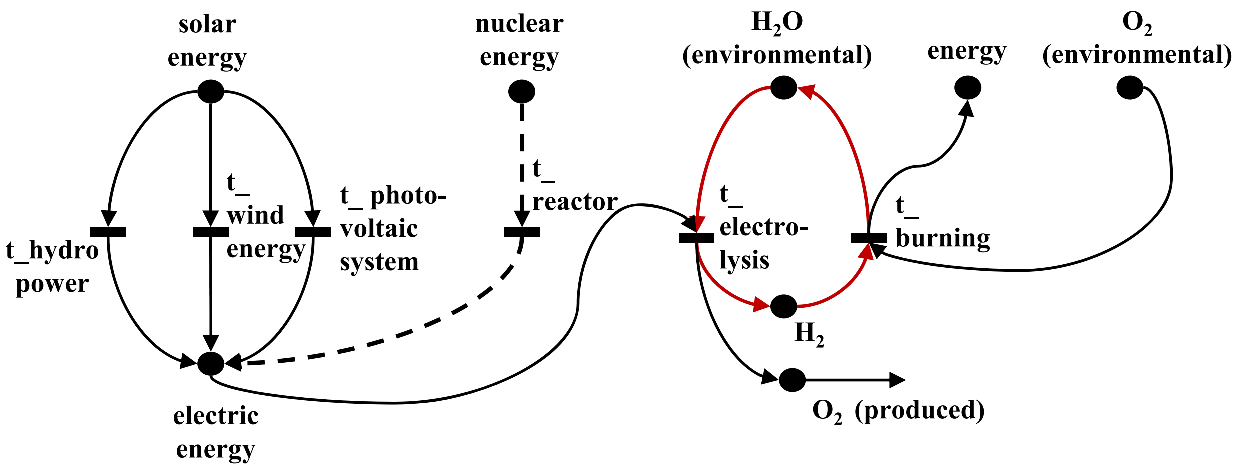

Fig. 4. Recycling in hydrogen-based storable energy (highlighting the main carbon-neutral recycle route).

{Solarenergy→(t_hydro_-powerANDt_Wind_energyANDt_*Photovoltaic*_system)→Electric_energy→t_Electrolysis→H_2→t_Burning→Energy}

This solution utilizes solar energy, without carbon resource consumption and carbon-dioxide emission, and with a reasonable storage ability, as well. In addition, delocalized electrolysis plants, combined with batch hydrogen transportation, makes it possible to avoid the extension of pipeline systems.

The principles, summarized in Section 3.2 are evident in this system, as follows:

Dominance of cyclic maximal pathways: the transformation of electrical energy from a single external renewable resource-based input to an easily storable fuel energy is solved by a single cyclic material pathway, describing the conservation of hydrogen and oxygen atoms.

Limited pool of fundamental components: H_2O, H_2 and O_2.

Coordinated structural organization of assembly and disassembly: decomposition (electrolysis) and composition (production by burning) of H_2O.

Resilience supporting storage of recycling resources: H_2 makes possible the temporary storage and concentrated spatial transportation of the fluctuating energy production from the renewable natural resources.

3.3.2. Recycling of carrier bags from household waste

The simplified example for the structure of ***household-used plastic and paper carrier bag recycling*** is shown in Fig. 5. This model is derived from the case study of Thakker and Bakshi (2021a), transformed to the analysis of the respective net structure, and maximal net pathways. Also the generation and simulation of the PPS model, derived from the process net, is illustrated in this Figure. The detailed description of the case

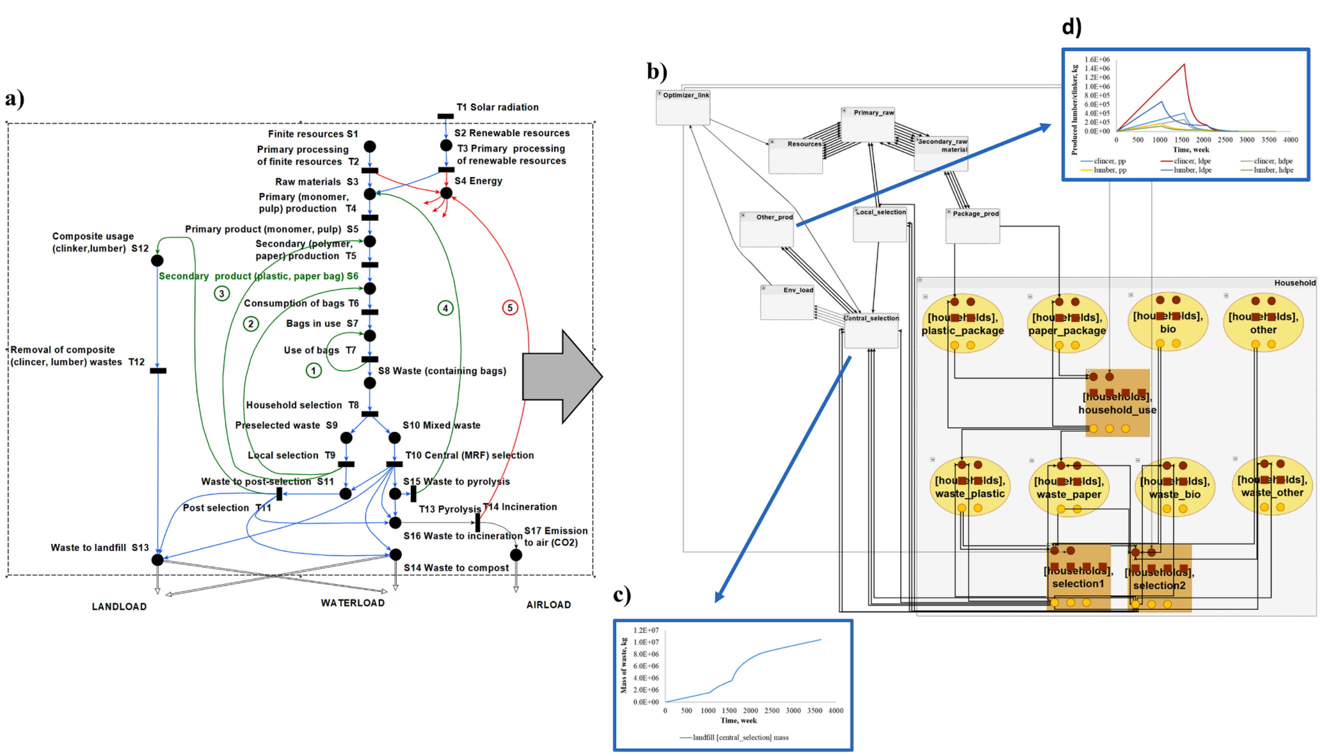

Fig. 5. Recycling loops and transferring routes in the structure of household-used carrier bags a) Process net view; b) Programmable Process Structure with examples for simulation results, c) Delayed changes of landfill; d) Stored material in lumber and clinker.

study can be found in Section S4 of Supplementary materials.

Fig. 5a shows the net of state and transition elements for the studied system. The recycle structure of the example contains 5 maximal cyclic routes, as follows:

C1 {S7→T7→S7}– Reuse of bags in household for PLA, PP, LDPE, HDPE;
C2 {S6→T6→S7→T7→S8→T8→S9→T9→S6}– Recycling to resin (polymer) for reuse of PLA;
C3 {S5→T5→S6→T6→S7→T7→S8→T8→S9→T9→S5}– Recycling to monomer for reuse of PLA;
C4 {S3→T4→S5→T5→S6→T6→S7→T7→S8→T8→S10→T10→S15-→T13→S3}– Recycling to raw materials for reuse of hydrocarbon from pyrolysis of PP, LDPE and HDPE, as well as biomass for pulp from Paper;
C5 {S3→T4→S5→T5→S6→T6→S7→T7→S8→T8→S10→T10→S16-→T14→S4→Energy_to_processes} – Recycling of PLA, PP, LDPE, HDPE and Paper through incineration to energy, utilized in multiple processes.

The PPS can be generated from the process net of Fig. 5a, according to a published method (Varga and Csukas, 2022). Fig. 5b illustrates the generated PPS of the carrier bag recycling example system.

To demonstrate the necessity of dynamic modeling, a characteristic part of the simulation results is shown in the included diagrams. Fig. 5c and 5d illustrate a case study about a 70-yearlong simulation, with the following conditions:

- separated PP, LDPE and HDPE waste is utilized for lumber and clinker production;
- lumber and clinker production starts from the beginning of the simulation, and last until 40 years;
- estimated lifetime of lumber and clinker products are 20 and 30 years, respectively.

Accordingly, the worn out composites starts to appear in the landfill after their lifetime (in the 20th and 30th years, as shown in the jumps in the curve of Fig. 5c). Moreover, this process continues after having stopped the production after 40 years. Amount of actually accumulated lumber and clinker can be followed in Fig. 5d.

More details about this and other scenarios are found in Part S4 of Supplementary materials.

The principles, summarized in Section 3.2, appear in this example, as follows:

Dominance of cyclic maximal pathways: Circularity can be enhanced by the increasing transformation of transferring process net pathways for the cyclic process net pathways (C1-C5). This is associated with decreasing both of the utilized raw materials and of the emitted waste to land, to water and to air.

The circular pathways of process net structure and the net-generated dynamic process models (Programmable Process Structures) make possible the tracking and accumulation of harmful materials. It supports the solution of the problems discussed by Zeng et al. (2022), focusing on recycling of inevitable harmful/toxic materials in circular economy.

The photosynthesis-based renewable materials (PLA, Paper) can be recycled more easily than the artificial products, because their reusability is supported by the embedded capabilities of natural materials.

Limited pool of fundamental components: Unnecessary diversity of carrier bag materials makes their separation and recycling more difficult. In contrast, the use of limited types of easily recyclable PLA or similar bio-based polymers or Paper can decrease both the utilization of the input resources and the output emissions to the environment. However, their application may be more expensive in a shorter time horizon. Actually huge number of plastic materials are produced from the six main polymer types (Faraca et al., 2019).

Coordinated structural organization of assembly and disassembly: Better coordination production and selection has great possibilities. As a simple example, think about the bar code or QR code designation of easily recyclable plastics for household identification with a simple mobile phone app. Also, the separated material ought to be recognized at returning by the consumer. This principle also confirms the need for decentralization, e.g., in preselected waste sorting and preprocessing.

Resilience supporting storage of recycling resources: Rational intermediate storage has an important role in the implementation and evaluation of recycling. Reprocessing at any level (as monomer, polymer, or composite component) needs an average composition of the recycling materials that must be supported by large enough temporary storage, as a positive example. However, apparently useful "temporary storage" of wasted PP, LDPE, and HDPE in form of lumber or clinker is valid for their 20–30 years long residence time, while afterward they shall contribute to landfill, as a negative example.

3.3.3. Dynamic assembly / disassembly structure for recycling rare elements of electronic goods

The principles, learnt from natural process structures, can also be utilized in the possible recycling-based conservation of inorganic materials, outside of biosphere.

Majority of rare (e.g. rare earth) elements, used for electronic goods (processors, chips, memories, LCDs, etc.), as well as for other accessories (batteries, solar panels, etc.) are mined from the anthroposphere accessible land layers. The location of mines may be a geopolitical issue, as well as they may be exhausted. However, there are more and more reserves in the used (and possibly wasted) goods, while this accumulation accelerates because of the shortening life-cycle of the products. This needs the intensification of intelligent disassembly, preprocessing, fine separation and recycling of rare elements. The simplified, essential structure of this recycling is summarized in Fig. 6.

The black colored dots, bars and edges correspond to a single well-defined recycle loop of a given element (e.g. indium, neodymium, etc.), while yellow color illustrates a small part of the additional and/or alternative solutions in the related design space.

In the realization of the major cycle {Element→t_Production→Products→t_Use→Primary_waste→t_Primary_selection→Selected_e_waste→t_Rough_preprocessing→Roughly_preprocessedelements→t_Fine_processing→Finely_preprocessedelements→t_Purification→Purifiedelements-→t_Final_processing→Element], the principles, learnt form the natural processes can be applied. The key issues are the followings:

- Stoichiometric assembly pattern of goods can support the multi-stage disassembly procedure. In the physical realization, this means that the manufacturers in the assembly process design have to take into consideration also the options of the relatively easy and well-defined disassembly of the parts, containing the rare elements in high concentration. Considering the accompanying information flow, disassembly could also be helped by the detailed and allocable, hierarchical description (ontology and stoichiometry) of the products' composition.
- The irrational diversification of human-synthesized goods ought to be limited, considering the aspects of effective recycling.
- The planning and operation of appropriate recycling needs a continuously updated knowledge about the goods and their assembly ontology (description) for the various storage-representing state elements. Especially the way of goods during the t_Use transition (highlighted by the lower red ellipse in Fig. 6) from the sold products to the Primary_waste needs more care because of their possible unknown accumulation and uncontrolled output.
- The t_Rough preprocessing and the storage of the roughly preprocessed elements (highlighted by the upper ellipse in Fig. 6) have

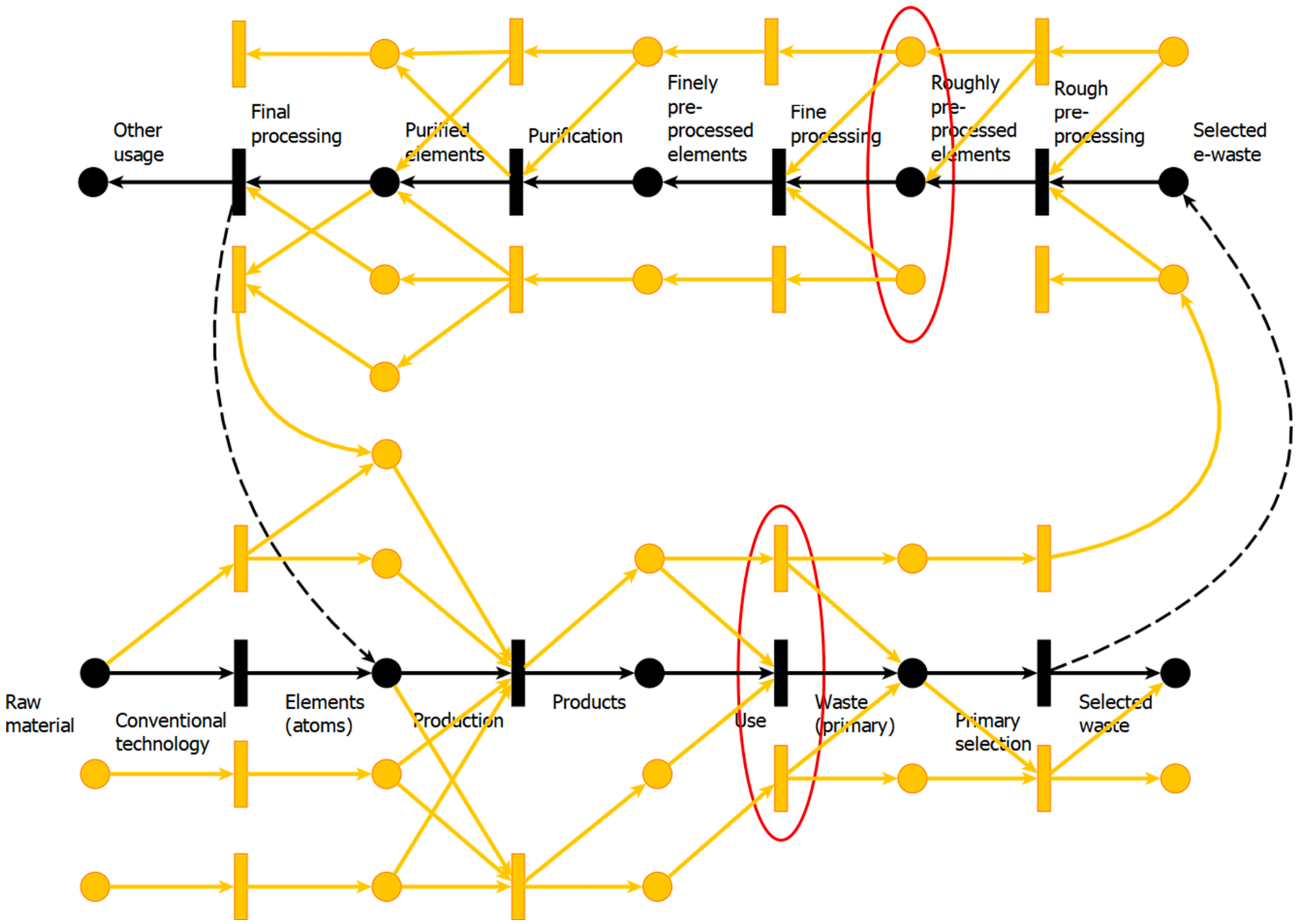

Fig. 6. Simplified assembly and disassembly structure in recycling of rare elements from used electronic devices.

also keynote role. The rough preprocessing is to be started immediately, before the final development of the t_Fine_processing and t_Purification technologies will have been available, because these processes result more concentrated and optionally cheaper raw materials, than the mines (especially if the reasonable mines will be exhausted). However, it is worth to organize large enough storage capacity, where the roughly separated parts are associated with their partial composition stoichiometries. This makes possible to mix large enough different batches of average composition that can be separated and purified, easier.

- Continuous calculation of dynamic component and atom balances has a keynote importance for the systemic planning and operation of the various sub-systems of recycling. Effective fine processing and purification needs an optimization procedure to develop viable preprocessing strategies, which produce those classes of preselected materials that can be selected easier (and with less cost).

The practical realization of the above summarized solutions needs the coupling of material flows and processing with consciously designed information flows and processing. According to the straightforward discussion about the interactions between digitalization and policy by Creutzig et al. (2022), development of circularity science will be supported by digitalization, obviously. Process net structures and Programmable Process Structures are prepared for the effective combination of material and information processing along the digitalized cyclic pathways.

4. Conclusions

Analysis of maximal pathways in the net structure of natural process systems has been applied to derive some essential features of the recycling-based conservation in nature, for their conscious utilization in man-made process systems.

The two classes of maximal pathways, covering the various process nets with overlapping, were the complete transferring pathways from an input to an output element, as well as the complete cycles, carrying conservational measures. Conservational measures were interpreted as the stoichiometric combinations of field- (or model-) specific conservation laws-based constant measures (like atoms in chemical and biological systems). Process nets determine the structure of the transportations and stoichiometric transformations of the case-specific conservational measures.

A novel result of this work is to show the recycling-related conservation-based principles, derived from the structural analysis of transferring and cyclic maximal pathways in natural biosystem and ecosystem, as follows:

- the local open transferring conservational pathways result in cycles at the system level, while the recycling of the conservational measures is driven by the solar radiation;
- the diversified species are built from a restricted pool of fundamental components;

- the sustainable recycling is supported by the structurally coordinated assembly and disassembly processes, coordinated by genetically embedded symmetrical structural patterns;
- the resilient recycling is controlled by the appropriate storage, resulting in average composition, regardless to the changing environmental conditions.

Another novel element is the analysis about how these recycling-related, conservation-based structural features are present and can be implemented in the planning and operation of the man-made processes, consciously. We illustrated the importance and evidence of these principles in simplified process structure examples

- for the carbon emission-free hydrogen energy cycle,
- for the recycling of carrier bags from household waste, as well as
- for the possible organization of assembly / disassembly logistics in electronic waste recycling.

The ultimate ideal objective of Bio-based Circular Economy is the zero exhaustion of finite resources with zero environmental emission, by means of the ideally complete reuse of the already photosynthesized organic and already mined inorganic materials. Accordingly, following the principles of natural assembly / disassembly systems, in the technological solutions the used products have to be decomposed into their primary components, repeatedly. This makes possible the decreasing pollution of atmosphere, soil and water, as well.

Storage has a special role to equalize the composition of the recycling by-products and waste, coming from various processes with seasonal, daily, environmental (e.g., meteorological) and other event-driven fluctuations. Appropriately selected storage results in average composition of recycling raw material for the more effective further processing, especially in the preprocessing and separation of valuable components (e.g., rare earth elements) from the used electronic goods.

To demonstrate the role of dynamic modeling, in the simplified model for recycling of carrier bags from household waste we illustrated how the process net structure can be applied for the generation of unified dynamic simulation models for the recycling conservational processes in the form of Programmable Process Structures.

The increasing complexity in analysis, planning and operation of large scale, long term complex recycling processes requires both a holistic upper-level overview with simplified models, and the consideration of causally transparent, dynamic balances at a lower level. Considering this issue, the future work tends to develop a framework that is capable to connect the holistic overview of up-to-date Life Cycle Analysis (LCA) with the non-linear, dynamic Programmable Process Structures of the underlying processes.

CRediT authorship contribution statement

M. Varga: Conceptualization, Methodology, Software, Formal analysis, Data curation, Visualization, Writing – original draft. **B. Csukas:** Conceptualization, Methodology, Software, Formal analysis, Writing – review & editing. **S. Khanal:** Formal analysis, Writing – review & editing, Visualization. **B.R. Bakshi:** Resources, Formal analysis, Writing – review & editing, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Respective data and information are available in the Supplementary material. Executable model and the auxiliary files will be made available upon request.

Acknowledgement

Research work of Monika Varga was supported by the Bolyai János Research Scholarship of the Hungarian Academy of Sciences.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.resconrec.2023.106919.

References

Arva, P., Csukas, B., 1988. Computer-aided process synthesis by fuzzy valuated structures. Comput. Chem. Eng. 12 (2–3), 215–224. https://doi.org/10.1016/0098-1354(88)85030-0.

Arva, P., Csukas, B. 1989. Synthesis of engineering objects by recursive fuzzy valuation of crisp combinations. Fuzzy Sets and Systems, 32, 13–33, https://doi.org/10.1016/0165-0114(89)90085-7.

Audino, Francesca, Pérez-Moya, M., Graells, M., Espuña, A., Csukas, B., Varga, M., 2020. A novel modeling approach for a generalizable photo-Fenton-based degradation of organic compounds. Environ. Sci. Pollution Res. 27, 22913–22934. https://doi.org/10.1007/s11356-020-08616-4.

Barras, C., 2020. Cyber-spinach turns sunlight into sugar. Nature. https://doi.org/10.1038/d41586-020-01396-4. May 7, 2020.

Batstone, D., Keller, J., Angelidaki, I., Kalyuzhnyi, S., Pavlostathis, S., Rozzi, A., Sanders, W., Siegrist, H., Vavilin, V., 2002. Anaerobic Digestion Model No. 1. IWA Publishing, London.

Biofuture Platform, 2018. Creating the Biofuture: A Report On the State of the Low Carbon Bioeconomy. Available online at. http://www.biofutureplatform.org/post/new-biofuture-report-global-greenhouse-gas-goals-out-of-reach-without-biofuels-and-bioproducts (accessed Nov 11, 2021).

Bisinella de Faria, A.B., Spérandio, M., Ahmadi, A., Tiruta-Barna, L., 2015. Evaluation of new alternatives in wastewater treatment plants based on dynamic modelling and life cycle assessment (DM-LCA). Water Res. 84, 99–111. https://doi.org/10.1016/j.watres.2015.06.048.

Brisson, N., Launay, M., Mary, B., Beaudoin, N., 2009. Conceptual Basis, Formalisations and Parameterization of the STICS Plant Model. QUAE, Versailles. Retrieved from. https://www.nss-journal.org/doc_journal/doc/forest/BR_66_1.pdf.

Chatterjee, A., Brehm, C., Layton, A., 2021. Evaluating benefits of ecologically-inspired nested architectures for industrial symbiosis. Resour. Conserv. Recycl. 167, 105423. https://doi.org/10.1016/j.resconrec.2021.105423.

Christensen, V., Walters, C.J., 2004. Ecopath with Ecosim: methods, capabilities and limitations. Ecol. Modell. 172 (2–4), 109–139. https://doi.org/10.1016/j.ecolmodel.2003.09.003.

Cipolla, G., Calabrese, S., Noto, L.V., Porporato, A., 2021. The role of hydrology on enhanced weathering for carbon sequestration I. Modeling rock-dissolution reactions coupled to plant, soil moisture, and carbon dynamics. Adv. Water Resour. 154, 103934. https://doi.org/10.1016/j.advwatres.2021.103934.

Creutzig, F., Acemoglu, D., Bai, et al., 2022. Digitalization and the Anthropocene. Annu. Rev. Environ. Resour. 47, 479–509. https://doi.org/10.1146/annurev-environ-120920-100056.

Csukas, B., Kozar, Z., Arva, P., 1989. Multicriteria valuated prolog synthesizing algorithms. Comput. Chem. Eng. 13 (4–5), 595–602. https://doi.org/10.1016/0098-1354(89)85043-4.

Debele, S.E., Kumar, P., Sahani, J., Marti-Cardona, B., Mickovski, S.B., Leo, L.S., Porcù, F., Bertini, F., Montesi, D., Vojinovic, Z., Di Sabatino, S., 2019. Nature-based solutions for hydro-meteorological hazards: revised concepts, classification schemes and databases. Environ. Res. 179, 1–20.

Deng, C., Zhang, Y., Bailey, R.T. 2021. Evaluating crop-soil-water dynamics in waterlogged areas using a coupled groundwater-agronomic model, Environmental Modelling & Software, 143, 105130, https://doi.org/10.1016/j.envsoft.2021.105130.

Ellen MacArthur Foundation, 2019. Circular Economy Systems Diagram. Accessed from. https://ellenmacarthurfoundation.org/circular-economy-diagram.

European Commission, 2021. Nature-based solutions in Europe. Eur. Environ. Agency rep. Accessed Nov 25, 2021 from https://ec.europa.eu/info/publications/nature-based-solutions-europe-european-environment-agency-report_en.

Faraca, G., Martinez-Sanchez, V., Astrup, T.F., 2019. Environmental life cycle cost assessment: recycling of hard plastic waste collected at Danish recycling centres. Resour., Conserv. Recyc. 143, 299–309. https://doi.org/10.1016/j.resconrec.2019.01.014.

Feldkamp, N., Bergmann, S., Strassburger, S., 2017. Online Analysis of Simulation Data with Stream-based Data Mining. In: Proceedings of the 2017 ACM SIGSIM-PADS Conference, AVM, pp. 241–248. https://doi.org/10.1145/3064911.3064915.

Gassman, P.W., Reyes, M.R., Green, C.H., Arnold, J.G, 2007. The soil and water assessment tool: historical development, applications, and future research directions. Trans. ASABE 50 (4), 1211–1250. https://doi.org/10.13031/2013.23637.

gPROMS, 1997–2020. Process Systems Enterprise. www.psenterprise.com/products/gproms.

Greasley, A., 2018. Using Analytics with Discrete-Event Simulation. In: SummerSim '18: Proceedings of the 50th Computer Simulation ConferenceJuly 2018, pp. 1–12. Article No.: 13. https://dl.acm.org/doi/10.5555/3275382.3275395.

Hanes, R.J., Bakshi, B.R., 2015. Process to planet: a multiscale modeling framework toward sustainable engineering. AIChE J. 61 (10), 3332–3352. https://doi.org/10.1002/aic.14919.

Hanes, R.J., Gopalakrishnan, V., & Bakshi, B.R. 2018. Including nature in the food-energy-water nexus can improve sustainability across multiple ecosystem services. Resources, Conservation and Recycling, 137, 214–228. https://doi.org/10.1016/J.RESCONREC.2018.06.003.

Henze, M., Grady Jr., C.P.L., Gujer, W., Marais, G.V.R., Matsuo, T., 1987. A general model for single-sludge wastewater treatment systems. Water Res. 21 (5), 505–515.

Holzworth, Dean P., Huth, Neil I., deVoil, Peter G., Zurcher, Eric J., Herrmann, Neville I., McLean, Greg, Chenu, Karine, et al., 2014. APSIM – Evolution towards a New Generation of Agricultural Systems Simulation. Environ. Modell. Software 62, 327–350. https://doi.org/10.1016/j.envsoft.2014.07.009.

Huynh, Q.N., 2016. CoModels: Engineering Dynamic Compositions of Coupled Models to Support the Simulation of Complex Systems. Pierre and Marie Curie University. Doctoral ThesisAvailable from. https://tel.archives-ouvertes.fr/tel-01544874/document.

Hynes, S., Burger, R., Tudella, J., Norton, D., Chen, W., 2022. Estimating the costs and benefits of protecting a coastal amenity from climate change-related hazards: nature based solutions via oyster reef restoration versus grey infrastructure. Ecol. Econ. 194, 107349 https://doi.org/10.1016/j.ecolecon.2022.107349.

Izquierdo, J., Sànchez-Marrè, M., Hamilton, S.H., Rodríguez-Roda, I., & Holmes, G. 2018. Which method to use? An assessment of data mining methods in environmental data science. environ. model. software, 110, 3–27. https://doi.org/10.1016/J.ENVSOFT.2018.09.021.

Johnson, O.A., Hall, P.S., Hulme, C., 2016. NETIMIS: dynamic Simulation of Health Economics Outcomes Using Big Data. Pharmacoeconomics 34 (2), 107–114. https://doi.org/10.1007/s40273-016-0384-1. PMID: 26879667.

Kamilaris, A., Kartakoullis, A., Prenafeta-Boldú, F.X., 2017. A review on the practice of big data analysis in agriculture. Comput. Electr. Agric. 143, 23–37. https://doi.org/10.1016/J.COMPAG.2017.09.037.

Keesstra, S., Nunes, J., Novara, A., Finger, D., Avelar, D., Kalantari, Z., Cerdà, A., 2018. The superior effect of nature based solutions in land management for enhancing ecosystem services. Science of The Total Environment 610–611, 997–1009. https://doi.org/10.1016/j.scitotenv.2017.08.077.

Kumar, P., et al., 2021. Nature-based solutions efficiency evaluation against natural hazards: modelling methods, advantages and limitations. Science of The Total Environment 784, 147058. https://doi.org/10.1016/j.scitotenv.2021.147058.

Lan, K., Yao, Y., 2019. Integrating Life Cycle Assessment and Agent-Based Modeling: a Dynamic Modeling Framework for Sustainable Agricultural Systems. J Clean Prod 238, 117853. https://doi.org/10.1016/j.jclepro.2019.117853.

Langemeyer, J., Baró, F., 2021. Nature-based solutions as nodes of green-blue infrastructure networks: a cross-scale, co-creation approach. Nature-Based Solutions 1, 100006. https://doi.org/10.1016/j.nbsj.2021.100006.

Liquete, C., Udias, A., Conte, G., Grizzetti, B., Masi, F. 2016. Integrated valuation of a nature-based solution for water pollution control. Highlighting hidden benefits, Ecosystem Services, 22(Part B), 392–401, https://doi.org/10.1016/j.ecoser.2016.09.011.

Lotka, A.J., 1925. Elements of Physical Biology. Williams & Wilkins Company, Baltimore. Accessed at 01/05/2023 from. https://archive.org/details/elementsofphysic017171mbp.

Marvuglia, A., Bayram, A., Baustert, P., Navarrete Gutiérrez, T., Igos, E., 2022. Agent-based modelling to simulate farmers' sustainable decisions: farmers' interaction and resulting green consciousness evolution. J Clean Prod 332, 129847. https://doi.org/10.1016/j.jclepro.2021.129847.

Michal, G., 1999. Biochemical Pathways. An atlas of Biochemistry and Molecular Biology. John Wiley & Sons, New York.

Michal, G., 2014. Biochemical Pathways. F. Hoffmann-La Roche Ltd. Available from. http://biochemical-pathways.com/#/map/2.

Miranda, P.E., 2018. Science and Engineering of Hydrogen-Based Energy Technologies: Hydrogen Production and Practical Applications in Energy Generation. Academic Press.

Namany, S., Govindan, R., Alfagih, L., McKay, G., Al-Ansari, T., 2020. Sustainable food security decision-making: an agent-based modelling approach. J Clean Prod 255, 120296. https://doi.org/10.1016/j.jclepro.2020.120296.

Petri, C.A., Brauer, W., 1980. Introduction to general net theory. In: Net Theory and Applications. Lecture Notes in Computer Science, 84. Springer, Berlin, Heidelberg.

Schmid, B., 2016. Decision-Making: are Plants More Rational than Animals? Current Biology 26 (14), R675–R678. https://doi.org/10.1016/j.cub.2016.05.073.

Shao, Y., Zhu, H., Wang, R., Liu, Ying, Liu, Yusheng., 2020. A simulation data-driven design approach for rapid product optimization. J. Comput. Inf. Sci. Eng. 20 (2), 021008 https://doi.org/10.1115/1.4045527. Paper No: JCISE-19-1176.

Sharif, B., Vik, S.l., Marshall, D.A., 2018. Applications of Big Data Analytics within a Dynamic Simulation Modeling Platform to Inform Osteoarthritis Care in Alberta. International Journal of Population Data Science 3 (3), 451. https://doi.org/10.23889/ijpds.v3i4.1035.

Sterner, T., Barbier, E.B., Bateman, I., et al., 2019. Policy design for the Anthropocene. Nat Sustain 2, 14–21. https://doi.org/10.1038/s41893-018-0194-x.

Suh, S., 2004. Functions, commodities and environmental impacts in an ecological–economic model. Ecol. Econ. 48 (4), 451–467. https://doi.org/10.1016/j.ecolecon.2003.10.013.

Tate, W.L., Bals, L., Bals, C., Foerstl, K. 2019. Seeing the forest and not the trees: learning from nature's circular economy. Resources, Conservation & Recycling, 149: 115–129. https://doi.org/10.1016/j.resconrec.2019.05.023.

Thakker, V., Bakshi, B.R., 2021a. Designing Value Chains of Plastic and Paper Carrier Bags for a Sustainable and Circular Economy. ACS Sustain. Chem. Eng. 9, 16687–16698. https://doi.org/10.1021/acssuschemeng.1c05562.

Thakker, V., Bakshi, B.R., 2021b. Toward sustainable circular economies: a computational framework for assessment and design. J. Clean. Prod. 295, 126353 https://doi.org/10.1016/j.jclepro.2021.126353.

US Army Corps of Engineers, 2013. Coastal Risk Reduction and Resilience. Directorate of Civil Works, US Army Corps of Engineers, Washington, DC. CWTS 2013-3Retrieved from: http://sagecoast.org/docs/sci_eng/USACE_Coastal_Risk_Reduction_final_CWTS_2013-3.pdf.

Varga, M., 2007. A mitokondrium és a kloroplaszt modellezésének összehasonlító elemzése és tanulságai (Model-based comparative analysis of mitochondria and chloroplast), in Hungarian. Acta Agraria Kaposvariensis 11 (2), 249–258. https://journal.uni-mate.hu/index.php/aak/article/view/1886.

Varga, M., Azzaro-Pantel, C., Flores-Perez, J.M., Csukás, B., 2019. Programmable process structure based analysis of hydrogen supply chains. Hungarian J. Industry Chem. 47 (2), 53–61. https://doi.org/10.33927/hjic-2019-20.

Varga, M., Berzi-Nagy, L., Csukas, B., Gyalog, G. 2020. Long-term dynamic simulation of environmental impacts on ecosystem-based pond aquaculture. ENVIRONMENTAL MODELLING & SOFTWARE (1364-8152): paper 104755. https://doi.org/10.1016/j.envsoft.2020.104755.

Varga, M., Csukas, B., 2017. Generation of extensible ecosystem models from a network structure and from locally executable programs. Ecol. Modell. 364, 25–41. https://doi.org/10.1016/j.ecolmodel.2017.09.014.

Varga, M., Csukas, B., 2018. Meta-modeling of Hydrogen Supply Chains: a Programmable Structure based representation. In: Azzaro-Pantel, Catherine (Ed.), Hydrogen Supply Chain: Design, Deployment and Operation. Academic Press Inc. Elsevier Science, UK, London, pp. 461–497, 588.

Varga, M., Gyalog, G., Raso, J., Kucska, B., Csukas, B., et al., 2021. Programmable Process Structures of Unified Elements for Model-Based Planning and Operation of Complex Agri-environmental Processes. In: Bochtis, Dionysis, et al. (Eds.), Springer Optimization. Chapter 11. Information and Communication Technologies for Agriculture—Theme III: Decision, 978-3-030-84151-5, 483069_1_En.

Varga, M., Prokop, A., Csukas, B., 2017. Biosystem models, generated from a complex rule/reaction/influence network and from two functionality prototypes. Biosystems 152, 24–43. https://doi.org/10.1016/j.biosystems.2016.12.005.

Veintimilla-Reyes, J., De Meyer, A., Cattrysse, D., Tacuri, E., Vanegas, P., Cisneros, F., Van Orshoven, J., 2019. MILP for optimizing water allocation and reservoir location: a case study for the Machángara river basin. Ecuador. Water (Switzerland) 11 (5). https://doi.org/10.3390/w11051011.

van den Bergh, 2020. Six policy perspectives on the future of a semi-circular economy. Resources, Conservation and Recycling. 160, 104898. https://doi.org/10.1016/j.resconrec.2020.104898.

Varga, M., Csukas, B., 2022. Foundations of Programmable Process Structures for the unified modeling and simulation of agricultural and aquacultural systems. Info. Processing in Agric., in press, j. pre-proof. https://doi.org/10.1016/j.inpa.2022.10.001.

Venkata Mohan, S., Dahiya, S., Amulya, K., Katakojwala, R., Vanitha, T.K., 2019. Can circular bioeconomy be fueled by waste biorefineries — A closer look. Bioresour. Technol. Rep. 7, 100277 https://doi.org/10.1016/j.biteb.2019.100277.

Yang, H., Csukas, B., Varga, M., Kucska, B., Szabó, T., Li, D., 2019. A quick condition adaptive soft sensor model with dual scale structure for dissolved oxygen simulation of recirculation aquaculture system. Comput. Elect. Agr. 162, 807–824. https://doi.org/10.1016/J.COMPAG.2019.05.025.

Yao, T., Geng, Y., Sarkis, J., Xiao, S., Gao, Z. 2021. Dynamic neodymium stocks and flows analysis in china. resources, conservation & recycling. 174, 105752. https://doi.org/10.1016/j.resconrec.2021.105752.

Zeng, X., Li, J., 2021. Emerging anthropogenic circularity science: principles, practices, and challenges. iScience 24 (3), 102237. https://doi.org/10.1016/j.isci.2021.102237.

Zeng, X., Ogunseitan, O.A., Nakamura, S., Suh, S., Kral, U., Li, J., Geng, Y., 2022. Reshaping global policies for circular economy. Circ. Econ. 1 (1), 100003 https://doi.org/10.1016/j.cec.2022.100003.

Zeng, X., 2023. Win-Win: anthropogenic circularity for metal criticality and carbon neutrality. Front. Environ. Sci. Eng. 17 (23) https://doi.org/10.1007/s11783-023-1623-2.