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Efficiency assessment in co-production systems based on modified emergy accounting approach

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ABSTRACT

Emergy accounting in a system with co-production branch is of great scientific interest since each branch corresponds to a different transformity value. In previous studies, limitations associated with emergy accounting in co-production systems have been highlighted where some "inputs" have to be added to obtain a "useful" product from a "co-product" – giving rise to inaccuracies in the emergy accounting process. To address these methodological aspects of emergy assessment in co-production systems, a modified physical quantity method (MPQM) – that goes in line with the standard emergy algebra – has been proposed in order to provide a different perspective for accounting co-products efficiency. The robustness of MPQM has been verified by taking the case study of *Eucalyptus* pulp production and a comparison is made against conventional and energy/exergy weighting methods. As per the results, MPQM was able to provide accurate results for co-production systems as compared with other emergy accounting methods. However, the case of *Eucalyptus* pulp production was found to be "inefficient" following the MPQM approach. These findings are expected to strengthen the methodological aspects of emergy accounting based on the physical quantity criterion.

1. Introduction

Since extensive resource consumption associated with industrial activities across the globe, efficient resource utilization has become even more crucial. In this regard, resource efficiency could be termed as the maximum utilization of material resources with minimal wastes of any type (e.g. materials, energy, time, and money) from the extraction to consumption phase. From another perspective, the sustainable development practices are highly dependent on industrial activities worldwide (Lokko et al., 2018; Navarrete et al., 2020). In this regard, industrial production systems have been actively seeking to promote efficient resource utilization in the last several decades – distinctively illustrated after the industrial revolution. A number of studies and assessments have been performed which verified the role of efficient resource use in industrial production systems. To address sustainability concerns from rising global production activities during the 1970s, Howard T. Odum, an ecologist by profession, realized that economic activities were not a mere function of economic rules, rather, limitations of an ecosystem also dictated those activities. This led to the conceptual development of "emergy" in the later years (Brown and Ulgiati, 2004a).

Emergy analysis is considered a systematic approach among different tools that is used to quantitatively assess the efficiency of production systems and/or their activities (Chen et al., 2017; Zhong et al., 2016). Emergy is defined as "the available energy of one kind (usually solar) used up directly and indirectly to generate a service or product" (Odum, 1996). Therefore, it is the total (direct plus indirect) energy in terms of a single source, such as solar energy, which is required to produce a product (or provide a service). This means that emergy represents net material and energy resource flows within individual production systems and evaluates resources, goods or services in common units of solar energy, measured as solar emergy (sej) (Amaral et al., 2016; Liu et al., 2016). Moreover, the concept of emergy can be used to derive key policies on sustainable development around the world as the method evaluates resource use efficiency of a system based on system theory and system ecology (Brown and Herendeen, 1996; Brown and Ulgiati, 2004b; Odum et al., 1997).

Emergy assessments have witnessed rising relevance and application particularly since the early 1980s (He et al., 2020). In addition, the emergy approach has been widely employed specially to assess of industrial production efficiency comprising a variety of sustainability

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indices and industrial sectors. In this regard, Wang et al. (2006) assessed the sustainability of combined heat and power (CHP) plants based on material and energy circularity indices in an eco-industrial park (EIP). Geng et al. (2010) used emergy to develop performance indices at the industrial park level in order to characterize their sustainability level. The impact of Chinese paper industry on regional sustainability was studied by Ren et al. (2010) to assess best policy scenarios using a set of modified emergy-based indices. Following this, benefits from industrial symbiosis activities, such as energy and resource savings and eco-efficiency enhancement, were evaluated in an industrial park by Geng et al. (2014) using the emergy approach. Similarly, Zhe et al. (2016) used emergy accounting together with IPAT equation and decomposition analysis to determine environmental pressures attenuated through industrial symbiosis at the industrial park level. More recently, Zhang et al. (2017) used emergy method and input–output tables to identify sector-specific resource intensities in Chinese economy. For further reading on emergy application on industrial ecosystems, we refer to published literature (Amaral et al., 2016; Goh and Lee, 2010; Kharrazi et al., 2014; Liu et al., 2018; Shao and Chen, 2016; Yang et al., 2013).

As per our understanding and the review of the literature, majority of existing research is based on the emergy accounting for system-level production efficiencies (e.g. developing and applying novel or existing emergy indices) and overall systems comparison while mostly ignoring complex resource interactions in a co-production system (Cao and Feng, 2007). However, a "production system" consisting of several types of branches and intersections must have its standard emergy accounting procedures and co-production is one of the branches in production systems. And with the absence of emergy rules concerning co-production systems, emergy accounting in production processes with co-products needs greater attention to avoid inaccurate results (Brown and Herendeen, 1996). Thus, we see this research gap highly important from a methodological perspective of emergy application in complex industrial systems. Some of the attempts to address this research gap have been made (Bastianoni and Marchettini, 2000; Cao and Feng, 2007; Kamp and Ostergard, 2013; Vieira and Domingos, 2005) yet their efforts are still not conclusive and need further attention from a methodological development's view point. Therefore, this study aims to fill this gap and address some of the limitations in emergy evaluation specifically in co-production systems with the integration of a novel approach based on modified physical quantities. The proposed method is also verified using a case study of *Eucalyptus* pulp production.

This paper is organized as follows: Section 2 discusses the methodological characteristics of emergy accounting in general and its application in co-production systems. This section also presents an overview of existing procedures in emergy evaluation and illustrates the proposed method. Section 3 introduces a case study to verify the proposed methodology and section 4 demonstrates the results and discussions in detail. Also, this section indicates some of the research limitations and future scope. Finally, main findings of this work are concluded in Section 5.

2. Methodological aspects of co-production and emergy accounting

In systems networks, there are several kinds of branches and intersections. Emergy accounting of systems network depends on the type of branches and intersections. Much of the confusion in emergy accounting comes when the types of branches and connections are not identified for the appropriate evaluation procedure. At the same time, to minimize errors and increase accuracy, emergy accounting in system networks should follow the rules stated in emergy algebra (Odum, 1996). The rules of emergy algebra have been introduced by Brown and Herendeen (1996) and are as follows:

1. Total source emergy to a process is assigned to the output of processes.
2. Co-products from a process have total emergy assigned to each pathway
3. When a pathway splits, the emergy is assigned to each branch based on the share of total energy flow on the pathway.
4. Double counting emergy is not allowed within a system (in feedbacks or merged co-products) i.e. their sum cannot be greater than the source emergy from which they were derived.

The emergy of a product is calculated by multiplying the energy with transformity. Transformity is the conversion factor that converts energy and matter flow in a system into solar emergy. Transformity is defined as emergy per unit of available energy and its unit in sej/J The transformity is usually expressed in mass (sej/g). If the transformity is expressed in money (sej/\$), it is called Emdollar. Transformity is a core concept in emergy assessment that measures the work efficiency involved in conversion of solar emergy into product and gives the position of an energy flow within the hierarchical structure (Brown et al., 2004). High transformity value indicate that more energy is required to produce a product (thus ranked higher in emergy hierarchy).

In the aspect of emergy algebra concerning co-production systems, the networks could develop two different pathways in production process, that is, the split pathway and the co-production pathway (Cao and Feng, 2007). In this regard, the difference between split and co-product pathway should be clearly outlined before the accounting process. In split branching, a pathway divides into two branches of the same kind and each path has the same transformity (for example: a steam supply pipe divided into two branches going to two different locations). In co-production branching, the flow in each branch is different with a different transformity value. Thus, co-products are joint products with more than one output. All products from a co-production system have an economic value and branching occurs with energy transformation. For example, paper and electricity production in pulp production industry. Thus, co-production processes present an interesting yet challenging aspect of emergy accounting.

In emergy calculation of a product or service, the information on energy content of a resource is widely available, however, the transformity values are often unknown. Therefore, accurate information on transformities is a limiting factor in most emergy accounting procedures. Furthermore, emergy accounting of co-production systems is more complex since transformities of individual product systems are unknown. Generally, to address this limitation, transformity in co-products is calculated based on the input and output of energy and matter in the system. There are existing methods which have attempted to calculate the transformity in co-production systems, however, the transformity estimations can become challenging due to the underlying assumptions made for transformity allocation.

2.1. Transformity evaluation in co-production systems

In a system with two or more products simultaneously produced, the results of a non-accurate emergy analysis could be misleading (Bastianoni and Marchettini, 2000). Since in the emergy accounting of systems with co-products, all input emergy must be assigned to individual outputs (as each output accounts for all input emergy to make a particular output), thus, making the transformity of individual outputs different (Herendeen, 2004). This energy transformation using a co-production system has been illustrated in Fig. 1. As depicted, the co-production system has two inputs and two outputs with different individual transformity values. In this type of a co-production system, it is considered highly difficult, if not impossible, to evaluate the unknown fraction of inputs becoming part of the co-products x and y which results in an inaccurate estimation of the transformity values of all co-products (Vieira and Domingos, 2005).

However, the above described production system could be simplified by assuming individual production systems which may use more than one input but can only produce a single product as illustrated in Fig. 2.

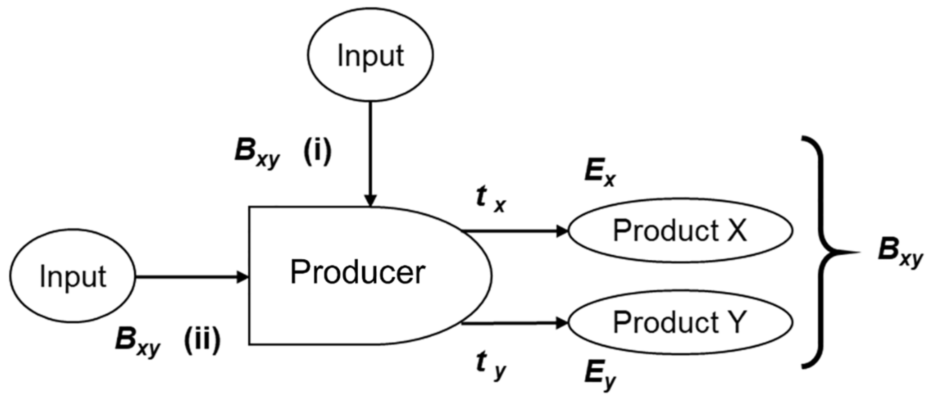

Fig. 1. Emergy transformation using a simplified co-production system with two inputs and two outputs {Note: B_{xy} is the emergy of inputs *i* and *ii* [sum of B_{xy}(i) and B_{xy}(ii)], E_x and E_y are the energies of coproducts *x* and *y*, respectively; t_x and t_y are the transformities of product *x* and *y*, respectively}.

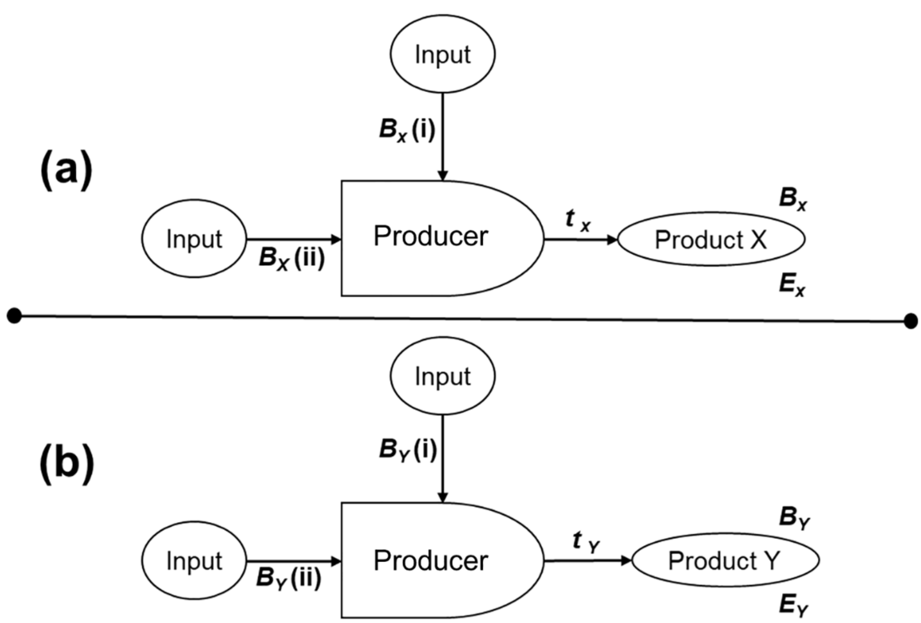

Fig. 2. Emergy transformation using a separate production system for individual products [Note: B_x and B_y are the emergy of the individual products *x* and *y*, respectively].

As shown in Fig. 2 (a), production of *x* takes place having an emergy value of B_x whereas in Fig. 2 (b), production of *y* takes place having an emergy value of B_y. Both products have a transformity value equal to t_x and t_y, respectively. In this type of a production system, accurate transformity values could be easily estimated since only a single product has been generated.

Coming back to the co-production illustrated in Fig. 1, applying single product's transformity calculation procedure, as performed in conventional methods, would lead to inaccurate emergy estimates since more emergy is required to support all products of an co-production system when compared to a single product system (Kamp and Ostergard, 2013). According to Odum (1996), in co-production systems, total emergy can be allocated to individual products as shown in Eq. (1):

$$t_x = \frac{B_{xy}}{E_x}, t_y = \frac{B_{xy}}{E_y} \tag{1}$$

where B_{xy} is the emergy of the two inputs in the system, and E_x and E_y are the energy requirement for making the product *x* and *y*, respectively.

The emergy of the products calculated using this transformity value in co-production systems could lead to complications and in the worst case, inaccuracies. This means that the net output emergy will be greater than the net input emergy indicating a non-additive emergy of co-production systems. This also goes against the emergy algebra which state that the sum of output emergy cannot be greater than the input emergy, indicating that co-production systems are unfeasible as compared with single output producing systems. Though there have been new emergy indicators developed to address the limitations of emergy accounting in co-production systems (Bastianoni and Marchettini, 2000) yet their application has been termed rather complex in nature (Vieira and Domingos, 2005). According to Bastianoni and Marchettini (2000), co-production could be more efficient with lesser environmental impacts with respect to separate productions, whereas two distinct processes could be more effective in using local resources. This calls for emergy models that are easy to apply and able to produce accurate results at the same time.

Another popular method to calculate transformity values in co-productions systems is called "energy/exergy weighting approach". In this method, energy or exergy can be used as a weighting factor which can be allocated using Eq. (2):

$$\widehat{B}_x = \frac{E_x}{E_x + E_y}\widehat{B}_{xy} and \widehat{B}_y = \frac{E_y}{E_x + E_y}\widehat{B}_{xy} \tag{2}$$

Where $\widehat{B}_x$ and $\widehat{B}_y$ are the emergy of two inputs x and y, respectively, and $\widehat{B}_{xy}$ is the emergy of two inputs. Using these energy/exergy allocations, "redefined transformities" $\widehat{t}_{xy}$, $\widehat{t}_x$ and $\widehat{t}_y$can be calculated using Eq. (3):

$$\widehat{t}_{xy} = t_y = t_x = \frac{\widehat{B}_{xy}}{E_x + E_y}, \widehat{B}_x = E_x t_x, and \widehat{B}_y = E_y t_y \tag{3}$$

2.2. Modified physical quantity method (MPQM)

Considering the limitation associated with existing methods, in this study, a novel approach based on the physical quantity method is presented in an attempt to address problems associated with transformity evaluation in co-production systems. This MPQM method has been proposed after modifying the standard physical quantity method to cater for accurate transformity assessments. In emergy literature, the physical quantity method has been widely applied for allocating monetary costs in joint-accounting. The standard physical quantity method allocates joint costs based on physical measures such as volume, weight, surface area, or any other measure of physical characteristics (Drury, 1992; Jain, 2000; Jiambalvo, 2018). In modified physical quantity method, adopted and presented in this study, joint transformity is used to allocate transformity of individual products in co-production systems. Moreover, joint transformity has been previously used to analyze the efficiency of resource consumption in co-production systems. In technical terms, joint transformity "$\widehat{t}$" is the ratio of the emergy of inputs to the sum of energy contents of outputs (Bastianoni and Marchettini, 2000). Similarly, weighted average of transformities "$\overline{t}_{xy}$" has been introduced and when "$\widehat{t}$" is less than "$\overline{t}_{xy}$", the co-production represents the most efficient energy use. Mathematically, joint transformity and weighted average of transformities can be calculated as given by Eq. (4) and (5), respectively.

$$\widehat{t}_{xy} = \frac{\widehat{B}_{xy}}{E_x + E_y} \tag{4}$$

$$\begin{aligned} \overline{t}_{xy} &= \frac{E_x}{E_x + E_y} t_x + \frac{E_y}{E_x + E_y} t_y \\ &= \frac{E_x}{E_x + E_y} t_{xy} + \frac{E_y}{E_x + E_y} t_{xy} \\ &= \frac{B_x + B_y}{E_x + E_y} \end{aligned} \tag{5}$$

where E_x and E_y are the energies of co-products x and y, respectively, t_x and t_y are the transformities of x and y through separate production, and $B_x$and B_y are the emergy values when products x and y are produced individually.

In order to modify the above described approach, the joint transformity of entire co-production system is calculated as a first step in MPQM methodology. Following this, joint transformity will be allocated to individual products. Lastly, emergy of each product will be estimated by multiplying individual transformity values with their respective energy values. Mathematically, following equations are used in MPQM to allocate joint transformity to individual products, as given by Eq. (6):

$$Individual\ coproduct\ transformity = \frac{energy\ of\ individual\ coproduct}{total\ energy\ of\ output\ from\ system} \times joint\ transformity$$

Or,

$$t_x = \frac{E_x}{E_x + E_y} \times t_{xy} \text{ and } t_y = \frac{E_y}{E_x + E_y} \times t_{xy} \tag{6}$$

Here,t_x and t_y represent transformity of individual products x and y, respectively, E_x and E_y represent energy of individual products x and y, respectively, t_{xy} is the joint transformity in a co-production system belonging to separate products. Once the transformity of individual products has been allocated using the above equations, emergy can be calculated by multiplying transformity value with the energy values as given by Eq. (7):

$$Emergy\ of\ individual\ coproduct = Individual\ coproduct\ transformity \times Energy\ of\ coproduct$$

Or,

$B_x = t_x \times E_x$ and $B_y = t_y \times E_y$ (7)where EM_x and EM_y (i.e., in terms of B_x and B_y, respectively) are the emergy of product x and y, respectively, using the MPQM method. Using this method, the transformity values of individual products are similar thus it is expected that the allocation process would be simplified as individual and co-production systems are treated equally. In addition, errors arising from double counting are also expected to be eliminated using this approach.

3. Case study of *Eucalyptus* pulp production

In this section, the proposed MPQM method has been applied to *Eucalyptus* pulp production to assess the robustness and accuracy of the method. The case of *Eucalyptus* pulp production will also be discussed followed by some of the important methodological limitations of this work.

A case study of *Eucalyptus* pulp production system is presented in this section. The case study is based on the data presented by Vieira and Domingos (2005). In the case study, pulp production system co-produces pulp and electricity. In this production system, pulp is the main product while electricity is co-product. The economic value and energy content (i.e., energy required for production) of the main product is higher than the co-product, thus, the main product (with high energy requirements) should have higher transformity and the co-product (with low energy requirements) should have lower transformity (Lei et al., 2014). Detailed emergy diagram of *Eucalyptus* pulp production is illustrated as Fig. 3.

As shown, renewable resource input into the production system includes sunlight and water whereas purchased resource inputs include fossil fuels and chemicals necessary for manufacturing and processing. Detailed data concerning resource inputs and product outputs in the pulp production process is provided in Table 1.

4. Results and discussion

The results of application of (i) conventional, (ii) energy/exergy weighting, and (iii) MPQM methods are shown in Table 2 (illustrating transformity and emergy values based on existing methods in relation to the method proposed by this study). Based on the conventional method, the transformity values calculated for pulp and electricity were multiplied with energies of pulp and electricity to calculate individual emergy. The total output emergy was found to be 7.94E+17 sej based on the conventional emergy accounting method. However, as shown, the output emergy was higher than the input emergy, which goes against the emergy algebra rule 4 (i.e. the total output emergy cannot be greater than input emergy). This indicates the methodoligical limitations of the conventional emergy approach concerning co-production systems.

Based on the energy/exergy weighting method, total output emergy (3.98E+17 sej) was equal to the total input emergy (Table 1), however, this method used the single transformity for co-product emergy calculation. Again, this goes against the emergy algebra rule 3 which states that the transformity of individual co-product (branch) is different for co-production systems i.e. only in the split product systems each product can have similar transformity. Therefore, the results based on this method for emergy calculation in co-production systems could lead to innaccurate results.

Coming to the application of MPQM approach, emergy of pulp and

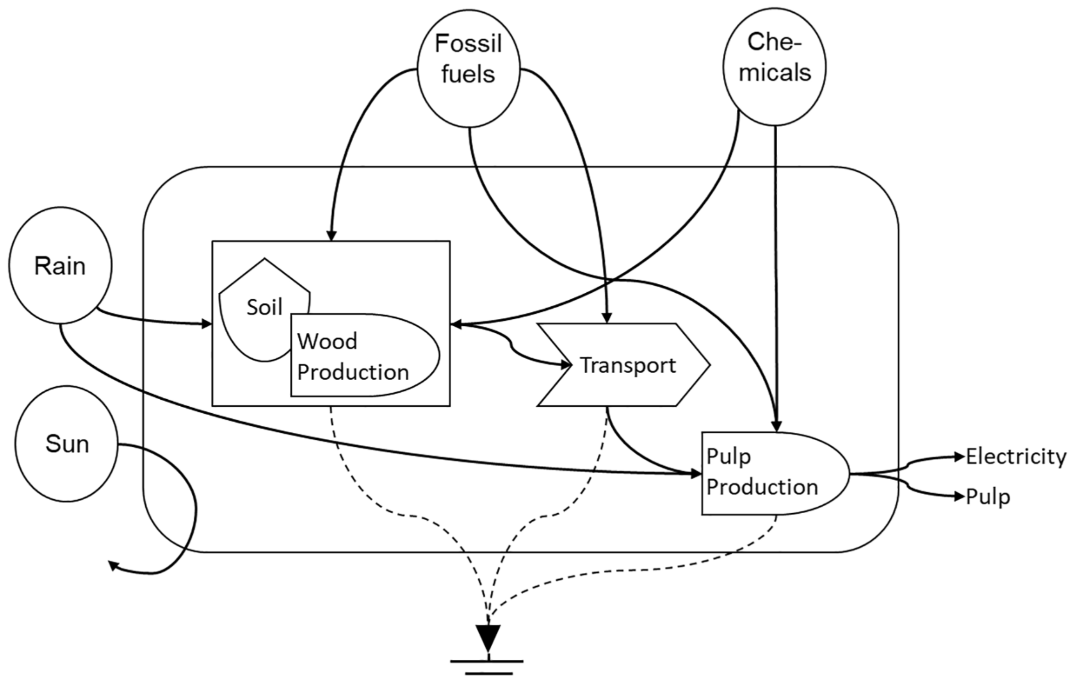

Fig. 3. Emergy diagram of eucalyptus pulp production.

Table 1
Emergy contributions to pulp production.[a]

No.	Input (unit)	Inflow (units/FU)	Emergy/unit (sej/Unit)	Emergy (sej/FU)
Input resources for *Eucalyptus* production				
1	Sunlight (j)	1.04E+14	1.00E+00	1.04E+14
2	Rain (water) (g)	6.40E+11	3.50E+04	2.24E+16
3	Nutrient Loss (g)	2.30E+04	1.68E+09	3.86E+13
4	Fuel (j)	6.44E+10	6.60E+04	4.25E+15
5	Coal (j)	4.98E+06	5.71E+04	2.84E+11
6	Natural gas (j)	8.20E+07	5.71E+04	4.68E+12
7	Nitrogen (fertilizer) (g)	1.98E+06	2.41E+10	4.77E+16
8	Phosphate (fertilizer) (g)	5.80E+04	2.20E+10	1.28E+15
9	Potash (fertilizer) (g)	0.00E+00	1.74E+09	0.00E+00
Transport				
10	Fuel (j)	1.98E+12	6.60E+04	1.31E+17
Pulp Production				
11	Water (g)	2.75E+10	1.28E+05	3.52E+15
12	Fuel (j)	9.39E+11	6.60E+04	6.20E+16
13	Chemicals (g)	9.92E+07	6.68E+08	6.63E+16
Total	———	———	**3.39E+17**	
Co-production				
14	Pulp (j)	7.66E+12		
15	Co– generated electricity (j)	3.96E+11		
Total (J)		**8.06E+12**		

[a]Considering the production of 1000 tons of printing and writing paper.
Where: seJ: Solar emjoules; yr: year; FU: functional unit, 1000 tons of printing and writing paper, corresponding to 610 tons of pulp.

electricity was found to be 3.59E+17 sej and 9.62E+14 sej, respectively. As shown in Table 2, the transformity and emergy values of the main product (i.e. pulp) are higher than the side product (i.e. electricity). Similarly, the sum of the output emergy (3.60E+17 sej) is lower than the total input emergy (3.98E+17 sej) which is in accordance to the emergy rules described in section 2 highlighting that the MPQM appraoch follows all the emergy algebra rules. This also proves that the MPQM appraoch is valid and accurate for emergy accounting in co-production systems.

Table 2
Transformity and emergy values using conventional, energy/exergy weighting, and MPQM methods.

Production	Pulp	Electricity	Total
Energy in co-products (j)	7.66E+12	3.96E+11	8.06E+12
Transformity			
Conventional method	5.19E+04	1.00E+06	1.05E+06
Energy/exergy weighting approach	4.94E+04	4.94E+04	9.88E+04
MPQM	4.69E+04	2.43E+03	4.93E+04
Emergy			
Conventional method	3.98E+17	3.96E+E+17	7.94E+17
Energy/exergy weighting approach	3.78E+17	1.95E+16	3.98E+17
MPQM	3.59E+17	9.62E+14	3.60E+17

Note: Emergy and transformity values are reported in sej and sej/Jrespectively.

4.1. Efficiency analysis

Based on Bastianoni and Marchettini (2000), efficiency of individual processes in co-production systems could be estimated using joint transformity $\widehat{t}_{xy}$ [given Eq. (4)] and weighted average of the transformities $\overline{t}_{xy}$ [given by Eq. (5)]. Using these equations, co-production could be "efficient" in terms of material and energy use when $\widehat{t}_{xy} < \overline{t}_{xy}$ indicating that co-production process will induce less stress on the environment for an equivalent output (in energy terms). On the flip side, when $\widehat{t}_{xy} > \overline{t}_{xy}$ the co-production process is termed "inefficient" in terms of resource consumption and energy input.

Following the above cited efficiency principles, transformity values based on the MPQM were used to determine joint transformity and the weighted average of the transformities. As per the results, $\widehat{t}_{xy}$ was found to be 4.94E+04 sej/J whereas $\overline{t}_{xy}$ was equal to 4.47E+4 sej/J illustrating that joint transformity was greater than the weighted average of transformities. This indicates that the case of pulp production is not "efficient" in terms of material and energy use and that it might not be a sustainable co-production process in the long term. The higher impact from the pulp production case study highlights the fact that efforts should be made to utilize all available exergy within the input resources in order to enhance production efficiency. The results also indicate that to reduce environmental load from pulp industries, resource conservation and waste recycling opportunities could be explored to maximize emergy potential of this industry.

5. Research limitations

The research limitations pertaining to the MPQM also exist. First, application of MPQM approach could be validated using multiple case studies involving different sectors as it is a newly proposed method for the transformity calculation in co-production systems. In this research, the proposed method was applied on the *Eucalyptus* pulp production with pulp as a main product and electricity as a side product. The application of MPQM showed promising results since the method follows all the emergy algebra rules. However, contribution of individual products in terms of energy and emergy contradicts our main findings. For instance, total energy of products (pulp and electricity) was 8.06E+12 j whereas the energy share (in total output energy) of the individual products, that is pulp and electricity, was 7.66E+12 j and 3.96E+11 j which is 95% and 5%, respectively. Similarly, the total output emergy of the products (pulp and electricity) was 3.60E+17 sej whereas the emergy share of individual co-products in total output emergy was 99.7% and 0.3%, respectively. This indicates that there exists a disparity with respect to energy and emergy share of co-products, therefore, a future analysis in terms of quantitative accounting of energy and emergy could be performed. This can be done as a follow-up of this work. Second, we used a limited number of emergy methods to determine transformity and emergy (i.e. conventional and energy/exergy weighting approach) to be compared with MPQM results, thus, the complete picture may still not be constructed. For a future work, multiple emergy accounting approaches would be needed and their results compared to assess the robustness of MPQM approach. Lastly, results based on MPQM method cannot be termed accurate unless its application on large ecosystems is done. This can be done by incorporating input–output tables and regional material flow statistics with emergy accounting to reach a broader consensus on the reliability and accuracy of MPQM approach proposed in this study.

6. Conclusions

This study developed and applied a novel modified physical quantity method for emergy accounting in co-production systems. The proposed method was analyzed in comparison with other methods such as the conventional, and energy/exergy weighting methods. To this end, *Eucalyptus* pulp production system was selected in which two co-products (pulp and electricity) are produced. Based on the results, conventional method did not fulfil emergy algebra rule 4 while emergy/exergy weighting method did not comply with emergy algebra rule 3. However, the MPQM results satisfied all the emergy algebra rules. However, the efficiency analysis, based on MPQM results, revealed that the pulp production system might not be "efficient" in terms of long-term material and energy consumption. Nonetheless, this study provided a different perspective on accounting co-products based on emergy analysis. As a future research direction, more work can be carried out to improve the robustness of MPQM approach and more discussions are needed to address methodological limitations related to transformity calculation in co-production systems.

CRediT authorship contribution statement

Keshab Shrestha: Conceptualization, Methodology, Software. **Izhar Hussain Shah:** Software, Data curation, Writing - review & editing. **Zhe Liu:** Writing - review & editing, Supervision. **Hung Suck Park:** Supervision, Project administration.

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.

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