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Ecological design of a production plant

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ABSTRACT

The concepts and solutions of sustainability, resource efficiency, and waste-free production are increasingly influencing our thinking, policy guidelines, and corporate strategies. However, some strategies extend beyond conventional sustainable approaches by embracing the fundamental operating principles of ecosystems. In this context, resilience—a natural risk management strategy—is incorporated into the design of a manufacturing company, considering all types of material flows, including solid, liquid, gaseous, and thermal. This ecological approach to resilience is applied to both the operational and financial aspects of the company, via concurrent analysis.

Results indicate that merely achieving zero waste emissions does not ensure sufficient resilience, a core requirement of ecosystems and a fundamental principle of the blue economy. Furthermore, it is found that a production system with a flexible product portfolio can adapt into a more ecologically resilient system, despite technological constraints. The resilience level of the production system in ecological and financial terms is similar. Several types of sensitivity analyses are conducted to deepen the insights into the processes.

1. Introduction

A manufacturing company can strive for sustainability in many ways. The materials used, the products produced, and social responsibility are all areas that can be transformed to facilitate this process. The solutions can reflect the possibilities, decision-makers' mindsets, and requirements of natural-ecological systems. There are several indicators that a manufacturing company can use to measure and assess sustainability. The Organization for Economic Co-operation and Development (OECD) lists several of these indicators such as non-renewable materials intensity, recycled/reused content, energy intensity, greenhouse gas intensity, recyclability, etc.… (OECD, 2024). However, there exists a more comprehensive and holistic method compared to the listed individual indicators because that integrates various dimensions into a unified framework and produces a system-level, resilience indicator, with which a system structure can be compared with the structure of resilient ecological systems. This indicator, which Lietaer et al. (2012), Ulanowicz (2009, 2014), and Ulanowicz et al. (2009) recommend, shows an organization's internal relationship and robustness. The indicator is calculated from an input-output table, using information theory elements, focusing on ecosystems. The main framework of this methodology is the Ecological Network Analysis (ENA). ENA is a holistic sustainability measurement (Kharrazi et al., 2013) that is already of general application used in several areas, such as in the modelling of cities (Bodini et al., 2012; Kiss and Kiss, 2018) or in economics, e.g. in the supply chain (Allesina et al., 2010). Goerner et al. (2009) also draw attention to the importance of the methodology in the economy. Based on the above, ENA is a standard and generally used method; the novelty of this paper lies in its unique application area.

This study uses the ENA methodology to make a production plant - in this case, a juice processing plant - resilient. The application is executed through the material flow of three possible implementations of the production process: a very detailed, an aggregated, and a simplified version. In all cases, there is a strive for zero waste emission, which is also the principle of industrial ecology or, among the theories developed in the new millennium, the circular and the blue economy. This study supports that only a plant with a sufficiently large number of activities is resilient in an ecological sense, that complies also with the principles of the blue economy.

Since profitability must also be considered in a business context, particularly because it is not strongly connected to the resilient money flow between the different business units. For this reason, a comparison

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is made between material and financial resilience.

The structure of the paper is as follows: First, the concept of resilience, and two prevailing theories of sustainability - the blue economy and the circular economy - are briefly overviewed. This part establishes the importance of using ecological principles in the economy. Second, the applied methodology is introduced, followed by a discussion of its application at a production company. Afterward, an extended sensitivity analysis is executed to deepen the knowledge of the system's behaviour with some important insights. A conclusion chapter with the potential shortcomings and further research plans closes the study.

2. Blue versus circular economies

Jaehn (2016) – among others – discusses the application of sustainable development in production systems. According to the author, sustainable production includes trends supporting resource efficiency and addressing the negative environmental challenges posed by economic growth. There are many trends in sustainable production. Friant et al. (2020) collected twenty contested paradigms; however, the present study only focuses on two characteristic trends: the *circular economy*, a mainstream approach toward sustainability, and the ecology-oriented *blue economy*.

Mainstream economics attempted to implement sustainability through environmental economics (Krishnan et al., 1998, p. Xxxv). They tried to incorporate the market valuation of environmental factors to allow using natural goods in economic models. However, according to ecological economists, more extensive efforts are needed to address the acute problems of our time. As an alternative, a methodology was developed which starts from the ground of biophysical realities (Krishnan et al., 1998, p. Xxxv, Common and Stagl, 2005), an approach also used by the blue economy (see below). Despite worldwide sustainability efforts, the socio-economic world has not yet transformed into a sustainable one. The Steffen et al. (2015) study found that we have already crossed significant sustainability boundaries of the planet, and according to Lovelock (2006), these transgressions are irreversible. This realization has led to a recent rise in resilience research (e.g., Janssen et al., 2006).

Resilience is a multi-dimensional concept (Alessi et al., 2020; Martini, 2020), with more approach. Ecological resilience (Holling, 1973) emphasizes the importance of measuring the ability to absorb shocks. The engineering concept of resilience is to measure the rate at which a system returns to equilibrium (Pimm, 1984; Alessi et al., 2020; Folke et al., 2010). A type of combined approach is adaptive resilience which refers to the ability to adapt, learn, and reorganize the system according to the changes in its environment (Alessi et al., 2020; Scheffer, 2009). An ecological system should be capable of handling all aspects of resilience with an appropriate structure. As Ulanowicz (2009) supports: a complex system responds to random events through feedback loops. This approach is used in this study. In socio-economic systems in general, aggregated composite indicators are used for measuring resilience, like the resilience dashboard of the European Commission (Commission, 2021) with the aggregation of 120, and the Economic Resilience Index (ERI, Hafele et al., 2023), with 27 variables.

The duality of approaches can be seen in subsequent theories, namely in the blue and circular economies underlying this study, where the blue economy favors the ecological, whilst the circular economy aligns more with the environmental economics approach. Resilience research is a direction toward the ecological approach.

2.1. The blue economy

The concept of the blue economy (BE) was introduced by Gunter Pauli (2010) in his report to the Club of Rome. Its purpose was to create an economy in harmony with the blue planet (Pauli, 2010, p. 278). In this approach, ecosystems form the foundation of the super-structure, the blue economy itself. The main principles of the BE are summarized in Pauli (2017, pp. 1-41). Below, we highlight the most important features from the perspective of this study. The BE principles clearly reflect nature's influence, such as in Principle 2.4: "The blue economy first and foremost steers innovation and entrepreneurship towards initiatives that respond to the basic needs of all with whom we share life on this planet." (Pauli, 2017). Since the entire blue economy concept is based on the consideration of nature and ecological systems (Nature is the Master, Principle 1.1), the whole concept is strictly system based. Many principles relevant to this study refer to system properties, such as systemic behaviour that cascades nutrients, matter and energy in a manner that eliminates waste, since any by-product becomes the source of a new product. In practice this means nested cycles within the common ecological-economics system, including material and energy, using primarily local resources. These systems prioritize economies of scope, not economies of scale (Principle 3.1). Therefore, competitiveness has different roots in these systems: one process generates multiple benefits and the materials and energy used are further utilized in the system, thus reducing the unit price. The latter approach is common in both economies of scope and scale. Other principles (e.g. Principle 1.2) highlight the risk-sharing nature of these systems and the optimal rather than the maximal use of the incorporated factors for the benefit of all. There are attempts toward the ecological orientation, considering blue economy principles. Brad et al. (2016) proposed a method for transitioning to the blue product design and Bogdan et al. (2014) suggested a practical approach to bridging the green and blue economies.

These principles clarify that the blue economy fundamentally built upon ecosystems, which can be seen as sophisticated "technologies"; long-lasting evolutionary developments that abide by natural laws. These systems have robust functionality: everything has its cause and purpose, and their diversity provides adaptability. The innovations selected for the blue economy (see the 100 innovations by Pauli, 2010), are characterized by their reproducibility, material and energy conservation, and their ability to operate without waste or pollutant emissions. Local conditions (available cheap resources, local regulations) are used efficiently and harmoniously and consist of small, interconnected cycles that form part of a larger, infinite cycle.

2.2. The circular economy

The circular economy (CE) now has a vast literature, both from a scientific and a practical point of view (for theoretical summary work, see Korhonen et al., 2018; Martins, 2016, and for practical applications, see, e.g. Fogarassy et al., 2016). The European Academies' Scientific Advisory Council (EASAC), a body of academies of sciences from the Member States of the European Union, has also produced comprehensive reports (EASAC, 2016a, 2016b, 2016c) on the circular economy.

The rapid spread of CE is largely explained by the resource scarcity (in China, CE is the most prevalent method (Ghisellini et al., 2016)). Some materials are only available in the "very critical" range, for example, prazeodymium, eodymium, dispersion, gallium or tellurium (EASAC, 2016b, tTable 2.1). The scarcity of resources increases the need to review recycling practices to date and introduce new theories and procedures. As the concept was primarily triggered by the lack of resources, many people view circular economy as a modern form of waste management (Ghisellini et al., 2016). However, Geissdoerfer et al. (2017, p. 759) argue that the circular economy is more than waste management: "…a regenerative system in which resource input and waste, emission, and energy leakage are minimized by slowing, closing, and narrowing material and energy loops. This can be achieved through durable design, maintenance, repair, reuse, remanufacturing, refurbishing, and recycling."

The CE appears to be a waste-free economic process, which aligns with only one of the principles of the blue economy, involving the flow of materials and energy with minimum loss. Clube and Tennant (2020) note that CE neglects radical, human-centric transformational aspects and follows the pathway of business-led economic growth. Despite these statements, CE has become extremely valuable due to its scope: it can be used for production processes that give rise to Steffens' "border crossings" and permeate our current economy. Reducing the impact of the main industrial processes is of utmost importance. Table 1 shows a comparison of the BE and the CE, using only the main important features.

In summary, aligning closely with ecological systems is the main feature of the blue economy, a goal not shared by the circular economy. From a different perspective, merely being circular is not enough to meet the basic needs of all (Principle 2.4). The main ecological principles should underpin the development of economic systems. Resilience is an important feature of these systems, which is a main indicator of the methodology employed in this paper. Therefore, designing and constructing resilient production plants could embody the most vital attributes of long-lasting, sustainable systems.

3. Methodology

Research regarding the permanent properties related to the development and growth of systems has been ongoing for a long time. Goerner et al. (2009) give a summary of this research supporting the idea that ecological and economic systems have the same laws of growth and development. Ulanowicz (2009) conducted a comprehensive study asserting that Ecosystem Network Analysis (ENA) can capture a general law. ENA has already integrated findings from various disciplines, such as physics and information theory, including the seminal work of Shannon (1948) According to this research, the efficiency increase (by positive feedback loops) and entropy (toward redundancy) together result in a dynamic balance within a system. As a result, an optimum is achieved through the mutual coexistence of these two processes, where the balance point can be identified within the system structure by ENA indicators. We adapt these indicators with which the robustness and resilience of an ecological system can be demonstrated. Input-output analysis developed by Leontief has been an integral part of the ENA and has been used in ecology since the 1960s, where research tailored to ecosystems continues to refine the methodology (see e.g. the works of Ulanowicz in the list of references).

3.1. A point of harmony

A point of harmony, which we call the resilience indicator of ENA, is proven by studies on ecosystems to show the optimum of the dynamic balance within the system. It is not good for a system to have a high degree of freedom, i.e., to be too redundant because then it lacks the organizing principle that moves and makes the whole system work. However, it is also disadvantageous for a system to be very efficient, as it loses the ability to adapt to changes in external conditions - to be resilient. The number and quality of the relationship between the elements within a system (internal structure) already carry some information. The numerous connections between the system elements indicate redundancy. In contrast, an overly constrained, efficient system is characterized by having only the necessary minimum level of connections between the elements.

The description of the process is represented by a graph using the language of discrete mathematics. The nodes represent the process quantities that flow into and out of the system element – we call this piece of flow as an event –, while edges link the related process quantities to each other. Like all graphs, this graph can be organized into a Leontief input-output table. The basis of ecological network analysis is the process of a system with n elements, where one designates the flow (of energy, money, material) from one element i (e.g. from species, industries) to another element, j, as T_{ij} and the total flow is $T..$, the total turnover of the system, where the dots denote summations. $T..$ is equivalent to $\sum_{ij} T_{ij}$. The cited references use both types of notations, even in a mixed form as in (4). For the sake of consistency with existing literature we also use both. This input-output table has all exogenous inputs (energy, imports) to the system in the last row and all outputs (a sink or export) out of the system in the last column. The whole starting table is, therefore, a $n + 2$ element matrix. With this type of table, one can describe the trophic flow of an ecological system; a country's economic system, where money flows from one industry to another, or a production plant, where the material flows from one working process to another one. Sometimes – as in our study – there are two output columns: one for the system waste and one for the usable products.

This matrix format follows the requirements of an input-output matrix, where p_{ij} is the probability of the occurrence of the events, determined by its size, related to the total sum of all events: $p_{ij} = T_{ij}/T..$. The higher this probability is, the more expected (or less unexpected) its occurrence, and this system event is more significant. An example: In the service industry, "providing service" has a high probability, which is not a surprise; however, "producing products" might be less probable and a bigger surprise. The less expected an event, the greater the surprise (s_{ij}) if it occurs. If such events characterize a system predominantly, then it can be rather redundant, i.e., several events serving the same purpose run in parallel. Some of that activity is redundant in a village with several honey producers, so competition might eventually drive smaller producers out of the market. The value of s_{ij} can be expressed by an indicator introduced by Boltzman (Ulanowicz et al., 2009), calculated by the logarithm of the probability of occurrence of the event:

$$s_{ij} = -k\log\left(p_{ij}\right) \tag{1}$$

where k is a positive constant term that can provide the appropriate dimension for a given event; it has no role in this study. The example of ecosystems shows that maintaining resilience requires a balance between the appropriate levels of freedom and efficiency. Mathematically, this problem can be solved by a so-called uncertainty indicator (h) that allows both directions to prevail. The uncertainty of an event is as follows:

$$h_{ij} = -kp_{ij}\log\left(p_{ij}\right) \tag{2}$$

where -log(p_{ij}) means how much of a surprise (s_{ij}) it would be to encounter this event; k is as in (1). The minus sign offsets the negative logarithm values (the p_{ij} -s are below one).

Summarizing the uncertainty index of each event, the (macro-state) uncertainty index for the whole system:

$$H = -\sum_{ij} kp_{ij}\log\left(p_{ij}\right) \tag{3}$$

The figure below shows the relationship between s, p, and h.

Table 1
Some of the most relevant differences between the circular and blue economy.

Features	CE	BE
Origin	Economy	Ecosystems
Scope	The whole economy	Mainly local
Cost advantages	Economies of scale	(mainly) Economies of scope
Structure	Waste removal from a polluting structure mainly with help of other industrial linkages.	Nature-like new structure with nested cycles (therefore, waste-free solutions).

From this, it can be seen that a certain event ($p = 1$) means neither surprise nor uncertainty since $h = s = 0$. If $p = 0$, the expected event does not occur, the surprise is maximal, but the product in (2) is also zero here. The uncertainty index reaches its maximum value at $p = 1/e$, regardless of the logarithm of any basis (with different values). In conclusion: An event must be sufficiently present to play a significant role in the system's operation yet there must also be space for creativity, the opportunity for change, and spontaneity. The figure also shows that the system must be closer to redundancy, creativity than full regulation to reach the optimal value, a kind of resilience. Thus, the maximum of the h-curve (see Fig. 1) can also be considered a certain point of harmony.

The expected probability for the *ij* events (p_{ij}^{ind}) can be determined by the product of the row and column total of the probabilities of events ($p_{i.}{}^{*}p_{.j}$), where the dots also represent the summations. The expected probability means independence from both (*i, j*) elements (compartments, industries, activities); none has more influence on the given connection. If p_{ij} is greater than p_{ij}^{ind}, this connection between the compartments or business units is greater than expected and more regulated with established customs, rules, and technological connections. If the value is lower than p_{ij}^{ind}, there is room for developing this connection. This independent probability's surprise value (s_{ij}^{ind}) can also be calculated (as in (1)). The level of regulation can be expressed as $x_{i|j} = s_{ij}^{ind}$ -s_{ij}, – where $x_{i|j}$ measures the constraint that *i* exerts on *j* - and the weighted sum of the average system-wide regulation and limit values (X) can be obtained using the following formula (Ulanowicz et al., 2009):

$$X = \sum_{ij} p_{ij} x_{i|j} = k \sum_{ij} p_{ij} log\left(\frac{p_{ij}}{p_{i.}\,p_{.j}}\right) \tag{4}$$

The most important indicator, α (which is the resilience indicator used in this paper), is the ratio of the already regulated part and the total capacity of the system, calculated in (3):

$$\alpha = \frac{X}{H} \tag{5}$$

In the case of full regulation, this value can also be 1, which is equivalent to a fully automated system. Such a system cannot change or react in the event of a malfunction. Ulanowicz (2009, Fig. 6) has shown that ecosystems are never so efficient that they cannot respond to unexpected situations. It is important to have a high degree of redundancy and parallel activities that make the system resilient. For matured ecological systems with many nodes, a typical α value is around 0.4 (Ulanowicz, 2014).

Ulanowicz et al. (2009), in their ecological example, illustrated the carbon turnover in the food chain in quantity between ecological compartments (T_{ij}). The total carbon throughput gave the total throughput of the system ($T..$), and the relative carbon content ($T_{ij}/T..$) transfers gave the p_{ij} values. In practical applications, one must always find an equivalent physical characteristic of the carbon turnover that is suitable for representing the whole process, such as money flow in economic systems.

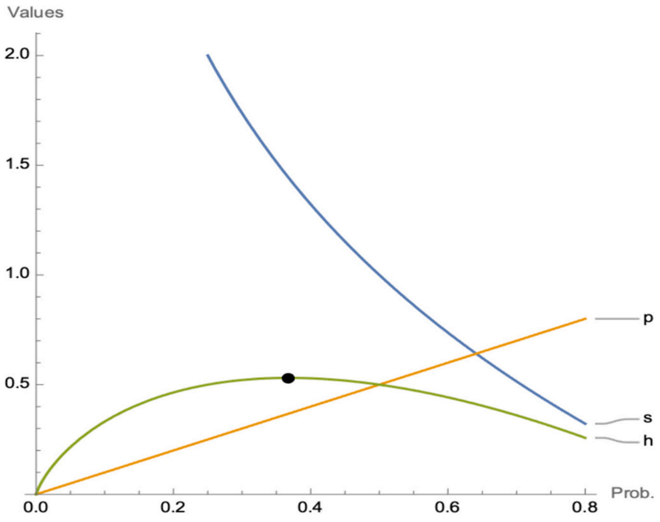

Fig. 1. Surprise index (s), probability index (p), and uncertainty index (h).

3.2. Robustness

The farther to the right the actual α value of the system is from the optimal point (representing the point of harmony), the more efficient the system is. In order to construct a robustness measure, the value of α is subjected to the same transformation as the probabilities, allowing α to be expressed as a value between 0 and 1. Thus, an optimum (*Fs*, the maximum of *h* in Fig. 1) can be obtained that best reflects the survival capacity of the system (from Ulanowicz et al. (2009), using natural logarithm):

$$Fs = -e\alpha^{\beta} ln\left(\alpha^{\beta}\right) \tag{6}$$

Here, *e* is used instead of *k*, for normalization to 1. The value of β in the exponent allows the optimum to be adjusted to the optimal value characteristic of different systems. In the study, we set the optimal α value to 0.4 (see above, as the value of matured ecological systems), that results in β of 1.0913.

The robustness of the system is also expressed by Ulanowicz (2014) by converting the value of *Fs* back to the original order of magnitude $R = Fs{}^{*}T...$ *R* is a very important structure indicator, e.g., to present the changes needed to design the optimal system. To do this, *R* is derived from each T_{ij} value to obtain values that show how and in what direction each T_{ij} value must be changed for the system to move toward the optimum (r_{ij}). The method of calculation is as follows (Ulanowicz, 2014):

$$r_{ij} = \frac{\partial R}{\partial T_{ij}} = Fs + \frac{T..Fs'}{C}\left\{ln\left[\frac{T_{ij}T..}{T_{i.}T_{.j}}\right] + \alpha ln\left[\frac{T_{ij}{}^{2}}{T_{i.}T_{.j}}\right]\right\} \tag{7}$$

where

$$Fs' = -e\beta\alpha^{\beta-1}\left[ln\left(\alpha^{\beta}\right) + 1\right] \tag{8}$$

and

C is the full capacity of the system: $T..{}^{*}H$.

Each *rij* value shows the direction in which it is worthwhile to develop the existing relationships toward building an optimal, robust system. The optimal α value plays a role here because the *rij*-values should be interpreted in relation to this.

3.3. Analytical toolbox of structure

In a system, nodes (compartments, production units) and relationships (edges, links or flows), create a system of relationships. Zorach and Ulanowicz (2003) outline a methodology to examine the system from these perspectives. The following indicators are developed for analysing a system, called network functions. The number of nodes (N = nodes) and their connections (F = flow) show the system's operation. These determine an average connection level (C = connections) with a simple arithmetic mean of $C = F/N$, which means the number of the average connections of one node. This level of connection is the extent, "breadth," of the system. If all participants do only their work (one input and one output for each N system element), then there is one flow for and one from each element, so the breadth of the system is only one. It is possible to determine how many roles the given system plays ($R = N/C$ = roles). This indicator expresses the "depth" of the system. In the case of two industries, agriculture, and service, if agriculture transfers products to the service industry, which provides services to the agricultural industry, then $N = 2$, $F = 2$, $C = F/N = 1$ (both industries have one connection) and $R = N/C = 2$ that is within the system two roles are separated. In economic systems, the more vertically interdependent the supply chains are, the greater the system's depth.

However, weighting is important for a complex system because the strength of the relationships can significantly modify the value of a given indicator. Zorach and Ulanowicz (2003) calculated the weighted indicators as follows:

$$C = \prod\nolimits_{i,j} \left(\frac{T_{ij}^2}{T_{i.}\ T_{.j}} \right)^{-\frac{1}{2}\cdot\frac{T_{ij}}{T_{..}}}$$

$$N = \prod\nolimits_{i,j} \left(\frac{T_{..}^2}{T_{i.}\ T_{.j}} \right)^{\frac{1}{2}\cdot\frac{T_{ij}}{T_{..}}}$$

$$F = \prod\nolimits_{i,j} \left(\frac{T_{ij}}{T_{..}} \right)^{-\frac{T_{ij}}{T_{..}}}$$

$$R = \prod\nolimits_{i,j} \left(\frac{T_{ij}T_{..}}{T_{i.}\ T_{.j}} \right)^{\frac{T_{ij}}{T_{..}}} \tag{9}$$

The weights are based on the importance of the nodes, which is calculated by the geometric means of the in- and outflows, compared to the total turnover ($T_{..}$). N is the weighted number of efficient nodes, F is the weighted flow value, C is the weighted relationship value of the system, and R is the number of roles in the system based on the weighted values. These indicators/network functions are used to characterize the apple juice plant plans.

4. Application

4.1. An apple juice production plant

The plan of a zero-waste apple juice plant was analysed using the measurement tools described above. Traditionally, the apple juice plant produces juice and waste with four activities. These activities are washing, pressing, pasteurization and packaging. Both in the blue and circular economy, a company uses its by-products in addition to external resources where possible. From now on, products intended for sale are referred to as end-products, and products reused in production as intermediate products will be called by-products. Products that are no longer suitable for use in the given production process, are also named by-products, indicating that they can be used in other production processes. Implementing the zero-waste principle and the blue economy approach allows us to create a system where the company (plant) can use the vast majority of the by-products generated during production, similar to an ecosystem. All the matrices correspond to a static, simultaneous (Zalai, 2012) input-output matrix; their row and column sums are equal, ensuring that incoming materials are fully traced. We apply three methods for describing the system processes: a very detailed one suitable for discrete event programming, which is a technical approach; one that focuses only on the main structural elements, usable for both CE and BE purposes; and a very reduced version, which is a solution only for CE. The description of these versions is as follows.

4.1.1. A full process-oriented version

A process description based on the process-oriented modelling principle for this type of plant is shown in Fig. 2 and the same processes

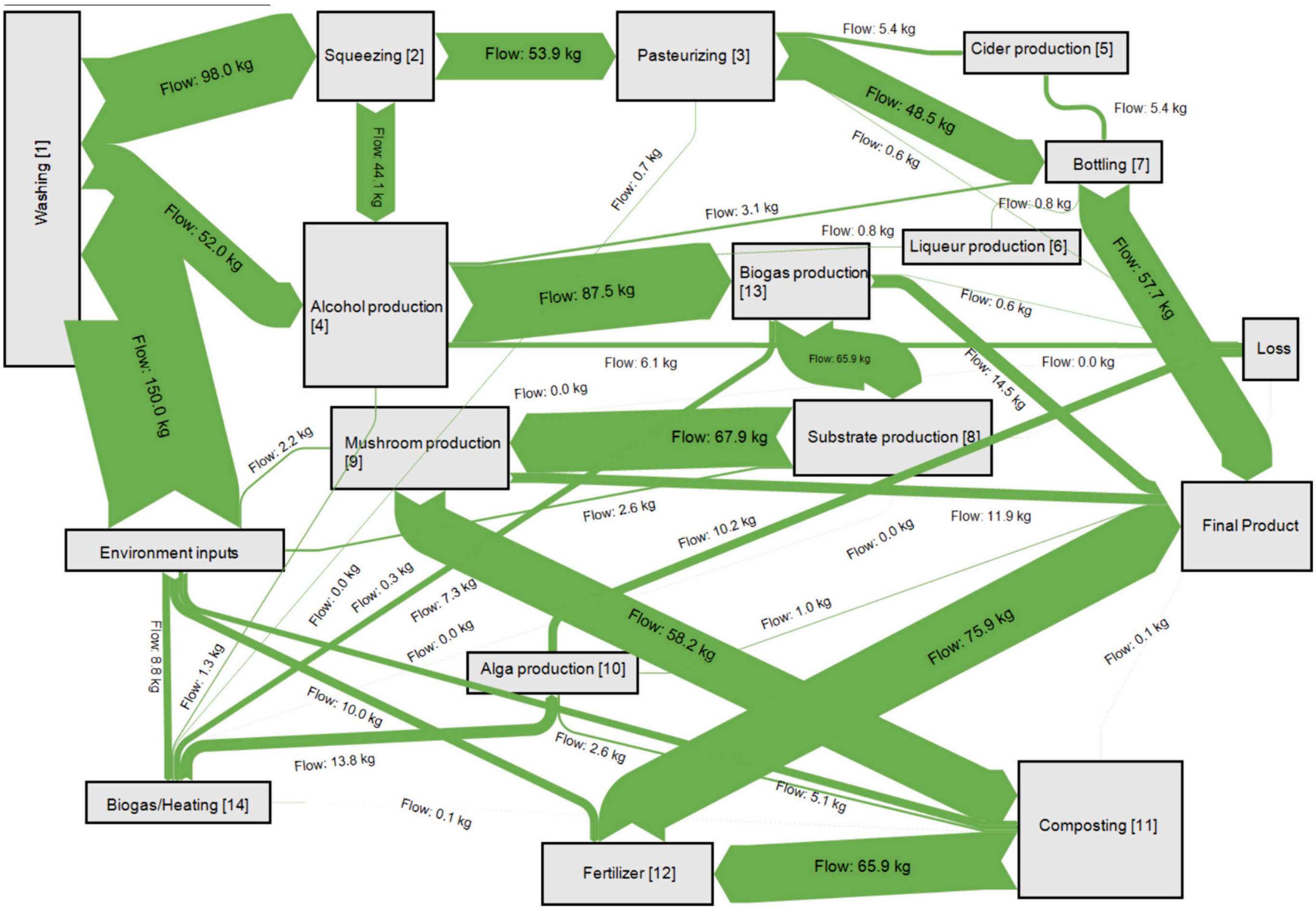

Fig. 2. The Sankey diagram of the full juice production system.

are listed in Table 2.

In Table 2, each sub-element can be followed. It is important to measure the flow process in natural terms. An example is waste, which is worthless but greatly impacts the environment. The environment is once listed as an input in one row, in row 15. In the columns, the output part is divided into two parts: loss and final products in Columns 15–16, where the loss directly impacts the environment. The complete procedure is from now on referred to as *P_Process* (*P* indicates the physical flows).

Table 2 shows the flow of the substance in kg from one activity to another. [*i, j*] denotes the material flow from production units *i* to *j*. So [1,2] means that 98 kg of material flows from the washer (washing) to the press (squeezing). The names of the columns are the same as the names of the rows; they are only marked with the index numbers. The rows below the '*Total*' detail the environmental inputs for better understanding. The substrate production needs 1.959 kg CaCO3 and 0.663 kg spawn from outside, summarized in the *Environmental inputs* row (2.6). The money flow of this table (the processes in monetary terms) is in the Appendix, Table A1.

The plant produces eight end products: (apple) juice, alcohol, cider, liqueur, mushroom, fertilizer, alga and biogas. In ecological systems, resilience is measured by a vital flow process, such as energy in kilocalories (/m^2/y), so it is important to find a common unit of measurement in which all processes can be measured. This common denominator might be the weight. Kilograms or litres are similar in weight; however, CO2 emissions and heating are more difficult to integrate. The unit used as the basic unit is *kg*, as 1 l of water is also 1 kg. Any resulting distortions (e.g., washing water containing fruit pieces) were ignored. For gaseous materials (there are three such elements, air, biogas and CO2), the unit of measurement is the kilograms needed to produce them. *Heating* is calculated the same way. The *Biogas/Heating* column [14] contains the ingredients for heating: the necessary amount of biogas (7.34 kg) and the corresponding quantity of air (8.76 kg from outside). In the row of *Biogas/Heating* this combined quantity (16.1) is distributed afterward (0.65 for *Pasteurizing,* 1.3 for Alcohol Production, etc. …). Losses can be found in the Loss column for each row (e.g., the loss for *Pasteurizing* [2] is 0.647 kg). All the combustion products in the process are collected and lead through the alga production basin (*Alga* column, *CO2*: 13.76). In the *Alga* [10] row, one part of alga goes for composting (2.618), a large portion (10.16) is loss (the CO2 can only be captured partly), and a small fraction (0.982) is sold as a liquid alga. All other flows in the matrix follow this logic.

4.1.2. An end-product-oriented version

The full, process-oriented representation mode shows the detailed relationship system of the plant at the level required by the process modelling. However, this paper analyses the structure, which does not need this level of detail. Ecological use includes compartments; the economy also includes aggregated units, such as industries/sectors. Therefore, aggregated values are used to depict the structure needed for the following analysis. The first three elements (washing, squeezing, and pasteurizing) will be combined as juice production. Bottling will be used for the final products in the juice, cider, alcohol and liqueur production. With this aggregation, a more condensed, structural matrix can be constructed, containing only seven end-production units from the eight (the alga is not considered here because of its marginal role as end-product), where only these compressed units (business activities) constitute the nodes. There are two matrices in Table 3. One represents the physical processes; the other represents the monetary terms connected to these processes.

This new version from now on referred to as *P_EndProduct* and *M_EndProduct*. In *M_EndProduct*, the price of the loss is only accounted in a symbolic value (1 unit) to avoid the distortion of the zero values of waste. Therefore, the "Loss" columns have the same values in both matrices. This version also reflects the completeness of the system, the aim of treating by-products, where possible, at the place of origin, similarly to ecological systems. Thus, this version also complies with the principles of the blue economy in this respect. Please also note the following differences between the two matrices (*P* and *M*): The liqueur and cider production is nearly meaningless in physical terms, but it has an impact in monetary terms. The biogas production volume is somewhat larger than the fertilizer; however, in monetary terms, it is only a third of it. Cider and liqueur directly produce the output from the input without loss. The mushroom has inputs from the environment; it needs heat, gives output to fertilizer and has a loss, so it is more deeply embedded into the whole process.

4.1.3. An efficiency-oriented version

There is also a version of the apple juice plant that strives for

Table 2
The full, process-oriented connection system of the apple juice plant (P_Process).

P_Process	[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]	[9]	[10]	[11]	[12]	[13]	[14]	Loss	Final pr.	Sum
Washing [1]		98.0		52.0													150.0
Squeezing [2]			53.9	44.1													98.0
Pasteurizing [3]					5.4		48.51								0.647		54.5
Alcohol production [4]						0.8	3.09						87.5		6.086		97.4
Cider production [5]							5.39										5.4
Liqueur production [6]							0.75										0.8
Bottling [7]																57.74	57.74
Substrate production [8]									67.91						0.33		67.94
Mushroom production [9]											58.21				0.034	11.92	70.16
Alga production [10]											2.618				10.16	0.982	13.76
Composting [11]												65.93			0.051		65.96
Fertilizer [12]																75.93	75.93
Biogas production [13]								65.3						7.34	0.583	14.52	87.7
Biogas/Heating [14]			0.65	1.3				0.033	0.034	13.76	0.051		0.29		0.003		16.1
Environment inputs	150.0							2.6	2.220		5.100	10.0		8.76			178.7
Sum	150.0	98.0	54.5	97.4	5.4	0.8	57.74	67.94	70.16	13.76	65.96	75.93	87.7	16.1	17.6	161.1	1040.
Fruit	100.0																
Water	50.0								2.220		5.100						
Air														8.76			
Spawn								0.663									
CaCO3								1.959									
Ash												10.0					

Table 3
The system of relations between the essential elements of the apple juice plant in physical (P_EndProduct) and monetary (M_EndProduct) terms.

P_End-product	[1]	[2]	[3]	[4]	[5]	[6]	[7]	Loss	Final pr.	Sum
Juice [1]		96.100	5.390					0.647	48.510	150.647
Alcohol production [2]				0.750			87.451	6.086	3.094	97.381
Cider production [3]									5.390	5.390
Liqueur production [4]									0.750	0.750
Mushroom production [5]						58.207		0.067	11.922	70.195
Fertilizer [6]								10.211	76.907	87.118
Biogas/Heating [7]	0.647	1.281			65.363	13.811	0.292	0.586	14.523	96.503
Environment inputs	150.				4.832	15.100	8.760			178.692
Sum	150.647	97.381	5.390	0.750	70.195	87.118	96.503	17.597	161.095	686.675

M-End-product	[1]	[2]	[3]	[4]	[5]	[6]	[7]	Loss	Final pr.	Sum
Juice [1]		1922	1078					0.6	9702	12,703
Alcohol production [2]				1500			1749	6.1	6188	9443
Cider production [3]									8085	8085
Liqueur production [4]									2625	2625
Mushroom production [5]						5821		0.1	6438	12,259
Fertilizer [6]								10.2	18,458	18,468
Biogas/Heating [7]	45	90			4575	967	20	0.58	1017	6715
Environment inputs	12,000				3310	12.6	8.76			15,331
Sum	12,045	2012	1078	1500	7885	6800	1778	17.6	52,512	85,628

efficiency, focusing only on the zero-waste principle. The relationship system of the model is as follows (Table 4), which is called *P_Efficient* and *M_Efficient* (in monetary terms):

With this model, they follow a design method in line with today's economic management principles, including the circular economy, characterized by efficiency and main product focus. It also does more than the core competencies due to the additional alcohol production. However, it does not use up by-products for other products. Instead, they try to "get rid" of them, respecting only the zero waste and circularity, not the blue economy principle.

There is only a technical transformation between the first and second plan that illustrates how to get rid of excessive detail to focus on structure. The importance of the first plan is to show the main features of a too-detailed plan. The comparison of the second (aggregated) and the third (simplified) versions is decisive from the viewpoint of this study.

5. Results and discussion

In this section, the flow of the physical and the monetary quantities are executed in parallel, where the physical quantities are labelled with prices in a local currency. Note that the loss worth nothing (assigned a symbolic price of 1 to a unit of loss).

5.1. Structural analysis

First, we summarise the names of the different types of matrices (process details or plans and the unity of the flows) in Table 5 to follow the analyses easier.

Table 4
A simplified version of the apple juice plant in physical (P_Efficient) and monetary (M_Efficient) terms.

P_Efficient	[1]	[2]	By-products	Final pr.	Sum
Juice production [1]		101.5		48.5	150.0
Alcohol production [2]			97.4	4.1	101.5
Environment	150.0				150.0
Sum	150.0	101.5	97.4	52.6	401.5
M_Efficient					
M_Efficient	[1]	[2]	By-products	Final pr.	Sum
Juice production [1]		2030		9702	11,732
Alcohol production [2]			97	8119	8216
Environment	12,000				12,000
Sum	12,000	2030	97	17,821	31,948

Table 5
The names of the six analysed matrices.

	Ecological units, P(hysical) quantities	Monetary units
Very detailed process	*P_Process*	*M_Process*
Only structural elements (final products)	*P_EndProduct*	*M_EndProduct*
A very reduced, efficient version	*P_Efficient*	*M_Efficient*

The following table shows the resilience index (α see Section 3.1) for the three types of plans and the characteristic values (network functions) described in the methodology section (3.3): C (weighted connections, relationship), F (weighted flows, process values), N (weighted number of efficient nodes), and R (number of weighted roles). In the following, "weighted" will not be used because only this type of function will be used. The columns are the types of plans, which are the bases of the calculations, described in Table 2 (and Table A1), Table 3 and Table 4 (without the summations).

The values calculated by monetary units are lower, apart from the weighted connections and the flow in the case of *M_EndProduct*. The relations between the indicators in the three types of plans are the same. The main factor to consider is α, the resilience index, which is closest to the optimal in *x_EndProduct* (both *EndProduct* matrices) from an ecological point of view since the average of mature ecosystems is also around 0.4, see Section 3.1. In the case of end products, α still indicates a too efficient structure in physical terms (ecological units) since it is higher than optimum, 0.518. However, in the case of monetary units, α is under the optimal 0.4 value. The 0.336 means that there is still room for increasing efficiency. The most possible reason for this difference is that the very low quantities of end-products, like alcohol, cider, and liqueur, are worth much higher in monetary terms, so the whole matrix became more equalized. Note that the difference was not caused by the loss being only valuated by a symbolic value of 1 because the loss's real price valuation resulted in nearly the same value (these outputs are not displayed here). Further analysis is provided in the *Sensitivity analysis* section.

The *x_Process* (see *P_process* in Table 2) versions are more efficient than the end-product-version (Table 3), which is explainable by the nearly functional connections between some elements, such as substrate production (for mushroom) and mushroom production. However, the most efficient (as expected) is the *x_Efficient* version, where there is not enough redundancy to solve the consequences of an accidental event, such as a significantly low price of juice or alcohol.

In *Connections* (the breadth of the system), also the *x_EndProduct* version has the highest value. In the *x_Process*, the connections are lower because of the more nodes (business activities) in the table. Finally, the simplified version of x*_Efficient* has much fewer connections. The higher values in the case of monetary terms might be due to the altered financial magnitudes.

The *Roles* (the system's depth) reduced significantly to about half from the *x_Process* to *x_EndProducts* and did not reduce more to *x_Efficient*. In the latter, all three levels (input-production-output) had separate roles (see Table 4). The same structure exists in *the x_EndProduct* version; only the production part is detailed, which has practically the same role in this detailed form as the "production" in the most efficient matrix. In the *x_Process* version, detailed processes as *bottling* created new roles. Roles are similar to trophic levels (in ecology), which is a maximum of 4.88 in any non-human species, while, e.g., in the case of a single food source of beef production, this value is much higher, 8.1 (Fiscus, 2009).

The decrease in the number of *Nodes* and the number of *Flows* (relationships) can be explained by the size of the system. Efficient processes weaving through the system are about 60% in the case of *x_EndProducts,* related to *x_Process*; however, nearly three times higher than that of *x_Effi*cient, showing a more complete, "ecological-like" system property. *Flows* of the *x_Endproduct* in monetary term has a higher value than in physical units, probably due to the increased monetary values of the end products (such as alcohol).

In summary, the functions reflect the aggregate level of the matrices, and the resilience indicators are closest to the optimal in the case of *x_Endproducts*, which is also expected. The only relatively unexpected value is the α in the case of monetary terms, which is much closer to the optimum; it is even "on the other side": there could be more efficient regarding the financial flows.

5.2. *Robustness – Possible changes*

Sensitivity analysis, as described in the *Methodology* part, is discussed in this section. Robustness values (Section 3.2) are calculated using (7) for each cell. The starting plan was the *P_Endproduct,* where the α value is greater than the optimal (too efficient, 0.518 in Table 6). The suggested modifications are performed based on the robustness values to create a more robust, more optimal juice production plant. The robustness values are purely technical: they do not consider any technological necessities (shown in the appendix (Table A2)). At this time, the suggested methodology is that the resulted matrix should be recalculated (again, with (7)) in a way that the key numbers (or technologically fixed values) are put back to their original value. In this case, in the suggested matrix, the original values contained in the first four rows/columns of the matrix (starting volume of juice, the alcohol, cider and liqueur production) were fixed until the time when they were similar to the original matrix. The process iterates through the matrix until a desirable output (good robustness) is reached. The original robustness values are around 1 (see Table A2). If the value is equal to 1, there are no suggested changes. If it is above, an increase; if it is below, a decrease is needed. For e.g., the value in *Environmental inputs* to *juice* is 0.666, and 150*0.666 = 99.9. In this case, two iteration steps were necessary to reach an optimal α value (0.403).

There are no suggested changes in the cider and liqueur production. If the original quantity (150 kg) is kept, the juice and alcohol productions are predetermined, so the first four columns and rows are kept. Therefore, mushroom, fertilizer and biogas productions are the focus of the possible changes. There are strong suggestions for increasing the mushroom and biogas production and decreasing the fertilizer production to make the system more resilient (see the *Final production* column of Table A2). However, the changes also have to follow the technology. E.g. if the total input for the mushroom production is 44.1 and the mushroom end-product ratio is about 20%, then the final mushroom production is about 8.8. Adjusting the values to technological possibilities (unlike the suggestion, the mushroom production could not be increased), the optimal α value still improved significantly, 0.439 (instead of 0.403). The optimal table is the following:

As a result, it can be concluded that it is possible to improve the resilience of the matrix (production plant design) even when there are fixed technological connections in the relationships within the production process, only changing the values in some, freely modifiable cases.

5.3. *Adding, removing activities*

In the previous section, the structure's resilience was modified by only altering the production quantities. Another type of sensitivity analysis is to examine the effect of adding or removing new business activities: How do these modify the resilience of the production plant?

Table 7 indicates that cider and liqueur production are neutral from a resilience point of view; the "Loss" values are about the same as the original values (in Table 3), but the mushroom production counts. In addition, heating is embedded deeply into this process, so it is worth seeing the role of biogas production/heating. Therefore, the resilience level of the matrix in the case of removing these activities is examined. Adding a new activity might also change the resilience level, so the role of a new activity (animal farm) is also investigated.

5.3.1. *Removal of variables*

First, two products with minor quantities (cider and liqueur) and one product with great production quantity (mushroom) were removed (see an explanation below Table 3). Second, in order to further simplify the process, heating was removed, which permeated the whole process, because it was connected to several areas which needed heating, and – as a comparison – all three products were removed together (mushroom, cider and liqueur), simulating a similarly big effect. These modified tables are not shown here. The results of the four new plans – the alpha and the network indicators – are shown in Table 8, similarly to Table 6. For better understanding, the original values from Table 6 (*x_EndProducts*) are shown on the right-hand side of the tables.

In the upper part of Table 8, the removal of cider and liqueur practically did not have an effect either in physical or monetary terms; there is a slight increase in efficiency and a decrease in network functions. Also, removing the mushroom is nearly equivalent to removing the two smaller activities in terms of resilience. In physical terms, because of the removal of the more embedded mushroom production, the network

Table 6
Comparison of the resilience indicator and the weighted network functions.

	Ecological units			Monetary units		
	P_Process	*P_EndProduct*	*P_Efficient*	*M_Process*	*M_EndProduct*	*M_Efficient*
α (resilience)	0.7083	0.518	0.767	0.598	0.336	0.551
N (nodes)	11.680	6.161	3.334	8.270	5.117	2.679
F (flow)	17.769	10.971	3.90	14.070	11.51	3.563
C (connections)	1.521	1.781	1.17	1.701	2.25	1.33
R (roles)	7.677	3.460	2.85	4.861	2.275	2.015

Table 7
Suggested new values based on the robustness indices of P_EndProduct.

	[1]	[2]	[3]	[4]	[5]	[6]	[7]	Loss	Final pr.	Total
Juice [1]		96.10	5.39					0.647	48.510	150.647
Alcohol production [2]				0.75			87.451	6.086	3.094	97.381
Cider production [3]									5.390	5.390
Liqueur production [4]									0.750	0.750
Mushroom production [5]						34.930		0.370	8.800	44.100
Fertilizer [6]								8.800	73.130	81.930
Heating [7]	0.647	1.281			31.90	20.000	1.710	1.870	41.753	99.161
Environment inputs	150.000	0.000			12.20	27.000	10.000			199.200
Total	150.647	97.38	5.39	0.75	44.10	81.930	99.161	17.773	181.427	150.647

Table 8
Portfolio reductions. The names of the removed end-products written on the header.

	No cider and liqueur		No mushroom		Original	
	physical	monetary	physical	monetary	physical	monetary
alpha	0.528	0.375	0.512	0.347	0.518	0.336
nodes	5.938	4.480	5.182	4.575	6.161	5.117
flows	10.300	8.860	8.815	9.562	10.971	11.51
connections	1.734	1.978	1.701	2.09	1.781	2.250
roles	3.424	2.265	3.046	2.189	3.460	2.275

	No heating		No cider, liqueur and mushroom		Original	
	physical	monetary	physical	monetary	physical	monetary
alpha	0.582	0.346	0.546	0.386	0.518	0.336
nodes	6.065	5.077	4.957	3.806	6.161	5.117
flows	9.761	11.188	7.929	6.881	10.971	11.51
connections	1.609	2.204	1.600	1.808	1.781	2.250
roles	3.769	2.304	3.099	2.105	3.460	2.275

functions are reduced more in all four cases compared to the original. Only one element moves in the opposite direction: the number of (weighted) flows in the case of cider and liqueur production removal (since this value is reduced). It means they were expensive products, with much higher weights than the mushroom sale.

In the lower part of Table 8, the heating removal significantly affected the efficiency in physical terms because an “equalizer” factor was removed. Note that the biogas production was not removed. The network functions related to the starting position did not really change (nor in the monetary part). However, in the monetary part, the efficiency only increased partially. The three-products-removal, which was made to impose a similarly big effect, caused less efficiency increase in physical and more increase in monetary term evaluation. Network functions are reduced in both cases; however, because of the financial re-evaluation of the flows, this reduction is much higher in monetary terms.

In summary, the financial valuation of the flows dampens the excessive efficiency values, measured in physical quantities. The removal of even three products still left enough diversity in the system. Also, the more “embedded” product is removed, the stronger the increase in efficiency (decrease in diversity). In both cases, the system remained closer to the optimum than the most efficient case (Table 4). This result is also rational because this case has not yet reached the level of simplification as the *X_Efficient* case. Note that resilience could not improve significantly with the removal of activities.

5.3.2. *Adding new activities*

Pig (or cow) farming is a possible new activity – added to the *P_EndProduct* (Table 3) – because the used mushroom substrate is a good feed for pigs (see Table 9). Only the necessary minimum factors are included, the regrouping of the substrate and the necessary heating from the input side, and – on the output side – it contributes to the biogas production (Heating). It also includes more environmental inputs (other types of feed).

The changes in the main features are in Table 10, similarly to Section 5.3.1.

As expected, the resilience of the production processes and the nodes, flows, and connections increased. The weighed roles have been reduced because only new activity is added to the productions within the same role.

Table 9
Pig farming as a new activity.

	[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]	Loss	Final use	Sum
Juice [1]		96.10	5.40						0.60	48.50	150.60
Alcohol production [2]				0.80			87.50		6.10	3.10	97.40
Cider production [3]										5.40	5.40
Liqueur production [4]										0.80	0.80
Mushroom production [5]						25.80		30.00	0.20	10.00	66.00
Fertilizer [6]									10.00	61.2	139.20
Heating [7]	0.60	1.30			55.0	20.40	0.30	1.00	0.60	23.00	174.30
Pigs [8]									73.00	18.00	91.00
Environment inputs	150.00				11.0	25.00	14.50	60.00	0.00	0.00	260.50
Sum	150.60	97.40	5.40	0.80	66.0	139.20	174.3	91.00	28.50	232.0	985.20

Table 10

Comparison of the new pig farming activity with the original P_End-product version ("Original").

	With pig farming	Original
alpha	0.4403	0.518
nodes	7.103	6.161
flows	15.218	10.971
connections	2.142	1.781
roles	3.316	3.460

Table 12

Comparison of the changed volume and the new connection versions with the original *P_End-product* version ("Original").

	New connection	Original
alpha	0.4126	0.518
nodes	6.901	6.161
flows	15.407	10.971
connections	2.233	1.781
roles	3.091	3.460

A new activity significantly improves the resilience level of the production plant, unlike activity removal.

5.4. Changes within the framework – New connections

As discussed in Section 5.2, the volume of some activities is allowed to change, even with technological limitations (Table 7). This section examines new connections between activities (Table 11) and the changes in the main features in Table 12. This new connection demonstrates using technologically possible but not yet implemented connections.

The new connection is the use of slurry from pigs for biogas production (72 in [8,7], and the necessary other modifications are also made, such as increased outputs in *Fertilizer*).

The new connection allows for more redundancy - in this case, the pig's slurry can be used inside - and the system will be more resilient. Note: It does not mean that every new connection would improve the structure's resilience. However, it means that technologically possible connections are worth examining from a resilience point of view.

These changes result in a decrease in the weighted roles and an increase in flows and connections. The role change, together with the explanation in Table 10, shows that the reduction in roles can increase the redundancy within the system: there are more types of activities for the same role. It is worth mentioning that with the volume change of the flows, both the weighed flows and connections could significantly increase. Some notes about the possible changes:

a) Some technological links do not allow values to change, but other relationships might be re-evaluated. The lower right corner (Table 7, bordered) can be varied in this case.

b) These values are guidelines. Iterations could finally result in an optimal system in a mathematical sense. However, technological limits would probably always divert the process from the optimum.

c) These calculations would not suggest values to cells (relationships) without connection.

6. Conclusion

In this study, some elements of the methodology of ecological network analysis are used in the design of a small (juice) production plant. Zero waste emissions and modern requirements for sustainability are recognized, but merely adhering to this principle does not result in a "natural", ecology-like operation. Mature ecological systems operate under ecological principles, one of the main ones being resilience. Resilience serves as a type of risk management in ecological systems because they are efficient enough (operational efficiency) and ready to adapt to changing circumstances (redundancy, diversity). It is also considered a form of insurance for the system (Baumgärtner and Strunz, 2014). It follows that adhering to the zero waste principle alone is not sufficient; an additional step is also necessary: applying the basic operational principles of ecosystems. To explore these scenarios, three plans for a small production company were created and examined. All of them can be considered waste-free. We stated that only a plant with numerous activities (economies of scope) is close to a resilient, therefore, to an ecologically oriented system.

There are solid, liquid, gaseous materials and even heat in a juice production plant, therefore, a method for unifying the different state materials was provided (instead of the energy used in ecology). Also, a method is suggested for achieving a necessary aggregation level for analysing the processes from a resilience point of view.

Limitations of the developed methodology are the following:

- More concepts exist for creating even the first matrix; one example is the question of heating. Is it necessary to include it in the process? As it was shown, it could alter the resilience level.
- Prices for losses and by-products between business units are always debatable and often result from negotiations.
- Structural resilience only increases the chance to react to market changes but cannot solve this type of difficulties. The stability of external effects is out of the scope of this study.
- Structural resilience only examines quantities, however, the quality of the plant processes is also an important aspect of resilience.

The findings presented in this paper emphasize the need to look beyond traditional sustainability and zero-waste initiatives to build resilient manufacturing systems. A key message is that production processes should follow ecological systems' risk management methods to provide resilience. This can be achieved by fostering adaptable production systems with flexible product portfolios, enabling companies to adjust production in response to technological and market changes. Such frameworks that support this flexibility should be promoted, given that most production systems are not fully constrained by technology, allowing for a certain degree of freedom in expanding the product portfolio.

Table 11

Structural changes. These portfolios contain the original P_End-product version ("Original") with a new connection between pig production and biogas heating.

	[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]	Loss	Final use	Sum
Juice [1]		96.10	5.40						0.60	48.50	150.60
Alcohol production [2]				0.80			87.50		6.10	3.10	97.40
Cider production [3]										5.40	5.40
Liqueur production [4]										0.80	0.80
Mushroom production [5]						25.80		30.00	0.20	10.00	66.00
Fertilizer [6]									20.00	119.2	139.20
Heating [7]	0.60	1.30			55.00	88.40	0.30	1.00	0.60	27.00	174.30
Pigs [8]							72.00		1.00	18.00	91.00
Environment inputs	150.00				11.00	25.00	14.50	60.00	0.00	0.00	260.50
Sum	150.60	97.40	5.40	0.80	66.00	139.2	174.3	91.00	28.50	232.0	985.20

CRediT authorship contribution statement

Tibor Kiss: Writing – review & editing, Writing – original draft, Validation, Supervision, Software, Resources, Project administration, Methodology, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Zsolt Hetesi:** Writing – review & editing, Writing – original draft, Validation, Supervision, Resources, Methodology, Data curation. **Viktor Kiss:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Project administration, Data curation.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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Data availability

Data will be made available on request.

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Appendix A. Appendix

Table A1
The full, process-oriented connection system of the apple juice plant, in monetary terms (M_Process).

M_Process	[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]	[9]	[10]	[11]	[12]	[13]	[14]	Loss	Final pr.
Washing [1]		8330		1040												
Squeezing [2]			4851	882												
Pasteurizing [3]					1078		9702								0,647	
Alcohol production [4]						1500	6188						1749		6086	
Cider production [5]							8085									
Liqueur production [6]							2625									
Bottling [7]																26,600
Substrate production [8]									4074							
Mushroom production [9]											1513				0,034	6438
Alga production [10]											262				10,16	294,5
Composting [11]												1978				
Fertilizer [12]																18,222
Biogas production [13]								1959						514	0,583	1017
Biogas/Heating [14]			45,3	89,7				2285	2377	963,2	3548		20,4			
Environment inputs	8025							1789,	1110		2,55	10		8,76		
Sum	8025	8330	4896	2012	1078	1500	26,600	3750	4078	963,2	1781	1988	1769	523	17,51	52,571
Fruit	8000															
Water	25								1110		2,55					
Air														8,76		
Spawn								378,7								
CaCO3								1410,								
Ash												10				

Table A2
Robustness values.

	[1]	[2]	[3]	[4]	[5]	[6]	[7]	Loss	Final pr.
Juice [1]		0.663	0.999					2.397	1.156
Alcohol production [2]				1.082			0.552	1.202	2.285
Cider production [3]									1.022
Liqueur production [4]									1.256
Mushroom production [5]						0.592		3.189	1.544
Fertilizer [6]								0.923	0.751
Heating [7]	2.987	2.517			0.574	1.372	3.203	2.288	1.562
Environment inputs	0.666				2.000	1.545	1.834		

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