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Review

Review of Emergy Analysis and Life Cycle Assessment: Coupling Development Perspective

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Abstract: Two methods of natural ecosystem assessment—emergy analysis (EMA) and life cycle assessment (LCA)—are reviewed in this paper. Their advantages, disadvantages, and application areas are summarized, and the similarities and differences between these two evaluation methods are analyzed respectively. Their research progress is also sorted out. The study finds that EMA and LCA share common attributes in evaluation processes and research fields, but they focus on different aspects of macrocosms and microcosms. The assessment of system sustainability is valued by both EMA and LCA, but the former has unique advantages in natural system input analysis, and the latter is more convincing in assessing environmental loading capacity. If the system boundaries of the two methods are expanded, in other words, factors such as ecosystem services, labor, and infrastructure construction are integrated into the upstream of the target system, and environmental impact is further analyzed using LCA in the downstream of the system, the two approaches would complete each other. The quantified results would be more objective. Therefore, these two theories have the necessity of coupling development. After reviewing recent coupling application cases, the results show that LCA and EMA have commonality in the upstream of the target system (mainly in inventory database construction), while the environmental impact assessment methods are different in the downstream. So the overall coupling analysis method is not formed. The current paper gives rational suggestions on the coupling development of the two systems in terms of the aggregate emergy flow table, the indicator system construction and indicator evaluation methods. In addition, it is necessary to introduce sensitivity analysis and uncertainty analysis in order to improve the reliability of assessment results. At present, the research on the coupling development of the two theories is in rapid development stage, but there are still many problems that need further exploration.

Keywords: emergy analysis; life cycle assessment; coupling evaluation; uncertainty analysis; sensitivity analysis

1. Introduction

At present, human production and consumption activities are completely dependent on the continuous supply of natural ecosystems, which are inherently complex and consist of several highly correlated subsystems. In the early stage, it was impossible to achieve quantitative research on natural ecosystems due to the lack of relevant theoretical research foundations [1]. In the middle of the 20th century, Odum et al. proposed the emergy analysis (EMA) theory based on theories of natural system energy control, ecology, and system theory [2]. It was mainly focused on the field of environmental science and ecology, which integrated environmental services into system analysis from the "donor" perspective and gradually developed into a scientific methodology [3]. The life cycle assessment (LCA) was born out of the research on energy consumption in the 1960s and 1970s [4]. It was initially used to analyze the human-oriented production process and system performance, and gradually extended to the field of raw material consumption and pollutant emissions. This method, which is highly practical, focuses on describing the crafting process and assessing the potential environmental impacts of strategic decisions and market policies [5].

Compared with EMA, LCA draws boundaries from a "user" perspective around human-dominated processes and systems. Environmental impact is divided into upstream and downstream impacts in LCA. The former includes processes such as resource input, production operation, and transportation, and the latter includes processes such as product output and pollutant treatment. These two theories share many similarities in their evaluation methods (model definition, data list, indicator evaluation, and results interpretation). Some scholars believe that EMA can be used to measure the "upstream" environmental impact of LCA in order to supplement the deficiency of the assessment phases of the life cycle impact [6]. Therefore, if the two evaluation methods are coupled together, the balance between human needs and natural services could be achieved, and the sustainability of natural ecosystems could be evaluated. In addition, it is possible to evaluate the resource utilization in the system. The aim of the current paper is to describe the similarities, differences, and coupling development methods of LCA and EMA based on exhaustive literature review, and provide feasible suggestions for its future development.

2. Theoretical Study on the Coupling of LCA and EMA

2.1. EMA Theory and Application

EMA is an environmental accounting method based on thermodynamic theory, which can achieve the sustainable assessment of the system by tracking the energy thermodynamic conversion path of resources, products, or services [7,8]. Based on EMA's specific algebraic rules, factors such as natural resources, production materials, ecosystem services, infrastructure construction, labor services, money, and information are converted into a single unit of emergy: sej. In this way, EMA could complete the spatio-temporal integration of different factors. It is suitable for analyzing complex ecosystems formed alternately from human economic activities and natural environment evolution [9–11].

EMA itself has an inherent "donor" (from the perspective of input, it belongs to the resource gift given by the natural ecosystem to the target system) perspective, commonly using emergy indicators to quantify the sustainability of a natural ecosystem in order to distinguish the dependence of different components in the system on solar energy and to assess the resource supply of the system in different energy levels [12]. At present, other evaluation methods, such as exergy analysis and ecological footprint theory, etc., have difficulties measuring the contribution of the natural ecosystem to economic development from a macro perspective [13,14]. EMA also has shortcomings from the perspective of accuracy. Criticism mainly comes from the fields of economics, physics, and engineering [15–17]. This has restricted the development of EMA theory.

There are four phases in the EMA target system. First of all, determine the system boundary and plot emergy system diagram, identify the main components, the interrelationship between the components, and the material flow and energy flow. Second, construct an emergy analysis table with

the input of major energy or other resources of the target system and output to the natural ecosystem. Third, build the emergy indicator system and calculate relevant indicators according to the indicator system. Since the relevant indicators have their own focus, the evaluation indicators are also different. Finally, interpret the result. The sustainability of the system should be analyzed and the relevant optimized scheme should be proposed.

At present, EMA is in a rapid development stage, but it still has several deficiencies. First, the EMA needs to improve the environmental effect assessment of the target system. Direct environmental impacts caused by resources, services, or products are incorporated into EMA data accounting [17]. However, it is not possible to use EMA to analyze direct or indirect environmental impacts specifically like LCA, which are caused by resource consumption, waste, or pollutant emissions, such as potential harm to the human body, ecological health, etc. Second, there are standardization issues in EMA methodology. Since the natural resources and climatic conditions of target system locations are different, and the emergy data has distinct regional characteristics, there is a localization problem of Unit Emergy Value (UEV). So far there are few clear and accurate UEV models to cope with this problem and no standard processing methods for model uncertainty analysis [17,18]. Third, EMA is greatly influenced by subjective factors in the determination of system boundaries and the choice of condition-assuming methods, and lacks the uncertainty analysis of emergy data, which affects the data's accuracy. Finally, EMA has unclear conceptual terms. For example, the "emergy baseline" has been repeatedly revised by researchers since its introduction. Although the emergy baseline has been determined so far, some scholars have made mistakes, mixing the UEV of old and new baselines, which have caused certain obstacles for the promotion and use of EMA [19–21].

At an early stage, EMA developed a series of indicators to evaluate eco-technological processes, such as Emergy Yield Ratio (EYR), Environmental Loading Ratio (ELR), Emergy Sustainability (ESI), Emergy Support Ratio (ESR), etc. After years of development, new emergy indicators have been continuously proposed to achieve assessments for different ecosystems, such as Renewable Percentage (%Re) [22], Energy Recovery Ratio (ERR) [23], Emergy Benefit after Exchange (EBE) [24], Net Profit (NP) [25], etc. As an effective tool for environmental management and policy planning [17], EMA has been widely used in a variety of macroscopic systems, such as agricultural systems [26–29], industrial systems [30–32], urban systems [33–35], etc. In addition, EMA is also widely used in the micro-system level, such as food production [36], energy supply [37,38], ecosystem services [39], waste disposal [40,41], and so on.

2.2. LCA Theory and Application

As a sophisticated environmental management tool, LCA enables the quantitative assessment of potential environmental impacts during the life cycle processes of a product or system. Now it is the standard procedure for studying the environmental performance of production processes. LCA can not only accurately analyze the environmental loading of its entire life cycle for specific products, but can also enable the horizontal comparison of different products to provide decision-making advice [42]. The evaluation model also has high flexibility to handle more complex and multi-scenario evaluation targets. Therefore, LCA has great advantages in the quantitative assessment of environmental impacts. Based on the "user" perspective, LCA believes that material consumption and environmental impacts will occur in all phases of the target system's life cycle [43]. Therefore, the input and output distribution of material and energy on each phase is refined to clarify the environmental performance of the target system. At present, LCA has become one of the most important tools of sustainability assessment, environmental certification, and product development. Since ecosystem services and resource factors are provided "for free" by the natural environment, they are often ignored by LCA, which limits the comprehensiveness of LCA [44].

LCA is divided into four phases [45]. The first phase is to define the goal and scope. The scope depends on the subject and aim of the study. The goal determines the depth and the breadth of LCA. The second phase is life cycle inventory analysis (LCI). It is an inventory with output and input data

according to the system boundary. The third phase is life cycle impact assessment (LCIA). The purpose of this phase is to provide additional information for analyzing LCI results. The final phase is to conduct a life cycle interpretation [46]. The results of LCI and LCIA are summarized and discussed in this phase. Conclusions and advices are reached in accordance with the scope and goal definition.

LCA also has some deficiencies. First of all, some scholars believe that its limitation lies in focusing only on the environmental impact of system emissions, without quantifying the environmental impact of ecosystem services, partially renewable and non-renewable resources, such as sunlight, rain, surface erosion, etc., [47–49]. Second, some researchers believe that the interpretation of the LCA system boundary lacks scientific basis, which results in strong subjectivity in the system boundary, and there are errors or even contradictions in calculation results. For instance, on the issue of comparing the environmental impacts of plastic cups and disposable paper cups, two researchers may arrive at opposite conclusions using different system boundary divisions [50,51]. Third, LCA is highly dependent on basic data. If the inventory data lags, the evaluation conclusions may not perfectly reflect the environmental impact of the current product [21]. Finally, most LCA currently use a single standard approach. In practice, the target system is often affected by many factors such as environment, technology, and capital. Therefore, environmental loading obtained by LCA cannot meet the overall requirements of multi-angle evaluation.

Therefore, some scholars have proposed an optimization approach based on multi-criteria methods for this situation. So the comprehensive evaluation of multiple parameters can be achieved to overcome complex decision problems [52].

At present, LCA has been widely used in macroscopic fields, such as industrial sector strategic planning [53,54], public system decision-making optimization [55], economic strategic planning [56], system sustainability development [57], etc. In addition, it is also widely used in microscopic fields, such as industrial building materials [58], the battery industry [59], steel production [60], waste disposal [61], biomass utilization [62], and so on.

The advantages, disadvantages, and complementarities between EMA and LCA are listed in Table 1.

Table 1. Advantages, disadvantages, and complementarities between emergy analysis (EMA) and life cycle assessment (LCA).

Item	Advantages	Disadvantages	Complementarities
EMA	Convert different kinds of resources into a single unit Donor-side perspective	Environmental effect assessment Standardization issues Accuracy problems Unclear conceptual terms	**Application area:** Both macroscopic and microscopic systems **Application purpose:** Natural ecosystem sustainability analysis **Analysis procedures:** Similar four phases **Research methodology:** Uncertainty analysis and sensitivity analysis
LCA	Environmental impact assessment User-side perspective	Lack environmental impact of ecosystem services System boundary determination problems Basic data lag problems Single standard approach	

2.3. Sensitivity Analysis and Uncertainty Analysis

The representativeness of parameter statistics is difficult to fully guarantee, and there are uncertainties inside and outside the system. Therefore, with the development of related theories, sensitivity analysis and uncertainty analysis are gradually incorporated into the evaluation methodology to improve the accuracy of assessment results.

There are many cases of sensitivity analysis in LCA research. Most of them analyzed the changing trend of characteristic indicators by changing system input flow. Therefore, the key factors affecting the target system environment were identified and the optimization scheme was proposed accordingly [63–65]. In addition, some scholars improved the LCA sensitivity analysis methodology for specific target systems. For example, Yu et al. proposed a new ecological design scheme, which used the sensitivity coefficient of LCI uncertainty to determine the key factors of the ecological design and accordingly proposed a targeted ecological design scheme [66].

On the other hand, there are only a few sensitivity analysis cases in EMA research at present. Most of them are similar to LCA sensitivity analysis methods, and they analyzed the changing trend of sustainability indicators based on changes of input flow. Ulgiati et al. developed a Sustainability Multi-criteria Multi-scale Assessment (SUMMA) model. By adjusting input quantity and the variable unit of the relevant influence coefficient, the sensitivity analysis of inventory data and impact indicator was carried out to determinate the reliability of the evaluation and key nodes in the evaluating process [67]. Liang et al. used the number of input flow and the mixture ratio as variables and the emergy index of sustainability as a dependent variable to determine the influence of input flow changes on sustainability changes. He analyzed the importance of biomass production and utilization on the sustainability of hydrogen production systems using this method [68].

Uncertainty analysis is very important for the reliability of ecosystem sustainability assessment models. It is more extensively used in LCA research and most of them used the parameter uncertainty analysis method, which is used to determine the inventory data source uncertainties [69]. At present, LCA uncertainty analysis methods mainly include the Monte Carlo analysis algorithm [70–72] and the Taylor expansion method [73–75]. A small portion of the analyses used fuzzy set theory [76]. Uncertainty analysis has been used less in EMA studies, most of which were tracing the source of uncertainty. For example, Amaral et al. discussed the source and processing methods of numerical uncertainty. It was considered that the system energy inflow and conversion factor calculation were the main sources of uncertainty, so the emergy evaluation process was always accompanied with numerical uncertainty [77]. Ingwersen et al. discussed the basic algorithmic differences of UEV and the sources of model uncertainty, and used the Monte Carlo model to analyze the applicability of analytical solutions and random solutions in EMA [78].

In EMA and LCA coupling studies, some scholars introduced uncertainty studies. Elvira et al. used the Monte Carlo model to simulate the uncertainty of the analysis results in order to solve the bias in data collection and the processing procedure [79]. Wesley et al. constructed an uncertainty model based on lognormal distribution to reduce the error caused by emergy calculation and data error, which provided a reference for determining the main factors that affect uncertainties [80]. Reza et al. used fuzzy set theory to evaluate the uncertainty of UEV and discussed effects caused by different uncertainty sources in assessment and the decision-making field [81].

3. Coupling Development Process

Based on the above literature reviews, we found that there is a high similarity between EMA and LCA in many aspects. First of all, in terms of analysis procedures, they both go through four steps of system boundary determination, data list analysis, model calculation, and result interpretation. There are similarities between the two methods from the perspective of the evaluation process. Second, in terms of application areas, both theories can be applied to the macro- and micro-level studies, in which each of them has formed quite a bit of research already. For example, EMA is widely used in industrial systems, agricultural systems, urban systems, etc., while LCA is generalized in fields of ecosystem services [82,83], food production [46,84], biomass diesel [85,86], building assessment [87], etc. Furthermore, in terms of research methodology, both theories have proposed the uncertainty analysis of inventory data and the sensitivity analysis of calculation results. Some scholars believe that it is necessary to apply the uncertainty and sensitivity analysis methods to the coupling of the two theories, which could facilitate the development of the coupling theory [88].

In this paper, through the software "citespace", papers with the themes of "emergy" and "life cycle assessment" were visually analyzed, and various "node types", such as "category", "keyword", and "type", were integrated. By combing the mutual reference relationship of related coupling literature research, the evolution of the coupling development of EMA and LCA was further clarified.

According to Figure 1, the coupling development of the two methods has gone through two stages. The first is the budding stage, from the beginning of 21st century to 2008. In order to expand the system boundary in ecosystem exergy analysis, Hau et al. introduced the EMA algorithm and the LCA concept [9]. When Sciubba and Ulgiati attempted to conduct coupling analysis between exergy and emergy, they proposed that the introduction of the LCA database could improve the accuracy of coupling analysis. Ulgiati et al. believed that renewable emergy provided by natural ecosystems could compensate for LCA's shortcomings in ecosystem product and service calculations [67]. This research idea provided important reference for future coupling studies. Based on the thermodynamic input-output model, Ukidwe et al. developed an assessment method for the accumulated consumption of ecological energy. The concept was highly similar to EMA, which emphasized quantifying the energy consumption of producing natural resources in order to make up for the lack of LCA in this area [89]. Pizzigallo et al. conducted research from different perspectives on the same case [90]. In this study, the input-output analysis using LCA highlighted the environmental performance of the target system, and the relationship between the production process and natural resources was discussed based on EMA, which revealed the complementarity of the two methods. In short, the coupling research is relatively limited and it is limited to the feasibility study of multi-scheme coupling in the field of environmental assessment, which laid the theoretical foundation for the development of coupling research.
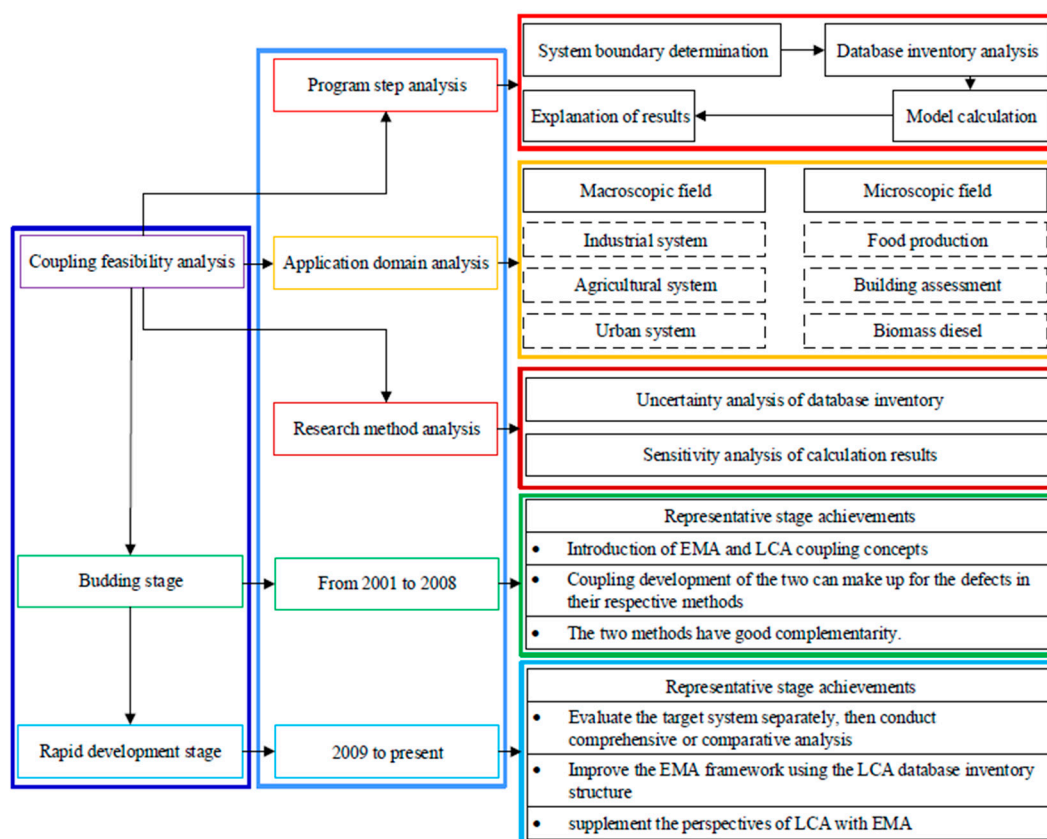

Figure 1. Emergy analysis (EMA) and life cycle assessment (LCA) coupling development research results.

Since 2009, the coupling study between EMA and LCA has had a rapid development. The research results at this stage are mainly divided into the following three categories. The first category is to

perform EMA and LCA evaluations on the target system separately, and then perform comprehensive or comparative analysis. Srinivasan et al. used LCA to estimate the life cycle energy value from the perspective of energy utilization and compared it with the life cycle emergy estimated by EMA [91]. In this way, they formed a scheme for incorporating upstream energy into the life cycle energy usage metric. Li et al. proposed a new coupling scheme, Hybrid Emergy-LCA (HEML), by using EMA to assess the emergy trend of resources and services, listing LCA inventory results to discuss system environmental performance, defining new indicators to integrate the two evaluation results [92]. Therefore, the annual emergy requirement of the target system could be quantified. Cui et al. used EMA and LCA to evaluate the target system separately, and then combined the resource consumption structure and the environmental performance of the target system to explore its sustainability [93]. The second category is to use LCA structures, indicators or inventory data to refine the EMA framework. Brown et al. referred to the widely used process input standard classification method in LCA and discussed spatial scale, boundary conditions, and input classification schemes that should be applied in EMA [94]. In this way, a general judgment framework suitable for EMA was proposed. Rugani et al. believed that using the LCI database and the LCA matrix framework to optimize EMA is the key for the coupling between EMA and LCA [95]. Reza et al. developed the emergy-based LCA framework in order to transfer currency cost into emergy and formed a sustainable comparative evaluation framework coupled with EMA and LCA [96]. Through this study, the input and output streams of the life cycle inventory database could be converted into equivalent emergy. Marvuglia et al., introduced the Software for Calculating Emergy based on life cycle inventories (SCALE), which realized the rigorous and reproducible calculation of the target products or service [19]. Their research is an effective exploration of the integration of the standardized LCI and EMA. The third category is to supplement the perspectives of LCA with EMA, which is to integrate ecological resources and service factors based on EMA in the upstream of the target system and to assess environmental impact based on LCA in the downstream of the target system [46,97]. In order to solve the problem of how to quantify ecological damage by the LCA midpoint evaluation model, Rugani et al., proposed to use UEV data as the affecting characterization factors of LCA [98]. By doing this, ecological losses could be quantified and the deficiencies of EMA in environmental performance assessment could be compensated. To solve the problem of uncertainty characterization in EMA, Ingwersen et al. developed a model that used emergy as an indicator of LCA. As a result, resources and services acquired from natural ecosystems could be quantified [80]. Gala et al. believed that EMA had a problem with waste and by-products' emergy distribution [99]. Therefore, LCA resource recycling and energy recovery processing mechanisms were introduced. And then EMA was supplemented based on the user's perspective. As a result, a recycling resource synergy process was formed. In short, the influence of coupling research between EMA and LCA in this stage has been greatly enhanced in the field of natural ecosystem assessment. The methodological basis has been laid for the next stage of the coupling development.

4. Coupling Development Prospect

Based on the summary of the EMA and LCA coupling methods literature, it is reasonable to believe that two aspects should be the focus of future coupling development: emergy indicator system construction and indicator evaluation.

Emergy flow table construction: Based on the common characteristics (emergy flow input and output) of EMA and LCA in database inventory construction, it is recommended to couple them by constructing the aggregate analysis table. The main idea is to list the input and output resources of the system, respectively, according to the LCA database inventory method at the stage of purchasing resource emergy accounting. The system input module incorporates ecological resources, labor services, and other factors. System output would be divided into two categories: product and waste [92,100]. The table is different from the single emergy analysis table or LCA database inventory, which not only

expands the system boundary, but can also clearly analyze the input proportion of the input emergy flow in the upstream of the target system.

Emergy indicator system construction: The construction of the emergy indicator system has always been one of the main hotspots in EMA academic research [96]. Li et al. (2009) believed that environmental impact is mainly quantified by the indicator ELR in EMA, which can only show the regional environmental load of the system but cannot accurately analyze the pollutant emissions caused by the system operation process [92]. Thus, the indicator WR (Waste Ratio) was proposed to optimize the treatment of the system waste. Reza et al. expanded the EMA indicator system and developed a new set of indicators correspondingly [96]. They also revised the EL (Emergy Equivalent of Loss) indicator, which can be used to quantify various parameters into emergy, such as human health loss, ecological loss, and solid waste emission loss in LCA. Srinivasan et al. summarized the advantages and disadvantages of combining EMA with two LCA schemes and revealed a relatively clear optimization direction for the emergy indicator system [91]. The comprehensiveness of Economic Input-Output life cycle assessment (EIO-LCA) in the assessment of upstream energy use was revealed and the advantages of Ecologically based life cycle assessment (ECO-LCA) in architectural design, construction, and operation were reflected. In short, some new indicators will be proposed correspondingly with the requirements of research objectives. Indicator system construction will be an important direction for EMA and LCA coupling research.

Emergy indicator evaluation: The selection of a reasonable and effective indicator evaluation method is an important prerequisite for EMA and LCA coupling analysis. Kursun synthesized dimensionless indicators of EMA, standardized indicators of LCA, and cost indicators [101]. The research idea of optimal combination was put forward by means of multi-objective linear programming. Liu et al., 2017, introduced DALY (Disability-Adjusted Life Years) and PDF (Potentially Disappeared Fraction of Species) to calculate the human health and ecosystem loss emergy caused by different emissions, and then incorporated them into the emergy indicator system [100]. This method provided a new idea for the coupling scheme based on the EMA indicators.

Generally speaking, the evaluation methods of EMA and LCA coupling are different, but whether turning parameters into emergy or making indicators dimensionless, all coupling ideas are effective explorations of EMA and LCA coupling studies. The coordination degree is one of the most important characteristics to characterize the sustainable development level. Therefore, it is necessary to discuss whether it is possible to introduce cooperative entropy theory into EMA and LCA coupling studies. By introducing synergistic entropy function, more accurate collaborative clustering could be achieved, which is based on the full usage of EMA and LCA parameters, and the synergy relationship intensity of case systems could be obtained. In this way, a more comprehensive judgment could be provided for target system sustainability evaluation [102].

5. Conclusions

The theoretical basis and application areas of EMA and LCA were summarized, and the potential links between LCA and EMA based on different perspectives were discussed in this paper. EMA is a donor-side evaluation method, which makes the evaluation scope more perfect based on its compatibility with economic and social factors. On the other hand, as a user-side assessment method, LCA is more sensitive to system resource consumption and environmental impact due to its sophisticated and flexible framework. Based on the current analysis, the LCA framework can compensate for the insufficiency of the normalization of emergy flow distribution and the comprehensiveness of impact analysis in the EMA procedure. EMA can be used to supplement LCA with resource-localized treatment options and the quantitative analysis of ecosystem services. Therefore, the two theories can complement each other, which provides the necessary foundation for the coupling development of LCA and EMA.

The coupling research of LCA and EMA will be deepened step by step, and it is considered that the best trend of coupling development is to exert their maximum functional advantages. At present,

some scholars have studied the coupling methods, but the coupling approaches are different and lack unanimously approved methodologies. Therefore, the following aspects should be highlighted as the requirements of coupling development. First, speed up the optimization and updating process of the LCA inventory database, improve its accuracy, and gradually incorporate the ecosystem service data into it. Second, strengthen the standardization and consistency research on the flow distribution rules of EMA and LCA. The coupling methodology research should be strengthened also. Third, EMA and LCA indicator system construction and its evaluation methods need to be continuously improved. Fourth, the uncertainty degree is high due to the differences of coupling methods and inherent special properties in the UEV. It is necessary to develop a more complex version of the stochastic model or to adopt mathematical modeling to strengthen the study of the uncertainty analysis of the coupling between EMA and LCA in order to improve the accuracy of the coupling assessment. Based on the above issues, the development of EMA and LCA coupling was prospected in three aspects—emergy flow table construction, emergy indicator system construction, and emergy indicator evaluation—in this review, which hopes to provide a coupling analysis method that can be extended.

Author Contributions: Q.W., H.X., Q.M. and X.Y. assumed the idea and wrote the manuscript. J.Z. (Jian Zuo), J.Z. (Jian Zhang), S.W. and M.W. revised the manuscript. All authors approved the final version of this paper. Writing—review and editing, Q.W. and H.X. Writing—original draft preparation, Q.W. and Q.M.; formal analysis, X.Y.; supervision, J.Z. (Jian Zuo), J.Z. (Jian Zhang), S.W. and M.W. All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Lou, B.; Qiu, Y.; Ulgiati, S. Emergy-based indicators of regional environmental sustainability: A case study in Shanwei, Guangdong, China. *Ecol. Indic.* **2015**, *57*, 514–524. [CrossRef]
2. Brown, M.T.; Ulgiati, S. Emergy-based indices and ratios to evaluate sustainability: Monitoring economies and technology toward environmentally sound innovation. *Ecol. Eng.* **1997**, *9*, 51–69. [CrossRef]
3. Vassallo, P.; Paoli, C.; Fabiano, M. Emergy required for the complete treatment of municipal wastewater. *Ecol. Eng.* **2009**, *35*, 687–694. [CrossRef]
4. Morrison, M.; Srinivasan, R.S.; Ries, R. Complementary life cycle assessment of wastewater treatment plants: An integrated approach to comprehensive upstream and downstream impact assessments and its extension to building-level wastewater generation. *Sustain. Cities Soc.* **2016**, *23*, 37–49. [CrossRef]
5. Boustead, I. Resource implications with particular reference to energy requirements for glass and plastic milk bottles. *Int. J. Dairy Technol.* **1974**, *27*, 159–165. [CrossRef]
6. Raugei, M.; Rugani, B.; Benetto, E.; Ingwersen, W.W. Integrating emergy into LCA: Potential added value and lingering obstacles. *Ecol. Model.* **2014**, *271*, 4–9. [CrossRef]
7. Hau, J.L.; Bakshi, B.R. Promise and problems of emergy analysis. *Ecol. Model.* **2004**, *178*, 215–225. [CrossRef]
8. Cho, C.J. An exploration of reliable methods of estimating emergy requirements at the regional scale: Traditional emergy analysis, regional thermodynamic input-output analysis, or the conservation rule-implicit method. *Ecol. Model.* **2013**, *251*, 288–296. [CrossRef]
9. Brown, M.T.; Herendeen, R.A. Embodied energy analysis and EMERGY analysis: A comparative view. *Ecol. Econ.* **1996**, *19*, 219–235. [CrossRef]
10. Odum, H.T.; Doherty, S.J.; Scatena, F.N.; Kharecha, P.A. Emergy evaluation of reforestation alternatives in Puerto Rico. *For. Sci.* **2000**, *46*, 521–530.
11. Ju, L.P.; Chen, B. Embodied energy and emergy evaluation of a typical biodiesel production chain in China. *Ecol. Model.* **2011**, *222*, 2385–2392. [CrossRef]
12. Yang, Q.; Liu, G.Y.; Hao, Y.; Zhang, L.X.; Giannetti, B.F.; Wang, J.J.; Casazza, M. Donor-side evaluation of coastal and marine ecosystem services. *Water Res.* **2019**, *166*, 115028. [CrossRef] [PubMed]

13.　Geng, Y.; Sarkis, J.; Ulgiati, S.; Zhang, P. Measuring China's circular economy. *Science* **2013**, *339*, 1526–1527. [CrossRef] [PubMed]

14.　Jiang, M.M.; Chen, Z.M.; Zhang, B.; Li, S.C.; Xia, X.H.; Zhou, S.Y.; Zhou, J.B. Ecological Economic Evaluation Based on Emergy as Embodied Cosmic Exergy: A Historical Study for the Beijing Urban Ecosystem 1978–2004. *Entropy* **2010**, *12*, 1696–1720.

15.　Mansson, B.A.; McGlade, J.M. Ecology, thermodynamics and H.T. Odum's conjectures. *Oecologia* **1993**, *93*, 582–596. [CrossRef]

16.　Cleveland, C.J.; Kaufmann, R.K.; Stern, D.I. Aggregation and the role of energy in the economy. *Ecol. Econ.* **2000**, *32*, 301–317. [CrossRef]

17.　Brown, M.T.; Campbell, D.E.; Franzese, P.P.; Ulgiati, S. The geobiosphere emergy baseline: A synthesis. *Ecol. Model.* **2016**, *339*, 89–91. [CrossRef]

18.　Sciubba, E. On the Second-Law inconsistency of Emergy Analysis. *Energy* **2010**, *35*, 3696–3706. [CrossRef]

19.　Marvuglia, A.; Benetto, E.; Rios, G.; Rugani, B. SCALE: Software for CAL culating Emergy based on life cycle inventories. *Ecol. Model.* **2013**, *248*, 80–91. [CrossRef]

20.　Brown, M.T.; Ulgiati, S. Updated evaluation of exergy and emergy driving the geobiosphere: A review and refinement of the emergy baseline. *Ecol. Model.* **2010**, *221*, 2501–2508. [CrossRef]

21.　Zhang, X.H.; Wei, Y.; Pan, H.Y.; Xiao, H.; Wu, J.; Zhang, Y.Z. The comparison of performances of a sewage treatment system before and after implementing the cleaner production measure. *J. Clean. Prod.* **2015**, *91*, 216–228. [CrossRef]

22.　Brown, M.T.; Ulgiati, S. Emergy evaluations and environmental loading of electricity production systems. *J. Clean. Prod.* **2002**, *10*, 321–334. [CrossRef]

23.　Song, Q.; Wang, Z.; Li, J.; Duan, H.B. Sustainability evaluation of an e-waste treatment enterprise based on emergy analysis in China. *Ecol. Eng.* **2012**, *42*, 223–231. [CrossRef]

24.　Lu, H.F.; Campbell, D.E.; Li, Z.A.; Ren, H. Emergy synthesis of an agro-forest restoration system in lower subtropical China. *Ecol. Eng.* **2006**, *27*, 175–192. [CrossRef]

25.　Zuo, P.; Wan, S.W.; Qin, P.; Du, J.J.; Wang, H. A comparison of the sustainability of original and constructed wetlands in Yancheng Biosphere Reserve, China: Implications from emergy evaluation. *Environ. Sci. Policy* **2004**, *7*, 329–343. [CrossRef]

26.　Ting, Y.I.; Xiang, P.A. Emergy analysis of paddy farming in Hunan Province, China: A new perspective on sustainable development of agriculture. *J. Integr. Agric.* **2016**, *15*, 2426–2436.

27.　Kang, D. Emergy Evaluation of Korean Agriculture. *J. Environ. Sci. Int.* **2017**, *26*, 1087–1099. [CrossRef]

28.　Sun, L.; Han, J.C.; Wu, F.Q. Emergy and benefit evaluation of "pig-methane-pomegranate" recycling agriculture in Guanzhong Plain. *Agric. Res. Arid Areas* **2017**, *35*, 199–242. (In Chinese)

29.　Chang, T.; Yang, D.G.; Huo, J.W.; Xia, F.Q.; Zhang, Z.P. Evaluation of Oasis Sustainability Based on Emergy and Decomposition Analysis. *Sustainability* **2018**, *10*, 1856. [CrossRef]

30.　Min, S.; Feng, X. New emergy evaluating indices for industrial systems. *Energy Source Part B* **2008**, *3*, 133–143. [CrossRef]

31.　Ren, J.; Liang, H.; Dong, L.; Sun, L.; Gao, Z.Q. Design for sustainability of industrial symbiosis based on emergy and multi-objective particle swarm optimization. *Sci. Total Environ.* **2016**, *562*, 789–801. [CrossRef] [PubMed]

32.　Sun, L.; Li, H.; Dong, L.; Fang, K.; Ren, J.Z.; Geng, Y.; Fujii, M.; Zhang, W.; Zhang, N.; Liu, Z. Eco-benefits assessment on urban industrial symbiosis based on material flows analysis and emergy evaluation approach: A case of Liuzhou city, China. *Resour. Conserv. Recycl.* **2017**, *119*, 78–88. [CrossRef]

33.　Qi, W.; Deng, X.Z.; Chu, X.; Zhao, C.H.; Zhang, F. Emergy analysis on urban metabolism by counties in Beijing. *Phys. Chem. Earth* **2017**, *101*, 157–165. [CrossRef]

34.　Huang, Y.; Liu, G.Y.; Chen, C.C.; Yang, Q.; Wang, X.Q.; Giannetti, B.F.; Zhang, Y.; Gasazza, M. Emergy-based comparative analysis of urban metabolic efficiency and sustainability in the case of big and data scarce medium-sized cities, A case study for Jing-Jin-Ji Region (China). *J. Clean. Prod.* **2018**, *192*, 621–638. [CrossRef]

35.　Keena, N.; Raugei, M.; Etman, M.A.; Ruan, D.; Dyson, A. Clark's Crow: A design plugin to support emergy analysis decision making towards sustainable urban ecologies. *Ecol. Model.* **2018**, *367*, 42–57. [CrossRef]

36.　Wang, X.L.; Tan, K.M.; Chen, Y.Q.; Chen, Y.; Shen, X.F.; Zhang, L.; Dong, C.X. Emergy-based analysis of grain production and trade in China during 2000–2015. *J. Clean. Prod.* **2018**, *193*, 59–71. [CrossRef]

37. Zhang, H.L.; Guan, X.; Ding, Y.; Liu, C. Emergy analysis of Organic Rankine Cycle (ORC) for waste heat power generation. *J. Clean. Prod.* **2018**, *183*, 1207–1215. [CrossRef]

38. Zhang, L.X.; Tang, S.J.; Hao, Y.; Pang, M.Y. Integrated emergy and economic evaluation of a case tidal power plant in China. *J. Clean. Prod.* **2018**, *182*, 38–45. [CrossRef]

39. Zhan, J.Y.; Zhang, F.; Chu, X.; Liu, W.; Zhang, Y. Ecosystem services assessment based on emergy accounting in Chongming Island, Eastern China. *Ecol. Indic.* **2019**, *105*, 464–473. [CrossRef]

40. Cai, W.; Liu, C.H.; Zhang, C.X.; Ma, M.D.; Rao, W.Z.; Li, W.Y.; He, K.; Gao, M.D. Developing the ecological compensation criterion of industrial solid waste based on emergy for sustainable development. *Energy* **2018**, *157*, 940–948. [CrossRef]

41. Wang, Y.Q.; Zhang, X.H.; Liao, W.J.; Wu, J.; Yang, X.D.; Shui, W.; Deng, S.H.; Zhang, Y.Z.; Lin, L.; Xiao, Y.L.; et al. Investigating impact of waste reuse on the sustainability of municipal solid waste (MSW) incineration industry using emergy approach: A case study from Sichuan province, China. *Waste Manag.* **2018**, *77*, 252–267. [CrossRef] [PubMed]

42. Maranghi, S.; Parisi, M.L.; Basosi, R.; Sinicropi, A. Environmental Profile of the Manufacturing Process of Perovskite Photovoltaics: Harmonization of Life Cycle Assessment Studies. *Energies* **2019**, *12*, 3746. [CrossRef]

43. Chang, D.N.; Lee, C.K.M.; Chen, C.H. Review of life cycle assessment towards sustainable product development. *J. Clean. Prod.* **2014**, *83*, 48–60. [CrossRef]

44. Liu, H.C.; Huang, Y.Q.; Yuan, H.Y.; Yin, X.L.; Wu, C.Z. Life cycle assessment of biofuels in China: Status and challenges. *Renew. Sustain. Energy Rev.* **2018**, *97*, 301–322. [CrossRef]

45. The International Standards Organization. *ISO 14040:2006 Environmental Management—Life Cycle Assessment—Principles and Guidelines*; International Standards Organization: Geneva, Switzerland, 2006.

46. The International Standards Organization. *ISO 14044:2006 Environmental Management—Life Cycle Assessment—Requirements and Guidelines*; International Standards Organization: Geneva, Switzerland, 2006.

47. Yong, S.P.; Egilmez, G.; Kucukvar, M. Emergy and end-point impact assessment of agricultural and food production in the United States: A supply chain-linked Ecologically-based Life Cycle Assessment. *Ecol. Indic.* **2016**, *62*, 117–137.

48. Benedetto, R.; Danielle, M.D.S.; Bo, P.W.; Jane, B.; Bhavik, B.; Blane, G.; John, M.J.; Ana, L.R.P.; Xin, Y.L.; Alexis, L.; et al. Towards integrating the ecosystem services cascade framework within the Life Cycle Assessment (LCA) cause-effect methodology. *Sci. Total Environ.* **2019**, *690*, 1284–1298.

49. Brown, M.T.; Buranakarn, V. Emergy indices and ratios for sustainable material cycles and recycle options. *Resour. Conserv. Recycl.* **2003**, *38*, 1–22. [CrossRef]

50. Mccubbin, N. Paper versus polystyrene: Environmental impact. *Science* **1991**, *252*, 1361–1363. [CrossRef]

51. Hocking, M.B. Paper versus polystyrene: A complex choice. *Science* **1991**, *251*, 504–505. [CrossRef]

52. Vukelic, D.; Budak, I.; Tadic, B.; Simunobic, G.; Kljajic, V.; Agarski, B. Multi-criteria decision-making and life cycle assessment model for optimal product selection: Case study of knee support. *Int. J. Environ. Sci. Technol.* **2017**, *14*, 353–364. [CrossRef]

53. Navajas, A.; Uriarte, L.; Gandía, L.M. Application of Eco-Design and Life Cycle Assessment Standards for Environmental Impact Reduction of an Industrial Product. *Sustainability* **2017**, *9*, 1724. [CrossRef]

54. Royne, F.; Hackl, R.; Ringstrom, E.; Berlin, J. Environmental Evaluation of Industry Cluster Strategies with a Life Cycle Perspective: Replacing Fossil Feedstock with Forest-Based Feedstock and Increasing Thermal Energy Integration. *J. Ind. Ecol.* **2018**, *22*, 694–705. [CrossRef]

55. Chiu, S.L.H.; Lo, I.M.C.; Woon, K.S.; Yan, D.Y.S. Life cycle assessment of waste treatment strategy for sewage sludge and food waste in Macau: Perspectives on environmental and energy production performance. *Int. J. Life Cycle Assess.* **2016**, *21*, 176–189. [CrossRef]

56. Koo, C.; Hong, T.; Park, J. Development of the life-cycle economic and environmental assessment model for establishing the optimal implementation strategy of the rooftop photovoltaic system. *Technol. Econ. Dev. Econ.* **2018**, *24*, 27–47. [CrossRef]

57. Giaccherini, A.; Baldassarre, A.; Donini, L.; Lepore, G.O.; Caneschi, A.; De, L.A.; Innocenti, M.; Montegrossi, G.; Giuseppe, C.; Oberhauser, W.; et al. Sustainable synthesis of quaternary sulphides: The problem of the uptake of zinc in CZTS. *J. Alloys Compd.* **2018**, *775*, 1221–1229. [CrossRef]

58. Yuan, X.L.; Tang, Y.Z.; Li, Y.; Wang, Q.S.; Zuo, J.; Song, Z.L. Environmental and economic impacts assessment of concrete pavement brick and permeable brick production process—A case study in China. *J. Clean. Prod.* **2018**, *171*, 198–208. [CrossRef]

59. Wang, Q.S.; Liu, W.; Yuan, X.L.; Tang, H.R.; Tang, Y.Z.; Wang, M.S.; Zuo, J.; Song, Z.L.; Sun, J. Environmental Impact Analysis and Process Optimization of Batteries Based on Life Cycle Assessment. *J. Clean. Prod.* **2018**, *174*, 1262–1273. [CrossRef]

60. Ma, X.T.; Ye, L.P.; Qi, C.C.; Yang, D.L.; Shen, X.X.; Hong, J.L. Life cycle assessment and water footprint evaluation of crude steel production: A case study in China. *J. Environ. Manag.* **2018**, *224*, 10–18. [CrossRef]

61. Larsen, J.D.; Hoeve, M.T.; Nielsen, S.; Scheutz, C. Life cycle assessment comparing the treatment of surplus activated sludge in a sludge treatment reed bed system with mechanical treatment on centrifuge. *J. Clean. Prod.* **2018**, *185*, 148–156. [CrossRef]

62. Welfle, A.; Gilbert, P.; Thornley, P.; Stephenson, A. Generating low-carbon heat from biomass: Life cycle assessment of bioenergy scenarios. *J. Clean. Prod.* **2017**, *149*, 448–460. [CrossRef]

63. Pelletier, N.; Pirog, R.; Rasmussen, R. Comparative life cycle environmental impacts of three beef production strategies in the Upper Midwestern United States. *Agric. Syst.* **2010**, *103*, 380–389. [CrossRef]

64. Smetana, S.; Mathys, A.; Knoch, A.; Heinz, V. Meat alternatives: Life cycle assessment of most known meat substitutes. *Int. J. Life Cycle Assess.* **2015**, *20*, 1254–1267. [CrossRef]

65. Wu, J.F.; Zhang, X.P.; Jia, L.; He, Y.F.; Huang, L. Life Cycle Assessment of Centrifugal Chiller on Environment Impacts and Its Key Influence Factors'. *J. Referig.* **2016**, *37*, 58–64. (In Chinese)

66. Yu, X.; Zhang, H.Q.; Shu, H.P.; Zhao, W.D.; Yan, T.; Liu, Y.H.; Wang, X. A Robust Eco-Design Approach Based on New Sensitivity Coefficients by Considering the Uncertainty of LCI. *J. Adv. Manuf. Syst.* **2017**, *16*, 185–203. [CrossRef]

67. Ulgiati, S.; Raugei, M.; Bargigli, S. Overcoming the inadequacy of single-criterion approaches to Life Cycle Assessment. *Ecol. Model.* **2006**, *190*, 432–442. [CrossRef]

68. Liang, H.W.; Ren, J.Z.; Dong, L. Is the hydrogen production from biomass technology really sustainable? Answer by Life Cycle Emergy Analysis. *Int. J. Hydrog. Energy* **2016**, *41*, 10507–10514. [CrossRef]

69. Chen, X.J.; Griffin, W.M.; Matthews, H.S. Representing and visualizing data uncertainty in input-output life cycle assessment models. *Resour. Conserv. Recycl.* **2018**, *137*, 316–332. [CrossRef]

70. Sonnemann, G.W.; Schuhmacher, M.; Castells, F. Uncertainty assessment by a Monte Carlo simulation in a life cycle inventory of electricity produced by a waste incinerator. *J. Clean. Prod.* **2003**, *11*, 279–292. [CrossRef]

71. Parisi, M.L.; Ferrara, N.; Torsello, L.; Basosi, R. Life cycle assessment of atmospheric emission profiles of the Italian geothermal power plants. *J. Clean. Prod.* **2019**, *234*, 881–894. [CrossRef]

72. Muller, S.; Mutel, C.; Lesage, P.; Samson, R. Effects of Distribution Choice on the Modeling of Life Cycle Inventory Uncertainty: An Assessment on the Ecoinvent v2.2 Database. *J. Ind. Ecol.* **2017**, *22*, 300–313. [CrossRef]

73. Hong, J.L.; Shake, S.; Rosenbaum, R.K.; Jolliet, O. Analytical uncertainty propagation in life cycle inventory and impact assessment: Application to an automobile front panel. *Int. J. Life Cycle Assess.* **2010**, *15*, 499–510. [CrossRef]

74. Hong, J.L. Uncertainty propagation in life cycle assessment of biodiesel versus diesel: Global warming and non-renewable energy. *Bioresour. Technol.* **2012**, *113*, 3–7. [CrossRef] [PubMed]

75. Hong, J.L.; Zhang, Y.L.; Xu, X.; Li, X.Z. Life cycle assessment of corn- and cassava-based ethylene production. *Biomass Bioenergy* **2014**, *67*, 304–311. [CrossRef]

76. Groen, E.A.; Heijungs, R.; Bokkers, E.A.M.; de Boer, I.J.M. Methods for uncertainty propagation in life cycle assessment. *Environ. Model. Softw.* **2014**, *62*, 316–325. [CrossRef]

77. Amaral, L.P.; Martins, N.; Gouveia, J.B. A review of emergy theory, its application and latest developments. *Renew. Sustain. Energy Rev.* **2016**, *54*, 882–888. [CrossRef]

78. Ingwersen, W.W. Uncertainty characterization for emergy values. *Ecol. Model.* **2010**, *221*, 445–452. [CrossRef]

79. Elvira, B.; Laura, V.; Alberto, C.; Ulgiati, S. Integrating life cycle assessment and emergy synthesis for the evaluation of a dry steam geothermal power plant in Italy. *Energy* **2015**, *86*, 476–487.

80. Ingwersen, W.W. Emergy as a Life Cycle Impact Assessment Indicator. *Ind. Ecol.* **2011**, *15*, 550–567. [CrossRef]

81. Reza, B.; Sadiq, R.; Hewage, K. A fuzzy-based approach for characterization of uncertainties in emergy synthesis: An example of paved road system. *J. Clean. Prod.* **2013**, *59*, 99–110. [CrossRef]

82. Sun, C.; Wang, Y.; Zou, W. The marine ecosystem services values for China based on the emergy analysis method. *J. Ocean Coast. Manag.* **2018**, *161*, 66–73. [CrossRef]

83. Pavan, A.L.R.; Ometto, A.R. Ecosystem Services in Life Cycle Assessment: A novel conceptual framework for soil. *Sci. Total. Environ.* **2018**, *643*, 1337–1347. [CrossRef] [PubMed]

84. Perez-Martinez, M.M.; Noguerol, R.; Casales, B.I.; Lois, R.; Soto, B. Evaluation of environmental impact of two ready-to-eat canned meat products using Life Cycle Assessment. *J. Food Eng.* **2018**, *237*, 118–127. [CrossRef]

85. Lardon, L.; Hélias, A.; Sialve, B.; Steyer, J.P.; Bernard, O. Life-cycle assessment of biodiesel production from microalgae. *Environ. Sci. Technol.* **2009**, *43*, 6475–6481. [CrossRef] [PubMed]

86. Saladini, F.; Gopalakrishnan, V.; Bastianoni, S.; Bakshi, B.R. Synergies between industry and nature—An emergy evaluation of a biodiesel production system integrated with ecological systems. *Ecosyst. Serv.* **2018**, *30*, 257–266. [CrossRef]

87. Pulselli, R.M.; Simoncini, E.; Pulselli, F.M.; Bastianoni, S. Emergy analysis of building manufacturing, maintenance and use: Em-building indices to evaluate housing sustainability. *Energy Build.* **2007**, *39*, 620–628. [CrossRef]

88. Finnveden, G.; Hauschild, M.Z.; Ekvall, T.; Guinee, J.; Heijungs, R.; Hellweg, S.; Koehler, A.; Pennington, D.; Suh, S. Recent developments in Life Cycle Assessment. *J. Environ. Manag.* **2009**, *91*, 1–21. [CrossRef]

89. Ukidwe, N.U.; Bakshi, B.R. Industrial and ecological cumulative exergy consumption of the United States via the 1997 input-output benchmark model. *Energy* **2007**, *32*, 1560–1592. [CrossRef]

90. Pizzigallo, A.C.I.; Granai, C.; Borsa, S. The joint use of LCA and emergy evaluation for the analysis of two Italian wine farms. *J. Environ. Manag.* **2008**, *86*, 396–406. [CrossRef]

91. Srinivasan, R.S.; Ingwersen, W.; Trucco, C.; Ries, R.; Campbell, D. Comparison of energy-based indicators used in life cycle assessment tools for buildings. *Build. Environ.* **2014**, *79*, 138–151. [CrossRef]

92. Li, D.; Wang, R.S. Hybrid Emergy-LCA (HEML) based metabolic evaluation of urban residential areas: The case of Beijing, China. *Ecol. Complex.* **2009**, *6*, 484–493. [CrossRef]

93. Cui, J.X.; Yan, P.; Wang, X.L.; Yang, J.; Li, Z.J.; Yang, X.L.; Sui, P.; Chen, Y.Q. Integrated assessment of economic and environmental consequences of shifting cropping systemfrom wheat-maize to monocropped maize in the North China Plain. *J. Clean. Prod.* **2018**, *193*, 524–532. [CrossRef]

94. Brown, M.T.; Raugei, M.; Ulgiati, S. On boundaries and 'investments' in Emergy Synthesis and LCA: A case study on thermal vs. photovoltaic electricity. *Ecol. Indic.* **2012**, *15*, 227–235. [CrossRef]

95. Rugani, B.; Benetto, E. Improvements to Emergy Evaluations by Using Life Cycle Assessment. *Environ. Sci. Technol.* **2012**, *46*, 4701–4712. [CrossRef] [PubMed]

96. Reza, B.; Sadiq, R.; Hewage, K. Emergy-based life cycle assessment (Em-LCA) for sustainability appraisal of infrastructure systems: A case study on paved roads. Clean Technol. *Environ. Policy* **2014**, *16*, 251–266. [CrossRef]

97. Duan, N.; Liu, X.D.; Dai, J.; Lin, C.; Xia, X.H.; Gao, R.Y.; Wang, Y.; Chen, S.Q.; Yang, J.; Qi, J. Evaluating the environmental impacts of an urban wetland park based on emergy accounting and life cycle assessment: A case study in Beijing. *Ecol. Model.* **2011**, *222*, 351–359. [CrossRef]

98. Rugani, B.; Benetto, E.; Arbault, D.; Tiruta-Barna, L. Emergy-based mid-point valuation of ecosystem goods and services for life cycle impact assessment. *Int. J. Metall.* **2013**, *10*, 249–264. [CrossRef]

99. Gala, A.B.; Raugei, M.; Ripa, M.; Ulgiati, S. Dealing with waste products and flows in life cycle assessment and emergy accounting: Methodological overview and synergies. *Ecol. Model.* **2015**, *315*, 69–76. [CrossRef]

100. Liu, G.Y.; Hao, Y.; Dong, L.; Yang, Z.F.; Zhang, Y.; Ulgiati, S. An emergy-LCA analysis of municipal solid waste management. *Resour. Conserv. Recycl.* **2017**, *120*, 131–143. [CrossRef]

101. Kursun, B.; Bakshi, B.R.; Mahata, M.; Martin, J.F. Life cycle and emergy based design of energy system in developing countries: Centralized and localized options. *Ecol. Model.* **2015**, *305*, 40–53. [CrossRef]

102. Sun, C.Z.; Zhang, K.L.; Zou, W.; Wang, Z.Y. Study on regional system of man-sea relationship and its synergetic development in the coastal regions of China. *Geogr. Res.* **2015**, *4*, 1824–1838. (In Chinese)