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Developing a procedure for the integration of Life Cycle Assessment and Emergy Accounting approaches. The Amalfi paper case study

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ABSTRACT

The analysis of complex systems requires an integrated application of different assessment methods also taking into account different scales and points of view to gain a systemic understanding of the investigated case study. Life Cycle Assessment (LCA) and Emergy Accounting (EMA) are both environmental assessment methods, showing many similarities in the way they are performed, especially with respect to the inventory construction and to the interpretation of results. They also show great differences, the main residing in the different perspectives they give. LCA applies a consumer side perspective, and its space and time scales are set at a boundary capable to include all the process phases in terms of location and durability and their direct impacts on the investigated areas. On the other hand, throughout its donor side perspective, EMA expands the boundaries of the system over the entire biosphere space and time scales. Differences and similarities between LCA and EMA may gain added value by their implementation within a procedural framework which exploits the characteristics of the two methods. The present work proposes a methodological procedure based on the sequential and integrated application of LCA and EMA methods, called LEAF (LCA & EMA Applied Framework). The traditional Amalfi paper production is used as a test case study. The procedure stems include: (i) an ex-ante LCA analysis, to identify the hotspots of the investigated case study; (ii) the assessment of the environmental performance of the system through the development of different EMA-based improvement scenarios built around the chosen hotspots; and (iii) an ex-post LCA application built on each scenario results in order to detect the different environmental burdens. The application of LEAF to the traditional Amalfi paper production shows that the use of a more sustainable energy source is an effective solution (among the set of proposed options) to increase the sustainability of the investigated system.

1. Introduction

Science presents highly specialization features: most often it requires a specialized knowledge base and a likewise approach to problems. This induced science to develop a wide range of specialties and subspecialties delineating separate fields of study and widening their knowledge base, making specialization unavoidable as the amount of information becomes too large for any individual scientist to deal with (Casadevall and Fang, 2014). The reductionist approach relies on the notion that fundamental entities form complex systems, whose properties are always found among those of their parts. According to reductionist views, knowledge of the parts is both necessary and sufficient for understanding the whole (Keller, 2019). Reductionism contributed to the development of science and to many of the advances of human civilization, but it also presents drawbacks, in the form of information overload, boundaries imposed to the flow of knowledge and oversimplification (Gallagher and Appenzeller, 1999). Although having proved very beneficial to the development of specific aspects of knowledge, reductionism often neglects that "the whole is greater than the sum of its parts" and it fails in providing solutions for human environment, social systems, economics, and survival, for "the missing information is not wholly in the microscopic components or in identification of the parts" (Odum, 2007). A top-down, or outward/inward, perspective is necessary, trying to explain the lower levels behavior from "the next larger scale" (Odum, 1996). This is not sufficient by itself though, as it is likely to provide an equally incomplete view as the traditional reductionism. One way strategies, top-down or bottom up, are invariably disregarding important parts of the picture, and only multi-perspective approaches can achieve a broader, if not full, understanding of systems (Nielsen, 2019). A step back is thus required in

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order to see the big picture, joining the parts is beneficial for understanding networks and investigate the performance of larger systems. Because of this, science also needs to adopt holistic perspectives to look at the problems, including environmental problems, at a larger scale, in order to see the complete picture (Odum and Odum, 2001). Systems presenting emerging properties cannot be described only by listing the composing elements: it is necessary to capture, understand, and describe the emerging system properties (Jorgensen, 2012).

When analyzing systems or processes, the simultaneous application of different assessment methods may be advantageous in the perspective of looking at them from different scales and points of view in order to gain a systemic understanding of the investigated case study. A wide range of environmental assessment methods have been developed through the years, each one of them answering to different questions and bringing different perspectives when tackling environmental problems (Eurostat, 2001; Finn, 1976; ISO, 2006; Jorgensen, 1995; Odum, 1996; Wackernagel and Rees, 1996). Some of them show comparable results, some apply entirely different perspectives, others show common features, whether giving separate results. The simultaneous application of different methods may be capable of providing different but complementary information. This is the case with Life Cycle Assessment (LCA) and Emergy Analysis (EMA) methods. The two methods bring to separate conclusions, LCA results regarding the burdens of human activities and EMA showing the environmental support to complex systems, not only human dominated. Nevertheless, LCA and EMA show similarities in the way they are carried out, mainly within the inventory and characterization steps (Santagata et al., 2019). Several researchers are attempting to combine LCA and EMA, and EMA has also been proposed to be considered as an additional upstream cost and impact within a Life Cycle Impact Assessment (LCIA) (Buonocore et al., 2015; Cano Londoño et al., 2019; Duan et al., 2011; Ingwersen, 2011; Kursun et al., 2015; Liu et al., 2017, 2019; Marvuglia et al., 2013; Nimmanterdwong et al., 2018; Raugei et al., 2007, 2014; Reza et al., 2014; Rugani and Benetto, 2012).

LCA focuses on a cradle to grave or a cradle to cradle approach, taking into consideration resources under human control, while EMA expands over the biosphere time and scales, accounting for resources generation, ecosystem services and societal aspects embedded in direct and indirect labor. In these terms, LCA addresses a 'consumer-side' perspective, while EMA adopts a 'donor-side' perspective (Cano Londoño, 2018; Gala et al., 2015; Raugei et al., 2014; Viglia et al., 2013).

Differences between LCA and EMA can be acknowledged and highlighted as complementary perspectives providing different insights and answers to different questions.

This work proposes a procedural method, named LEAF (LCA & EMA Applied Framework) for the integration of LCA and EMA by their sequential application to the case under investigation and by testing different scenarios, in order to gain a holistic understanding of the proposed solutions, to assess their feasibility and their constraints and to suggest solutions. This is of paramount importance also when assessing waste recovery and recycling pathways, characterized by multilevel frameworks that require complex, holistic accounting methods (Brown, 2015; Santagata et al., 2020). The proposed procedure is applied to the Amalfi paper production system as a case study. Although a number of LCA studies have been conducted about pulp and paper production and recycling (Ben Daya and Nourelfath, 2019; Corcelli et al., 2018a; Da Silva Vieira et al., 2010; Dias et al., 2007; González et al., 2011; Hohenthal et al., 2019; Jawjit et al., 2007; Li et al., 2020; Lopes et al., 2002; Nabinger et al., 2019; Silva et al., 2015), a much smaller number of EMA investigations can be found in the literature (Corcelli et al., 2018b; Ren et al., 2010). Moreover, analyses about common paper production cannot be applied to the very peculiar Amalfi paper, produced in Campania Region (Italy) since the XIII century, due to its particular production process. This makes the case study very telling to the purpose of the proposed assessment procedure.

The LEAF procedure is composed by different steps: i) an Ex-Ante LCA, identifying the hotspots within the investigated case study; ii) a number of EMA scenarios, modeled around the selected hotspots, to evaluate the performances of proposed solutions; iii) Ex-Post LCAs of each EMA scenario, to assess to what extent each proposed solution has addressed and maybe removed the hotspots identified by the Ex-Ante LCA. Solutions capable to address the hotspots will then be judged on the basis of environmental costs from EMA scenarios and their feasibility assessed. The sets of results delivered by the LEAF integrated procedure are therefore capable to provide a multi-perspective, multicriteria assessment of the whole system under study. The integrated method moves a step ahead beyond the simple simultaneous application of LCA and EMA and provides a comprehensive set of results based on the sequential and iterative application of the two approaches that affect each other until the best feasible solution is achieved.

2. Material and methods

2.1 Life Cycle Assessment

The LCA framework is defined by ISO standards and ILCD Handbook guidelines (ISO, 2006; ISO4, 2006, 1404; JRC, 2010). Life Cycle Assessment is a methodological framework to assess the potential environmental impacts and resources used throughout a product's life cycle, from raw material acquisition, via production and use phases, to waste management. The resulting environmental impacts are caused by consumption of resources, emissions of substances into the natural environment, and other environmental exchanges. LCA provides indicators related to many different environmental impact categories, such as climate change, stratospheric ozone depletion, depletion of resources, toxicological effects, among others (Pennington et al., 2004). LCA is a relatively recent method that has rapidly grown to become a standard tool to investigate the environmental performance of a wide range of human-dominated processes. It is standardized as a four stages tool (definition of goal and scope, inventory analysis, impact assessment and interpretation) for environmental management at global level. This study has been performed utilizing the SimaPro software version 9.0.0.49 (https://network.simapro.com/rg), the Ecoinvent database version 3.5 (Wernet et al., 2016), and the ReCiPe Midpoint (H) v.1.03 method (Huijbregts et al., 2017) for impacts assessment. The ReCiPe method provides characterization factors to quantify the contribution of processes to each impact category and normalization factors to allow a comparison across categories (Huijbregts et al., 2017). Characterized results cannot be compared, due to their different physical units, therefore a normalization procedure is applied. Normalization is a life cycle impact assessment tool used to express characterized impact indicators in a way that they can be compared, with reference to average impact values calculated for a given area in a given year (Goedkoop et al., 2009; Wegener Sleeswijk e al., 2008). The LCA impact categories explored in this study are listed in Table 1.

2.2 Emergy analysis

Emergy is defined as the available energy of one kind directly or indirectly used in a system for transformations leading to a product or a service (Brown and Ulgiati, 2004a; Odum, 1996). Emergy takes in consideration different kinds of support to the investigated system, like renewable and non-renewable local resources, imported resources and manufactured goods, information and know-how, and finally labor and services (L&S). Each item included in the inventory is characterized by a different hierarchical quality. The unit of EMA is the solar emjoule (sej), expressing the amount of available energy of one kind (solar) converging into a product, resource or service. The total emergy (U) is the whole environmental support to products and services, obtained multiplying all input items by an appropriate "environmental cost factor" named Unit Emergy Value (UEV, measured as sej/unit-of-

Table 1
ReCiPe Midpoint (H) Impact Categories.

Impact Category	Label	Unit
Fine particulate matter formation potential	PMFP	kg $PM_{2.5}$ eq
Fossil resource scarcity potential	FSP	kg oil eq
Freshwater ecotoxicity potential	FETP	kg 1,4-DCB
Freshwater eutrophication potential	FEP	kg P eq
Global warming potential	GWP	kg CO_2 eq
Human carcinogenic toxicity potential	HCTP	kg 1,4-DCB
Human non-carcinogenic toxicity potential	HNTP	kg 1,4-DCB
Ionizing radiation potential	IRP	kBq Co-60 eq
Land use potential	LUP	m^2a crop eq
Marine ecotoxicity potential	METP	kg 1,4-DCB
Marine eutrophication potential	MEP	kg N eq
Mineral resource scarcity potential	MSP	kg Cu eq
Ozone formation, Human health potential	OFHP	kg NO_x eq
Ozone formation, Terrestrial ecosystems potential	OFTP	kg NO_x eq
Stratospheric ozone depletion potential	ODP	kg CFC11 eq
Terrestrial acidification potential	TAP	kg SO_2 eq
Terrestrial ecotoxicity potential	TETP	kg 1,4-DCB
Water consumption potential	WCP	m^3

inflow) to convert raw resource inflows into the corresponding emergy values and finally summing them into a total emergy U. The UEV of a product is obtained by dividing U by the yield of product delivered. UEVs are called *transformity* when expressed as sej/J. Solar transformity is the solar emergy required to deliver one joule of a service or product. Since in each transformation step the available energy is used up to produce a smaller amount of energy of another form (Odum, 1996), the number of resource transformations processes and their efficiency affect the total demand of resources and the final value of the transformity. All emergy values refer to a Global Emergy Baseline (GEB), representing the total annual emergy driving the biosphere. This work makes reference to the 12.0E + 24 seJ/y GEB (Brown et al., 2016) and therefore all UEVs taken from the literature and calculated with reference to other baselines were converted accordingly.

The resources used in a system can be classified as locally available renewable (R) and non-renewable (N), and imported non-renewable (F) (Odum, 1996). Starting from this classification, several emergy based indicators can be calculated (Brown and Ulgiati, 2004b). Emergy indicators in this work, besides U and UEV values with and without L&S, include:

- *Emergy Yield Ratio:* EYR = U/F, measuring the performance in providing a yield by investing outside resources. The lowest value is when a process provides the same amount of emergy invested, and it is equal to 1.
- *Environmental Loading Ratio:* ELR = (N + F)/R, quantifying the load of a system on the environment as the amount of non-renewable on renewable resources used.
- *Environmental Sustainability Index:* ESI = EYR/ELR, combining the imported/local and the non-renewable/renewable dimensions, assessing the ability of using the least share of imported resources with the minimum load.
- *Renewable fraction of emergy used:* %REN = R/U. %REN indicates the fraction of emergy from local renewable resources.

Unlike LCA indicators, EMA indicators do not provide information about generated impacts but instead points out the process sustainability at the biosphere scale. The total emergy U is an extensive indicator, giving information about systems' dependence on direct and indirect environmental support, while UEVs, intensive indicators, express the quality of energy and material flows going through subsequent convergence and transformation stages (Odum, 1996). The other sets of indicators add the missing information about scale dependence, self-reliance, convergence and renewability (Santagata et al., 2019). These can be considered different kinds of quality-related Impact Categories, to integrate the impact-related ones from LCA. The renewability of selected imported items (splitting the related emergy flow as renewable fraction F_R and non-renewable fraction F_N) has been considered in this work for the calculation of indicators.

EMA indicators, as LCA impact categories, fulfill the task of explaining the behavior of investigated systems regarding the surrounding environment.

2.3 LCA/EMA integrated procedure

Previous studies provided first attempts in integrating LCA and EMA assessment methods. According to Duan et al. (2011), by applying of both EMA and LCA methods a systematic assessment of each phase of the investigated process becomes possible, through the understanding of emissions, impacts, environmental support and renewability. Ingwersen (2011) proposed the use of EMA as an "upstream" impact category, acknowledging the difficulties related to the lack of an organized UEVs database coupled with highly developed LCA software and databases and highlighted the issues related to LCA allocation rules, not present in EMA. Marvuglia et al. (2013) developed a first attempt of a software application complying with EMA algebra rules, allowing for the calculation of emergy flows from the Ecoinvent database. Raugei et al. (2014) underlined how EMA is a valuable addition to LCA thanks to their complementary perspectives, with EMA providing a measure of the environmental support (i.e. the work of environmental processes needed to replace resources used up). Buonocore et al. (2015) confirmed that performing EMA together with LCA includes resource inflows not considered by LCA, in so expanding its focus and generating additional performance indicators. The different perspectives applied by LCA and EMA when dealing with co-products and/or by products were also tackled by Gala et al (2015), who insisted on how the peculiar emergy algebra might represent a barrier for the integration, since the LCA user-side perspective differentiates among by-products and waste, while EMA's biosphere-side perspective does not make distinction among output flows. Liu et al. (2017) argued that the effects of emissions and burdens can be considered (and quantified through EMA) in terms of the indirect additional demand for resource investment. In Liu et al. (2019) the simultaneous LCA/EMA application was advocated as beneficial; these authors also suggest the adoption of the emergy unit measure (solar emergy joule, sej) when dealing with different air emissions in order to facilitate the comparison of mitigation strategies.

It clearly appears that most of the previous studies focused on the much needed complementary application of the two methods and of the interpretation of results, demonstrating how the perspectives adopted can be simultaneously taken into account.

The proposed LCA/EMA integrated procedure is depicted in Fig. 1. The LEAF procedure is based on the sequential application of LCA and

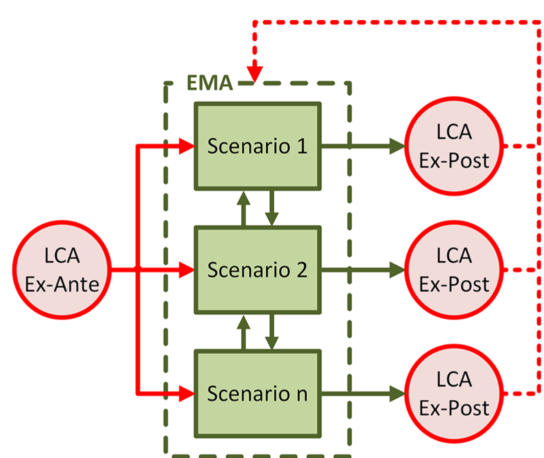


Fig. 1. LEAF LCA/EMA integrated procedure framework.

EMA. The first step includes the implementation of a preliminary LCA to provide a picture of the state of the system. This ex-ante LCA is needed in order to identify the hotspots of the investigated case study, in this work the Amalfi paper production, to be used as leverage points for building scenarios. Several hypotheses can be put forward by assuming different technological patterns capable to remove the identified hotspots. Scenarios are therefore based on specific improvement steps and then evaluated by means of EMA, to assess the demand for biosphere resource support and the environmental performance of the proposed solutions. Scenarios may adopt different points of view, in order to explore, among others: 1) a business as usual perspective, aimed at investigating the effect of better management of the process and in particular of the identified hotspots, by means of planned implementation of already well-known typologies of improvement (resource saving care and best available technologies); 2) a technology-based efficiency scenario, achieving an improvement of the system's performance through energy and material technology efficiency (special savings due to technology improvements, such as, for example, use of light emission diodes or replacement of a production pattern with a better designed one); 3) an eco-efficiency perspective, substituting energy and material hotspots with others characterized by better environmental performance ones (i.e., using renewable resources or at least less environmental demanding materials). The explored scenarios are expected to provide different emergy-based performances in terms of resource amounts and quality, in so showing different sustainability perspectives at the scale of biosphere. This means that we are in the presence of several different process options, expected to provide lower impacts at a given environmental cost. The actual results in terms of decreased impacts can be then tested by means of an ex-post LCA for each scenario, in order to assess if the hotspots and the related environmental cost have been actually removed. The ex-post LCA can influence the EMA in the term of tweaking and modifying the developed scenarios according to the obtained results towards the most sustainable solution.

This work investigates the paper production in Amalfi as case study by means of LEAF integrated procedure. Table 2 shows the inventory for the annual production of 8 tons of Amalfi paper. Machineries were excluded because of the very long life span of the majority of components (hundreds of years), contributing to very minimal extent to the annual impact. Table 2 also highlights the different perspective applied by the two methods within the inventory construction. While LCA focuses on the materials and energy flows under human control, EMA also considers the contribution from renewable sources, from labor provided directly as well as labor provided indirectly (i.e. services, infrastructures, know-how, information). Data in Table 2 are primary data coming from the staff of the investigated company, with the exception of the free environmental sources (sun, deep heat, wind, rain and runoff), estimated as in Brown et al. (2016). Emissions related to transportation, steam generation and wastewater treatment are from background data in the Ecoinvent database.

2.4 The Amalfi paper case study

Amalfi is a town in Campania Region, southern Italy, naming the famous coast near Salerno. The well-known Amalfi paper, a high quality and refined product, is produced here since the XIII century, based on a technology imported from China (XI century) by the Arabs. Nowadays, Amalfi paper is used for Vatican City State official documents, for high-end publications by publishing houses or for private purposes, like artistic ones or for wedding invitations. This high-end luxury paper was formerly made using scraps cotton, linen or hemp cloths, macerated in river water, using wooden mallets with iron nails, to obtain a fiber based sludge. The sludge was then mixed with animal glue and placed in a wooden mold with brass filaments. The sludge-containing molds were then stacked and pressed to remove water. The paper sheets obtained were then air dried. Almost all ancient paper factories have been destroyed by a flood, in 1954, and very few survived. Amalfi paper is currently made using cellulose and cotton fiber, respectively imported from Finland and Spain, but the paper making process is still the same as before. Ancient machinery, still working, is now activated by means of electric energy, and some modern machinery was also introduced, like boilers to produce steam or wastewater plants to treat process water before being discharged back into the river.

Fig. 2 shows a system diagram of the investigated case study according to the emergy algebra (Odum, 1996), that highlights all the input and output flows included in the system boundary. Glue and fibers are transported to the company site, where they are treated for

Table 2
Amalfi paper production inventory according to EMA and LCA methods.

Item	Unit	Quantity	
Input			
Sun	J	5.4E+12	EMA
Deep heat	J	4.9E+08	EMA
Wind	J	3.0E+09	EMA
Rain	J	1.6E+09	EMA
Runoff, geo	J	5.4E+07	EMA
Runoff, chem	J	2.6E+06	EMA
Water from river	m3	550	EMA, LCA
Cotton fiber	ton	6	EMA, LCA
Cellulose fiber	ton	16	EMA, LCA
Vegetal glue	kg	400	EMA, LCA
Electricity	kWh	64000	EMA, LCA
Heat from natural gas	MJ	6.2E+5	EMA, LCA
Cotton transport by sea	t*km	8.2E+3	EMA, LCA
Cellulose transport by sea	t*km	1.2E+5	EMA, LCA
Fibers road transport	t*km	1.1E+3	EMA, LCA
Labor	Unit	5	EMA
Services	€	5.4E+04	EMA
Output			
Amalfi paper	ton	8	
Treated water in river	m^3	18	

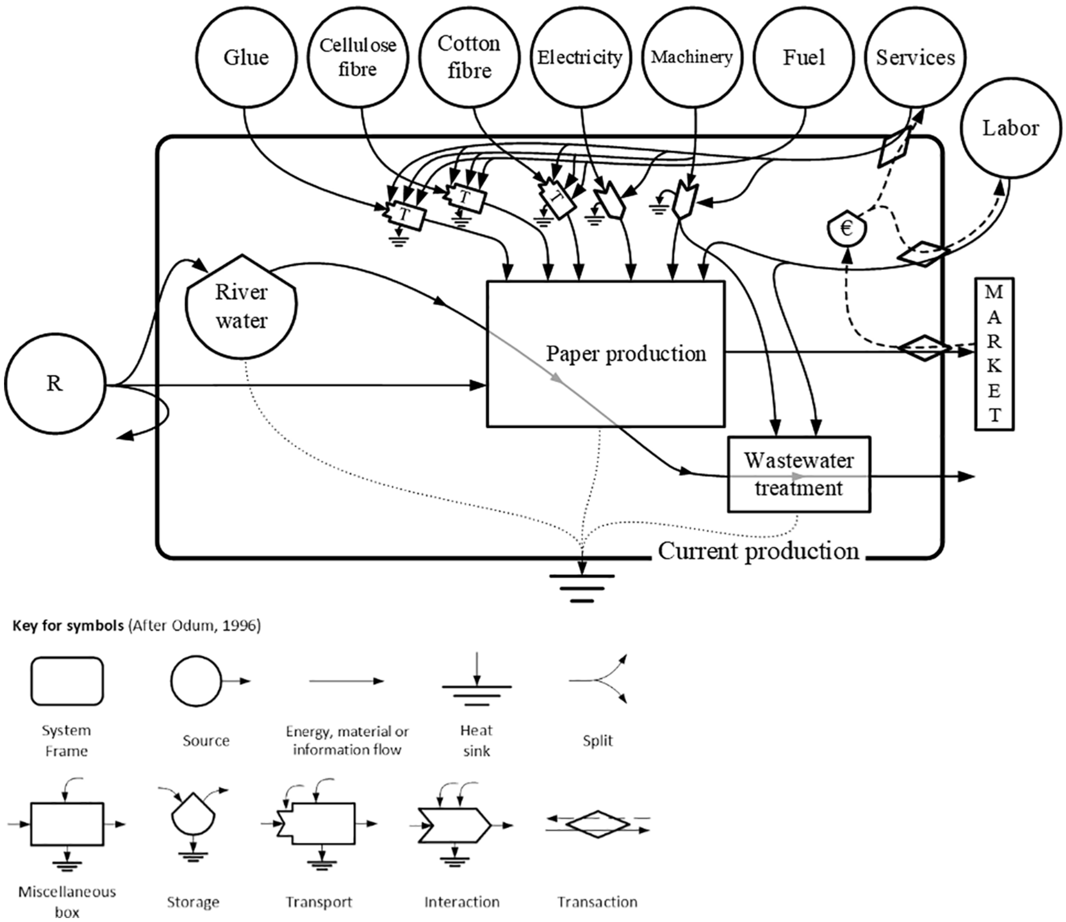


Fig. 2. System diagram of Amalfi paper production system.

paper production, by means of direct labor and machinery activated through electricity and steam generated from natural gas. The river water used for pulp production is recirculated several times within the production process before being treated in a small wastewater treatment plant and discharged back to the river. For both the LCA and EMA assessments, the annual production of Amalfi paper, equal to 8 tons, is chosen as Functional Unit (FU).

3. Results and discussion

3.1 Ex-ante LCA

The first group of results is from the ex-ante LCA, analyzing the system as it is. Table 3 lists both the characterized and normalized ReCiPe midpoint results of the ex-ante LCA. The highest impacts are observed for the toxicity related impact categories, in particular FETP and METP, respectively amounting to 2.1E + 03 and 3.3E + 03 (according to the normalized impacts).

In Fig. 3 the percentage contribution of inventory inflows to the impact categories is also shown. The main contribution comes from the electricity consumption, causing an average impact of about 45% in all the investigated impact categories. Cotton fiber and heat consumption generate about 18% of the impacts averagely, followed by cellulose fiber (9%), transport phase (6%) and glue (3%). Only a negligible contribution is attributable to wastewater.

Based on these LCA results and the advice of the staff from the paper production company, three different technological scenarios have been developed. The development of the following scenarios was performed keeping in mind both the improved sustainability of the system, that is the main goal of the proposed procedure, and the real feasibility of the

Table 3
ReCiPe Midpoint H characterized and normalized results for the production of 8 ton of Amalfi paper.

Impact category	Characterized		Normalized
PMFP	7.7E + 01	kg $PM_{2.5}$ eq	3.0E + 00
FSP	2.6E + 04	kg oil eq	2.7E + 01
FETP	2.6E + 03	kg 1,4-DCB	2.1E + 03
FEP	1.5E + 01	kg P eq	2.4E + 01
GWP	8.3E + 04	kg CO_2 eq	1.0E + 01
HCTP	1.7E + 03	kg 1,4-DCB	6.1E + 02
HNTP	3.5E + 04	kg 1,4-DCB	2.4E + 02
IRP	5.7E + 03	kBq Co-60 eq	1.2E + 01
LUP	3.7E + 04	m^2a crop eq	6.1E + 00
METP	3.4E + 03	kg 1,4-DCB	3.3E + 03
MEP	3.4E + 00	kg N eq	7.4E − 01
MSP	1.4E + 02	kg Cu eq	1.2E − 03
OFHP	1.3E + 02	kg NO_x eq	6.3E + 00
OFTP	1.3E + 02	kg NO_x eq	7.5E + 00
ODP	1.0E − 01	kg CFC11 eq	1.7E + 00
TAP	2.2E + 02	kg SO_2 eq	5.5E + 00
TETP	1.2E + 05	kg 1,4-DCB	1.1E + 02
WCP	1.7E + 04	m^3	6.5E + 01
			Total 6.5E + 03

proposed solutions, achieved thanks to a strong collaboration between researchers and company staff. Scenario 1 was developed as an improved business-as-usual scenario, as there are no changes within the company activities nor in the production of raw materials; the improvement consisted in choosing local sources thus avoiding transportation. Scenario 2 was developed avoiding changes within company

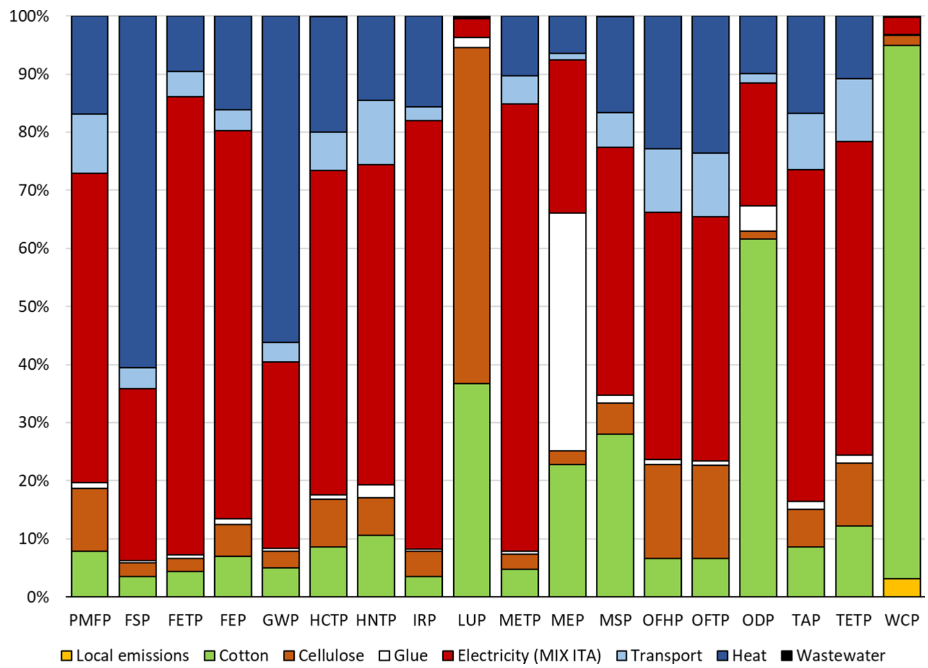


Fig. 3. Percentage contributions to the LCA characterized results of the production of Amalfi paper.

activities, but considering a less impacting, electric energy source already available on the market. Scenario 3, on the other hand, took into account a major action from the company itself, by means of the installation of PV modules for energy supply and the collection and use of scrap cloths as source of textile fibers, demanding additional resources for their treatment. Diagrams, EMA and LCA tables and graphs from Scenario 1, Scenario 2 and Scenario 3 can be found in Appendix A.

3.2 Scenario 1

The improvement we have considered in Scenario 1 is the use of local sources of textile and cellulose fibers, preventing the need for sea transportation of fibers from Finland and Spain. Cotton is not grown in Italy, so the scenario has been built taking into account the use of flax fiber, considered feasible by the paper making company.

Tables 4 and 5 respectively reports EMA indicators and related ex-post LCA results for Scenario 1.

U and UEV values decrease, from the value including L&S, of about 60% when L&S are not included. The percentage of renewability of 4% indicates a system heavily reliant on fossil resources, as indicated by other indicators. EYR value very near to 1 highlights how the process relies almost entirely on outside, non-renewable resources (F), also confirmed by the high ELR value, indicating how the non-renewable emergy within the system is much higher than renewable emergy. This reflects in a very low ESI value, in a way measuring the (low) sustainability of the investigated process as a ratio between its dependence from outside sources and from non-renewable ones.

Table 4
Emergy indicators for Amalfi paper production Scenario 1.

Indicator	Unit	
U (w L&S)	seJ	5.2E + 17
UEV Paper (w L&S)	seJ/g	6.5E + 10
U (w/o L&S)	seJ	2.2E + 17
UEV paper (w/o L&S)	seJ/g	2.7E + 10
EYR		1.04
ELR		24.29
ESI		0.04
%REN		4%

Table 5
ReCiPe Midpoint H characterized and normalized ex-post LCA results for the production of 8 ton of Amalfi paper Scenario 1.

Impact category	Characterized		Normalized
PMFP	6.4E + 01	kg $PM_{2.5}$ eq	2.5E + 00
FSP	2.4E + 04	kg oil eq	2.5E + 01
FETP	2.4E + 03	kg 1,4-DCB	2.0E + 03
FEP	1.4E + 01	kg P eq	2.1E + 01
GWP	7.7E + 04	kg CO_2 eq	9.6E + 00
HCTP	1.5E + 03	kg 1,4-DCB	5.3E + 02
HNTP	2.8E + 04	kg 1,4-DCB	1.9E + 02
IRP	5.4E + 03	kBq Co-60 eq	1.1E + 01
LUP	2.5E + 04	m^2a crop eq	4.1E + 00
METP	3.1E + 03	kg 1,4-DCB	3.0E + 03
MEP	2.9E + 00	kg N eq	6.2E-01
MSP	9.8E + 01	kg Cu eq	8.1E-04
OFHP	1.1E + 02	kg NO_x eq	5.2E + 00
OFTP	1.1E + 02	kg NO_x eq	6.3E + 00
ODP	4.4E-02	kg CFC11 eq	7.4E-01
TAP	1.9E + 02	kg SO_2 eq	4.6E + 00
TETP	9.1E + 04	kg 1,4-DCB	8.8E + 01
WCP	4.0E + 03	m^3	1.5E + 01
			Total
			5.8E + 03

Fig. A1, Table A1 and Fig. A2 in Appendix A respectively report the system diagram, the emergy accounting and the percentage contributions to LCA characterized results for Scenario 1.

The general trend of the LCA results is unchanged, with the highest values of normalized impacts in FETP and METP categories. Nevertheless, a reduction of characterized impacts is recorded ranging from 7% (in the case of FEP and GWP) up to 56% in ODP and 76% in WCP, due to the avoided transport and use of cotton. These results highlight the importance of local sources of textile fibers as well as the differences in the supply chains of cotton and flax.

3.3 Scenario 2

Scenario 2 includes the same type of paper production, but fed by an electricity mix composed of 100% renewable sources, provided in Italy on request without additional costs, in order to lower the impacts

Table 6
Emergy indicators for Amalfi paper production in Scenario 2.

Indicator	Unit	
U (w L&S)	seJ	4.6E + 17
UEV Paper (w L&S)	seJ/g	5.7E + 10
U (w/o L&S)	seJ	1.7E + 17
UEV paper (w/o L&S)	seJ/g	2.1E + 10
EYR		1.07
ELR		13.35
ESI		0.08
%REN		7%

Table 7
ReCiPe Midpoint H characterized and normalized ex-post LCA results for the production of 8 ton of Amalfi paper Scenario 2.

Impact category	Characterized		Normalized
PMFP	3.9E + 01	kg $PM_{2.5}$ eq	1.5E + 00
FSP	1.9E + 04	kg oil eq	1.9E + 01
FETP	6.8E + 02	kg 1,4-DCB	5.6E + 02
FEP	5.6E + 00	kg P eq	8.6E + 00
GWP	5.9E + 04	kg CO_2 eq	7.4E + 00
HCTP	9.8E + 02	kg 1,4-DCB	3.6E + 02
HNTP	1.8E + 04	kg 1,4-DCB	1.2E + 02
IRP	1.5E + 03	kBq Co-60 eq	3.1E + 00
LUP	3.6E + 04	m^2a crop eq	5.9E + 00
METP	9.5E + 02	kg 1,4-DCB	9.2E + 02
MEP	2.5E + 00	kg N eq	5.5E − 01
MSP	1.0E + 02	kg Cu eq	8.5E − 04
OFHP	7.5E + 01	kg NO_x eq	3.7E + 00
OFTP	7.9E + 01	kg NO_x eq	4.4E + 00
ODP	8.0E − 02	kg CFC11 eq	1.3E + 00
TAP	1.0E + 02	kg SO_2 eq	2.4E + 00
TETP	6.0E + 04	kg 1,4-DCB	5.8E + 01
WCP	1.8E + 04	m^3	6.7E + 01
			Total 2.1E + 03

Fig. A3, Table A2 and Fig. A4 in Appendix A respectively report the system diagram, the emergy accounting and the percentage contributions to LCA characterized results for Scenario 2.

generated by electricity consumption. This electricity mix is composed by hydro power (≈50%), geothermal power (≈24%), wind power (≈24%) and photovoltaic power (≈2%), with an estimated emergy renewability fraction of 68%.

In Tables 6 and 7 EMA and LCA results for Scenario 2 are listed respectively.

Compared to Scenario 1, Scenario 2 shows lower U and UEV values (≈20% without L&S and ≈12% with L&S). The lower UEV value and its improved renewability determines a slightly better EYR value than Scenario 1 (1.07 compared to 1.04), while ELR value is almost halved, indicating the decreased environmental pressure achieved by reducing the non-renewable emergy fraction, also generating ESI and %REN values almost doubled, because of the increased sustainability.

In this Scenario, the reduction of characterized impacts is even more marked than in Scenario 1, corresponding to more than 70% in FETP, IRP and METP and around 50% in PMFP, HNTP, TAP and TEPT compared with the system as it is (Table 3). On the other hand, the impact on LUP is higher than in Scenario 1 (3.4E + 04 *versus* 2.5E + 04 m^2a crop eq) and the impact on WCP (1.8E + 04 m^3) overcomes that recorded in the system as it is (1.7E + 04 m^3).

3.4 Scenario 3

Scenario 3 investigates the possibility of feeding the system only with locally installed photovoltaic power and using scraps cloths as source of textile fibers, as done in ancient times. This scenario has been confirmed as theoretically feasible by the paper making company, although the photovoltaic system cannot be directly installed on the company's building, due to restrictions for historical buildings; the cloths are supposed to be entirely made of white cotton and properly shredded. EMA and LCA results for Scenario 3 are reported in Tables 8 and 9 respectively. The effect of using a recovered feedstock (scraps cloths) but a less renewable energy source when compared to Scenario 2, causes Scenario 3 to have lower U and UEV values, but a slightly worse performance in the other indicators. PV electricity only shows an emergy renewability fraction of 2% (Kursun, 2016), due to the non-renewable emergy sources needed for panel construction, installation, maintenance and disposal much higher than the energy source itself (i.e. sun, with a *transformity* value equal to 1). Thus, the fraction of non-renewable emergy remains high, generating a EYR equal to 1.05, a higher pressure on environment (ELR = 20.75) and a lower sustainability (ESI = 0.05), with an overall renewability equal to 5%.

Table 8
Emergy indicators for Amalfi paper production Scenario 3.

Indicator	Unit	
U (w L&S)	seJ	3.8E + 17
UEV Paper (w L&S)	seJ/g	4.8E + 10
U (w/o L&S)	seJ	1.2E + 17
UEV paper (w/o L&S)	seJ/g	1.5E + 10
EYR		1.05
ELR		20.75
ESI		0.05
%REN		5%

Table 9
ReCiPe Midpoint H characterized and normalized ex-post LCA results for the production of 8 ton of Amalfi paper Scenario 3.

Impact category	Characterized		Normalized
PMFP	3.9E + 01	kg $PM_{2.5}$ eq	1.5E + 00
FSP	1.9E + 04	kg oil eq	1.9E + 01
FETP	8.9E + 02	kg 1,4-DCB	7.2E + 02
FEP	6.6E + 00	kg P eq	1.0E + 01
GWP	5.7E + 04	kg CO_2 eq	7.2E + 00
HCTP	1.1E + 03	kg 1,4-DCB	3.8E + 02
HNTP	2.1E + 04	kg 1,4-DCB	1.4E + 02
IRP	1.5E + 03	kBq Co-60 eq	3.2E + 00
LUP	2.4E + 04	m^2a crop eq	3.9E + 00
METP	1.3E + 03	kg 1,4-DCB	1.2E + 03
MEP	2.0E + 00	kg N eq	4.4E − 01
MSP	9.1E + 01	kg Cu eq	7.6E − 04
OFHP	7.2E + 01	kg NO_x eq	3.5E + 00
OFTP	7.6E + 01	kg NO_x eq	4.3E + 00
ODP	2.0E − 02	kg CFC11 eq	3.3E − 01
TAP	9.3E + 01	kg SO_2 eq	2.3E + 00
TETP	1.4E + 05	kg 1,4-DCB	1.4E + 02
WCP	1.0E + 03	m^3	3.9E + 00
			Total 2.7E + 03

Fig. A5, Table A3 and Fig. A6 in Appendix A respectively report the system diagram, the emergy accounting and the percentage contributions to LCA characterized results for Scenario 3.

The achieved LCA results are almost the same as in Scenario 2 in some impact categories, namely PMFP, FSP and IRP, whereas the generated impacts are generally lowered. In particular, significant environmental benefits are gained in ODP (80% lower than in the system as it is) and the impact on LUP is strongly reduced in comparison with Scenario 2 (2.4E + 04 m^2a crop eq). For FETP, FEP, HCTP, HNTP and METP, the generated impacts are higher than in Scenario 2 but still lower than in the system as it is, while the only impact higher than in all the other scenarios is recorded in TETP (1.4E + 05 kg 1,4-DCB *versus* 1.2E + 05 in the system as it is).

The presented LEAF integrated procedure provides a combined set

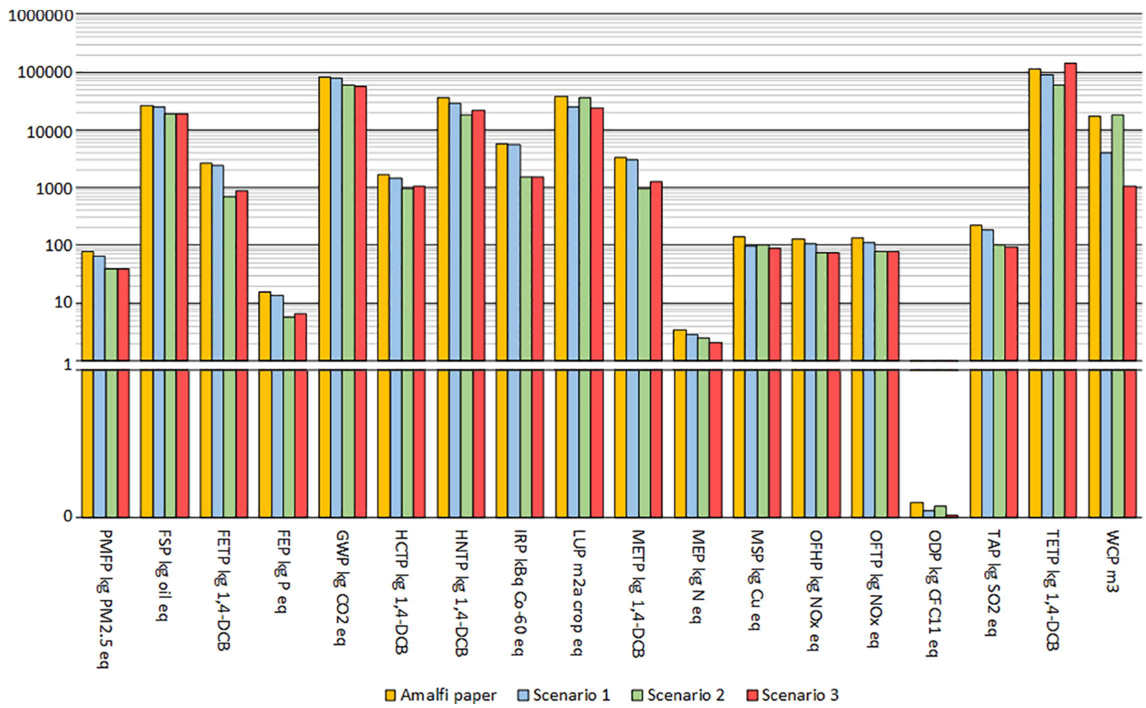


Fig. 4. Characterized LCA results comparison of the current production of Amalfi paper with the three proposed scenarios. The Y-axis is linear between 0 and 1 values and logarithmic for values greater than 1.

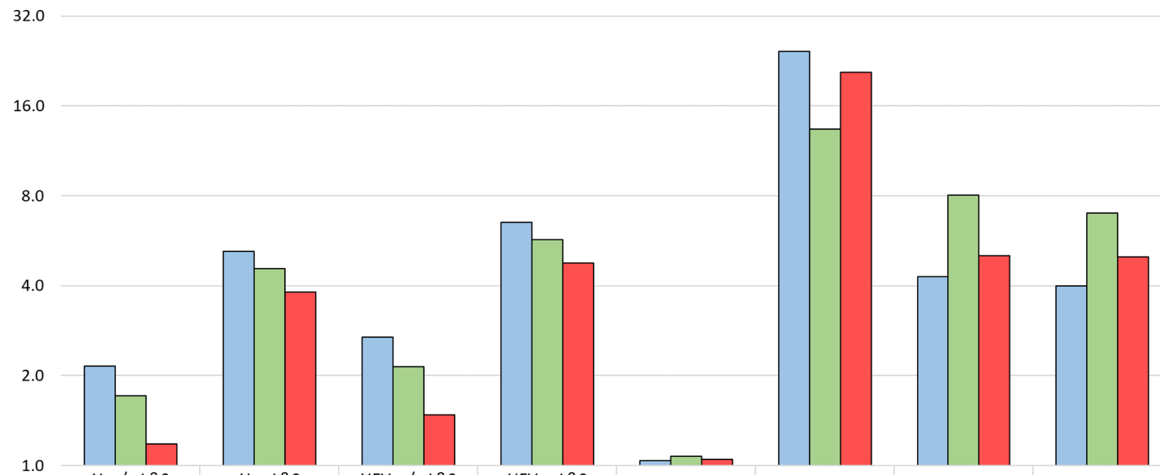
of LCA and EMA indicators for the built scenarios, with the aim of reducing environmental load and burdens of the investigated case study. Fig. 4 shows the characterized results of the current production of Amalfi paper as well as of the three proposed scenarios, presented in Tables 3,5,7 and 9. These results point out how Scenario 2 and 3 seem to be the most environmentally feasible choices, in terms of emissions and resources depletion. Scenario 2 shows an average reduction of ≈41% over all categories, the most relevant being within IRP (−74%), FETP (−73.7%) and METP (−71.7%). The smallest reduction is related to LUP (−3%), while a little increase equal to 2.4% can be observed within WCP. This change in burdens is entirely related to the different, renewable electricity mix adopted within Scenario 2. Scenario 3 is characterized by an average reduction of all categories equal to 47.4%, the largest within WCP (−94%), ODP (-80%) and IRP (−74%). The smallest reduction is observed for FSP (−28%). Scenario 3 is also characterized by a significant increase in TETP (+23%), even higher than the same impact category in the ex-ante LCA, caused by PV systems.

According to normalized results, the least impacting scenarios are Scenario 2, with a total normalized impact of 2138 points, and Scenario 3, 2662 points, compared to Scenario 1 (5841 points) and the current production, with a total normalized impact of 6505 points.

Fig. 5 sums up and compares the EMA indicators of the three scenarios listed in Section 3. Scenario 3 is characterized by a lower total emergy U, both with and without L&S, translating into a lower UEV for the produced paper. Other indicators, i.e. EYR, ELR, ESI, %REN, are more beneficial within Scenario 2. This is caused by the greater share of the renewable fraction of input emergy flows, as shown in Appendix A. The use of more environmentally sound sources in the electricity mix has the effect of lowering U and UEV values of the system, thanks to their lower UEVs compared to common fossil sources. They also present a larger renewability fraction. These two factors cause the reduction of the F_R/F_N fraction, delivering better performing indicators.

Based on the obtained LCA and EMA results, Scenario 2 and Scenario 3 are the most environmentally feasible solutions, presenting the lowest burdens and the lowest loads. Between the two, Scenario 2 can be implemented more easily, only depending on the substitution of the present electricity mix with another one already available to the consumers. Scenario 3 calls for the development of practices characterized, at present, by difficult implementation, i.e. the collection of white cotton-made scraps and the implementation of a photovoltaic system on the top of a building with a relevant historical value, protected by regulations not allowing any modification. Scenario 3 is also affected by the low value of the emergy renewability of PV electricity, a figure that may be increased by the adoption of novel techniques such as organic solar cells (Ajayan et al., 2020), demanding for new assessments.

The rationale of the LEAF procedure is that the ex-ante LCA provides a diagnosis of the impacts generated by the process as it is; the EMA studies identify the environmental and resource costs of proposed solutions, in order to understand how feasible they are from a supply side point of view; and finally the ex-post LCA provides a final check about the actual ability of the proposed solution to remove the ex-ante identified impact(s). The combination of LCA and EMA results obtained by the application of the proposed procedure provides a multi-perspective donor/consumer side assessment for a more holistic approach to environmental problems and complex systems. In principle, there is no limit to the set of options that can be put forward to improve the process under study based on solutions suggested by stakeholders, administrators, managers and scientists. On the basis of the obtained information, the analyst should be able to watch at the investigated framework from different angles, and find better solutions. The final policy issue is to ascertain to what extent society can afford the "cost" for impact removal or if the investigated process must simply be discontinued within a precautionary principle framework. However, the application of the LEAF procedure may be very time demanding with the addition of multiple scenarios, as it needs specific data for each proposed solution, to be analyzed through two different assessment methods. In particular, EMA is performed through calculations and modeling personally made by the analyst, unlike the standardized LCA, which benefits of several widely accepted databases and software, still lacking within the EMA method. This work purposely proposed a straightforward, simple case study, in order to efficiently explain the proposed procedure. The proposed LEAF procedure successfully



	U w/o L&S (*E+17 sej)	U w L&S (*E+17 sej)	UEV w/o L&S (*E+10 seJ/g)	UEV w L&S (*E+10 seJ/g)	EYR	ELR	ESI	%REN
Scenario 1	2.2	5.2	2.7	6.5	1.0	24.3	4.3	4
Scenario 2	1.7	4.6	2.1	5.7	1.1	13.3	8.1	7
Scenario 3	1.2	3.8	1.5	4.8	1.0	20.7	5.1	5

Fig. 5. . EMA indicators for Scenario 1, Scenario 2 and Scenario 3.

delivered a LCA/EMA integrated analysis whose results and findings are capable of influencing each other to propose possible and meaningful solutions and investigate their feasibility from multiple perspectives. The mutual influence engaged between the two methods and their sequential application is the added value of the proposed procedure. As highlighted in Fig. 1, EMA scenarios and their LCA burden analysis are designed to be mutually interconnected and iterative, in order to design and assess the best possible solutions. This represents a step forward compared to an independent application and interpretation of LCA and EMA methods to systems under investigation, as the sequential application of the two methods depicted in Fig. 1 is characterized by the possibility of reiterating the EMA-based building of scenarios and their LCA testing until the optimal conditions for the investigated systems are obtained. Within more complex systems, characterized by a larger number of steps, material and energy flows and diverse adopted technologies, reliable scientific solutions would be difficult to reach without a multidimensional, transparent and synergic framework as the one proposed. The integrated procedure is capable of generating indicators that can be used within the discussions between stakeholders and policy makers, in a precautionary principle perspective advocated by entities as the European Union and UNESCO when uncertainty and unsustainability features related to the use of resources become evident. The tendency towards an effective and fulfilling integration between LCA and EMA is clear. A conceptual framework capable of taking into account and successfully consolidating the different aspects considered by the two methods is much needed in order to gain a wider understanding of the analyzed systems, and the proposed LEAF procedure represents a step forward in that direction. Furthermore, a standardization of EMA method, the development of a recognized UEVs database and, perhaps, pieces of software to support the work of analysts would surely be very beneficial.

4. Conclusion

The proposed LEAF LCA/EMA integrated procedure is developed through the sequential application of LCA and EMA methods, providing a multi perspective analysis system. In this work, the procedure has been applied to the Amalfi paper production case study, through the creation of different optimization scenarios and the identification of the source of electric power as one of the most significant contributors, adding load to the ecosystem. The alternate application of LCA and EMA provided insights from the donor side (EMA) and from the consumer side (LCA), allowing a better and deeper understanding of the different investigated options and their feasibility, performances and burdens. The proposed procedure allows to investigate several options from different points of view with different approaches, revealing strengths and weaknesses of each designed scenario. The simultaneous calculation of LCA and EMA indicators successfully highlight the hotspots to be taken in consideration within the investigated case study, making possible the exploration of a holistic set of results reporting both the upstream environmental support to the analyzed system and the downstream impacts loading on the environment, analyzing, whether in the system as it is or in the scenarios proposed, the major contributions of every part to the whole. This enables a more holistic and multi-criteria approach to decision making and environmental management.

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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Appendix A

Scenario 1

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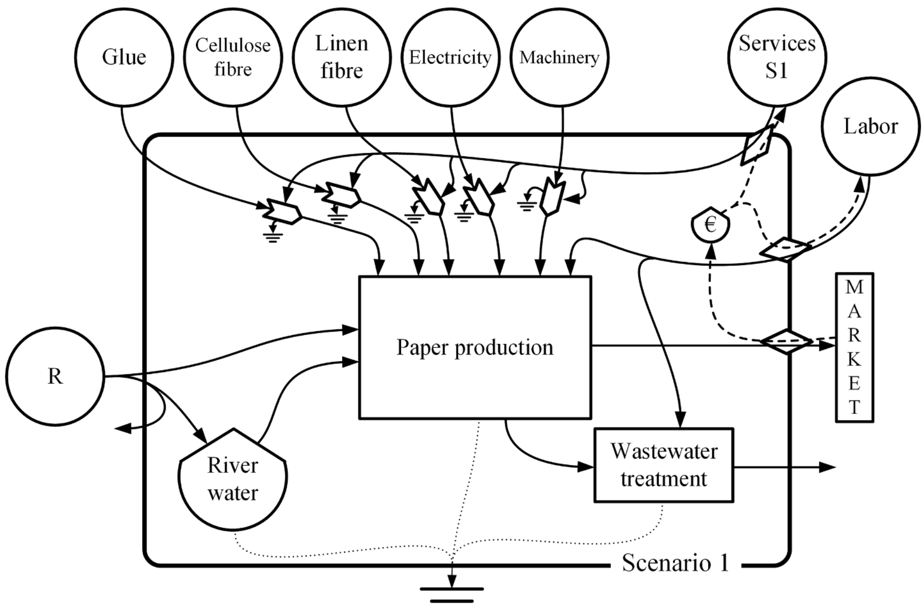

Fig. A1. System diagram of Amalfi paper production system Scenario 1.

Table A1
Emergy Accounting of Amalfi paper production Scenario 1.

#	Item	Unit	Inputs	UEV (sej/unit)	Emergy Flow (sej/year)	Refs
Renewable Inputs						
	tripartite					
1	Sun	J	5.35E + 12	1.00E + 00	5.35E + 12	[1]
2	Deep heat	J	4.87E + 08	4.90E + 03	2.39E + 12	[1]
	2nd and 3rd sources					
3	Wind	J	2.97E + 09	7.00E + 03	2.08E + 13	[1]
4	Rain	J	1.59E + 09	8.00E + 02	1.27E + 12	[1]
5	Runoff, geo	J	5.39E + 07	1.28E + 04	6.90E + 11	[1]
6	Runoff, chem	J	2.59E + 06	2.13E + 04	5.51E + 10	[1]
	Larger between sum of tripartite and 2nd and 3rd sources				2.08E + 13	
Imported Inputs						
7	Cellulose fibre	J	2.48E + 11	1.47E + 04	3.64E + 15	[2]
8	Flax fibre	g	6.00E + 06	1.24E + 10	7.47E + 16	[3]
9	Vegetal glue	g	4.00E + 05	6.78E + 04	2.71E + 10	[4]
10	Electricity	J	2.30E + 11	2.13E + 05	4.91E + 16	[5]
11	Natural gas	J	6.22E + 11	1.41E + 05	8.77E + 16	[6]
12	Wastewater treatment	g	1.80E + 04	4.83E + 05	8.69E + 09	[7]
13	Labor	Unit	5.00E + 00	4.35E + 16	2.18E + 17	[8]
14	Services	€	5.40E + 04	1.66E + 12	8.96E + 16	[8]
Output						
15	Amalfi paper (w L&S)	g	8.00E + 06	6.53E + 10	5.22E + 17	[3]
16	Amalfi paper (w/o L&S)	g	8.00E + 06	2.69E + 10	2.15E + 17	[3]

[1] Brown and Ulgiati (2016); [2] After Tilley and Felix (2009); [3] This work; [4] After Yan and Odum (2001); [5] After Brown and Ulgiati (2004b); [6] After Brown et al. (2011); [7] After Siracusa and La Rosa (2006); [8] After Pereira et al. (2013).
F_R considered: 35% cellulose; 1% Flax fiber; 6% L&S.

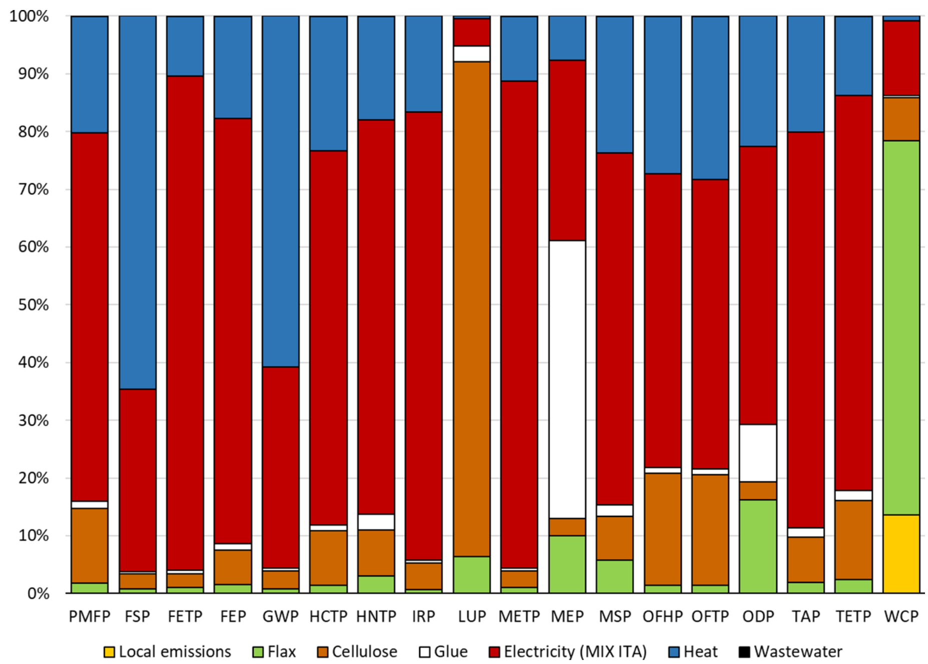

Fig. A2. Percentage contribution to the LCA characterized results of the production of Amalfi paper Scenario 1.

Scenario 2

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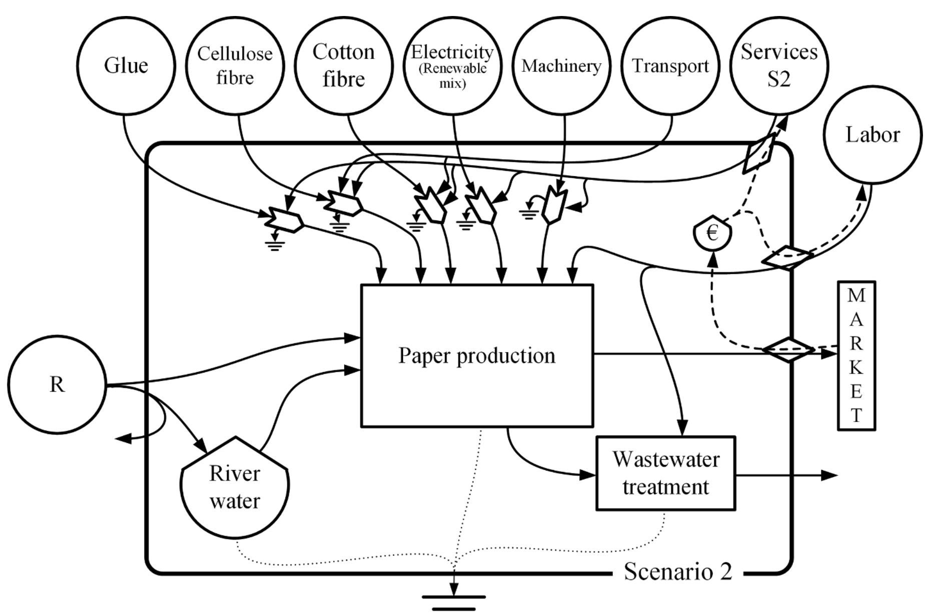

Fig. A3. System diagram of Amalfi paper production system Scenario 2.

Table A2
Emergy Accounting of Amalfi paper production Scenario 2.

#	Item	Unit	Inputs	UEV (sej/unit)	Emergy Flow (sej/year)	Refs.
Renewable Inputs						
	tripartite					
1	Sun	J	5.35E + 12	1.00E + 00	5.35E + 12	[1]
2	Deep heat	J	4.87E + 08	4.90E + 03	2.39E + 12	[1]
	2nd and 3rd sources					
3	Wind	J	2.97E + 09	7.00E + 03	2.08E + 13	[1]
4	Rain	J	1.59E + 09	8.00E + 02	1.27E + 12	[1]
5	Runoff, geo	J	5.39E + 07	1.28E + 04	6.90E + 11	[1]
6	Runoff, chem	J	2.59E + 06	2.13E + 04	5.51E + 10	[1]
	Larger between sum of tripartite and 2nd and 3rd sources				2.08E + 13	
Imported Inputs						
7	Cellulose fibre	J	2.48E + 11	1.47E + 04	3.64E + 15	[2]
8	Cotton fibre	g	6.00E + 06	1.06E + 10	6.37E + 16	[3]
9	Vegetal glue	g	4.00E + 05	6.78E + 04	2.71E + 10	[4]
10	Electricity (Renewable mix)	J	2.30E + 11	6.85E + 04	1.58E + 16	[3]
11	Natural gas	J	6.22E + 11	1.41E + 05	8.77E + 16	[6]
12	Wastewater treatment	g	1.80E + 04	4.83E + 05	8.69E + 09	[7]
13	Transport, van	t*km	1.10E + 03	1.80E + 11	1.98E + 14	[9]
14	Transport, ship	t*km	1.32E + 05	1.20E + 07	1.58E + 12	[10]
15	Labor	Unit	5.00E + 00	4.35E + 16	2.18E + 17	[8]
16	Services	€	4.13E + 04	1.66E + 12	6.85E + 16	[8]
Output						
17	Amalfi paper (w L&S)	g	8.00E + 06	5.71E + 10	4.57E + 17	[3]
18	Amalfi paper (w/o L&S)	g	8.00E + 06	2.14E + 10	1.71E + 17	[3]

[1] Brown and Ulgiati, 2016; [2] After Tilley and Felix, 2009; [3] This work; [4] After Yan and Odum, 2001; [6] After Brown et al., 2011; [7] After Siracusa and La Rosa, 2006; [8] After Pereira et al., 2013; [9] After Federici et al., 2003; [10] Estimated from Ecoinvent database.
F_R considered: 35% cellulose; 4% Cotton fiber; 68% Electricity (Renewable Mix); 6% L&S.

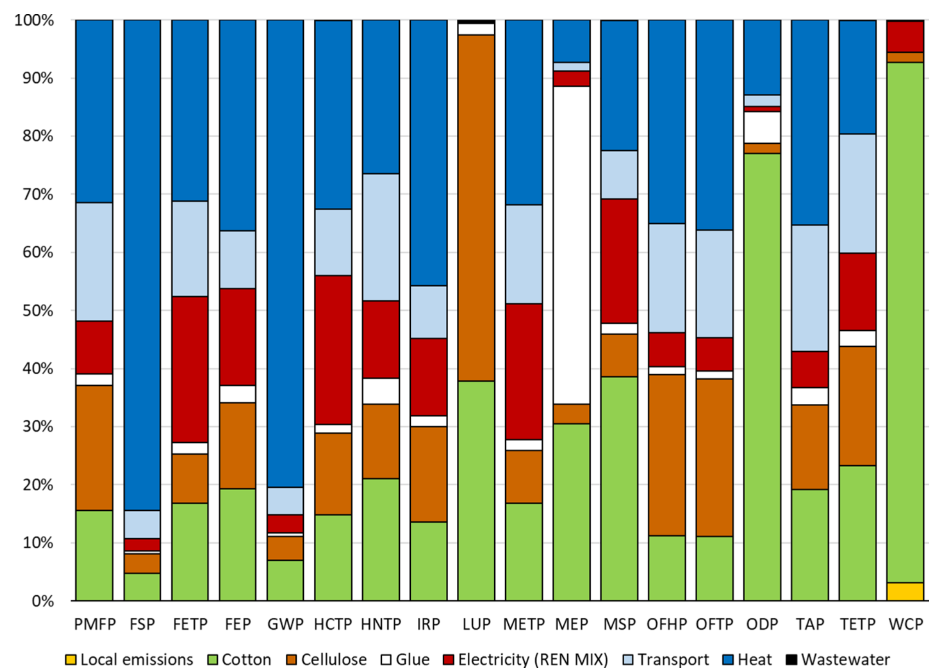

Fig. A4. Percentage contributions to the LCA characterized results of the production of Amalfi paper Scenario 2.

Scenario 3

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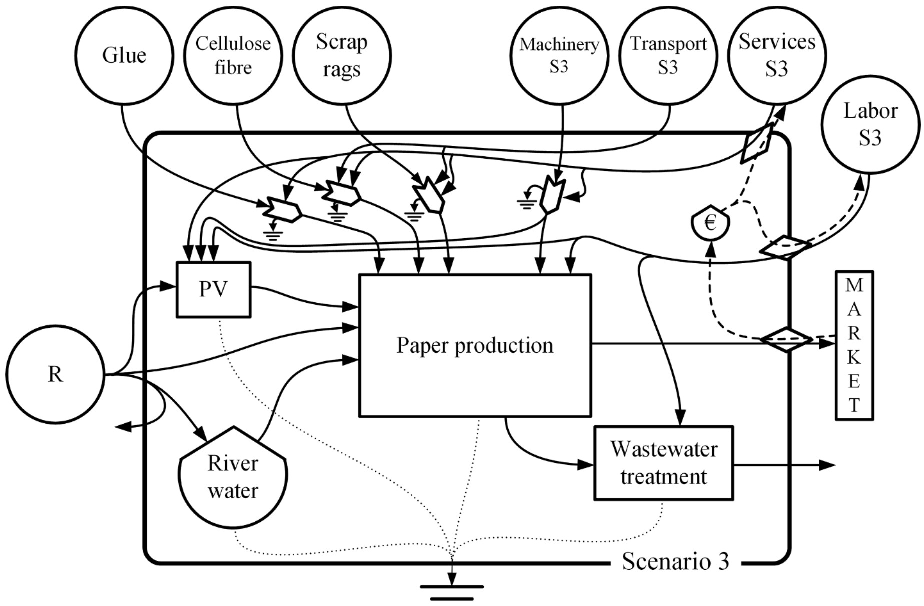

Fig. A5. System diagram of Amalfi paper production system Scenario 3.

Table A3
Emergy Accounting of Amalfi paper production Scenario 3.

#	Item	Unit	Inputs	UEV (sej/unit)	Emergy Flow (sej/year)	Ref
Renewable Inputs						
	tripartite					
1	Sun	J	5.35E + 12	1.00E + 00	5.35E + 12	[1]
2	Deep heat	J	4.87E + 08	4.90E + 03	2.39E + 12	[1]
	2nd and 3rd sources					
3	Wind	J	2.97E + 09	7.00E + 03	2.08E + 13	[1]
4	Rain	J	1.59E + 09	8.00E + 02	1.27E + 12	[1]
5	Runoff, geo	J	5.39E + 07	1.28E + 04	6.90E + 11	[1]
6	Runoff, chem	J	2.59E + 06	2.13E + 04	5.51E + 10	[1]
	Larger between sum of tripartite and 2nd and 3rd sources				2.08E + 13	
Imported Inputs						
7	Cellulose fibre	J	2.48E + 11	1.47E + 04	3.64E + 15	[2]
8	Scraps cloths	g	6.00E + 06	6.57E + 08	3.94E + 15	[11]
9	Vegetal glue	g	4.00E + 05	6.78E + 04	2.71E + 10	[4]
10	Electricity (Photovoltaic)	J	2.30E + 11	9.91E + 04	2.28E + 16	[12]
11	Natural gas	J	6.22E + 11	1.41E + 05	8.77E + 16	[6]
12	Wastewater treatment	g	1.80E + 04	4.83E + 05	8.69E + 09	[7]
13	Transport, van	t*km	8.66E + 02	1.80E + 11	1.56E + 14	[9]
14	Transport, ship	t*km	1.24E + 05	1.20E + 07	1.48E + 12	[10]
15	Labor	Unit	5.00E + 00	4.35E + 16	2.18E + 17	[8]
16	Services	€	2.75E + 04	1.66E + 12	4.56E + 16	[8]
Output						
17	Amalfi paper (w L&S)	g	8.00E + 06	4.77E + 10	3.81E + 17	[3]
18	Amalfi paper (w/o L&S)	g	8.00E + 06	1.48E + 10	1.18E + 17	[3]

[1] Brown and Ulgiati, 2016; [2] After Tilley and Felix, 2009; [3] This work; [4] After Yan and Odum, 2001; [6] After Brown et al., 2011; [7] After Siracusa and La Rosa, 2006; [8] After Pereira et al., 2013; [9] After Federici et al., 2003; [10] Estimated from Ecoinvent database; [11] After Odum, 1996; [12] Corcelli et al., 2017.
F_R considered: 35% cellulose; 2% Electricity (Photovoltaic); 6% L&S.

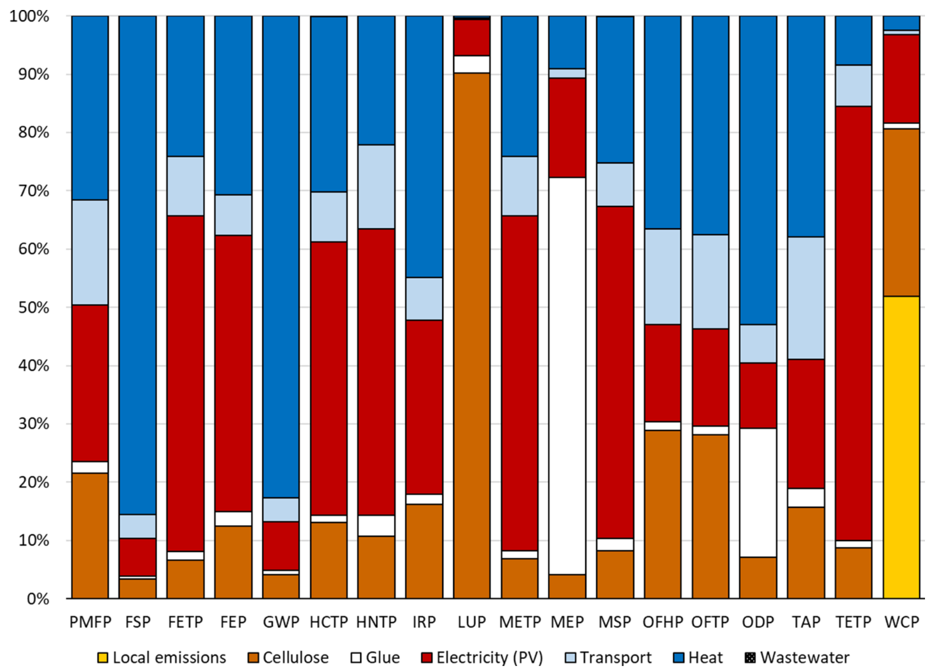

Fig. A6. Percentage contributions to the LCA characterized results of the production of Amalfi paper Scenario 3.

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