Distributed recycling for additive manufacturing: an ecosystem services perspective

1 Introduction

Distributed plastic recycling has emerged in the literature to face the socio-environmental challenges related to plastic waste management. The main hypothesis relies on the fact that a distributed and local spaces can provide recycled feedstock to transform it into finish (or prototypes) for a local community. To do so, the use of additive manufacturing enables the technical paths to achieve this objective. However, as with any recycling system, its feasibility must be evaluated before its implementation. Based on the sustainability concept, this research intends to investigate, how the ecosystem services are impacted due to the implementation of the plastic recycling chain. Although research has been conducted regarding on the technical and logistical feasibility of distributed plastic recycling, little is known about its pertinence from the ecosystem services perspective in a territory.

This study intends to explore the local impact derived from the implementation of a distributed plastic recycling chain in a territory. The purpose of this research is to identify the the set of principles, criteria and indicators from ecosystem services framework, that can be associated to distributed recycling approach, evaluating their pertinence in the local impact in terms of availability of data. The Green Fablab at LF2L is considered as case study to put in practice the development of a methodological framework considering sustainability dimensions, derived from the implementation of a distributed plastic recycling chain.

This study seeks to address the following questions: - What are the appropriate ecosystem service indicators for assessing an prospective filière as distributed plastic recycling? - How does the implementation of a distributed plastic recycling chain impact on ecosystem services? - What are the barriers and drivers for the development of a distributed plastic recycling chain in a territory?

While not all types of materials can be recycled given the technical difficulties, the estimation of the environmental advantage is needed to assess at early stages the pertinence of this distributed approaches. Main tasks in this research include a systematic literature review of ecosystem services in recycling field, and the creation of a database and online tool to map these element in the local territory.

2 Background

Foundational ideas on ecosystem services seek for conceptual and methodological tools with the major goal to increase public interest in biodiversity conservation through the recognition, accounting and valuation of the societal dependence on the ecological life support systems for the human well-being (Gómez-Baggethun et al. 2010). Today, ecosystems services field are being included in the decision-making through promotion of market Based Instruments for Payment for Ecosystems services schemes with the purpose of create and environmental governance according to the reality of impact on the natural capital (**ref?**). Nevertheless, commodification of nature's services by reductionist thinking about individual services runs the risk of unintended harm and unbalanced outputs. Systems thinking is essential for avoiding such harm (Gopalakrishnan, Bakshi, and Ziv 2016).

Ecosystem services (ES) are the ecological characteristics, function or processes that contribute (actively or passively) to the human well-being (Costanza et al. 1997, 2017). Ecosystem goods (e.g; Food) and services (e.g. waste assimilation) illustrate the benefits that human derive from the ecosystem functions (Costanza et al. 1997). It is needed to distinguish between the ecosystem's functions and processes from the ecosystem services concept itself. The former describes biophysical relationships that are carried out by nature regardless of whether or not human benefits. By contrast, the latter are those processes and functions where people can (or could have the potential (**ref?**)) obtain benefits. The ecosystem services do not flow to human well-being without crucial interactions with the different forms of capital (Natural, Social, Human, Built), which entails the need of understanding, modelling, measuring, and managing ES in a trans-disciplinary approach. Likewise, the concept of ecosystem dis-service denotes the processes and functions that affect humans in 'negative' way, making damage and costs (**ref?**). One major point that ES make clear is to raise awareness on the recognition of humanity's primary dependencies on the 'functions of' natural capital which reflects the fact that, however they may perceive themselves, humans are part of, and not apart from, nature (Ekins et al. 2003). This entails the necessity to create knowledge for trans-disciplinary approaches using ES as boundary object for sustainability for diverse stakeholders (Honeck et al. 2021).

Different initiatives have been reported to classify the ES, including the Millennium Ecosystem Assessment (MEA 2005), The Economics of Ecosystems and BiodiversityTBB (**ref?**), THe Intergovernmetal Plastform of Biodiversity and Ecosystem Services (IPBES) (**ref?**) and the Common International Classification of Ecosystem Services (CICES) . In the heart of the four main, they share four main categories of ES: **Provisioning** (e.g. food and medicines); **Regulating** (e.g. pollination and climate regulation), **Supporting** (e.g soil formation and fixation of solar energy) and **Cultural / Information** services (e.g. artistic inspiration and recreation) services are four broad catagories types of ES constitutes the core of most recent classifications and that are shared by the most frameworks (Pedersen Zari 2019).

Efforts on biodiversity conservation relies on the highlight of the economic aspects of biodiversity and the natural capital (Costanza et al. 1997) and the environmental inaction related to the cost of policy damage occurring in the absence of an effective regulatory framework (Bruel et al. 2016). From a strong sustainability perspective, a declining capital stock is an unambiguous indicator of unsustainability in the flow of goods and services that derive from it (Ekins et al. 2003). More important, the recognition of the non-substitutability of natural capital with regard to the other forms of capital; acknowledging the characteristics of irreversibility (such as species extinction or climate change), uncertainty and the existence of *critical* components that make a major contribution to welfare. The main core of the environmental problem relies on the use of use ecosystem's functions, mainly those that generate economic welfare, that are making a negative impact and influence on the natural capital stock, and even worse, on those functions that are responsible for ecosystem stability and resilience (Ekins et al. 2003).

The Common International Classification of Ecosystem Services (CICES) was developed to provide hiecharchally consistent and science-based classification to be used for natural capital accounting purposes (**ref?**). In CICES framework, (**Potschin?**) argued the conceptual framework of cascading aspect from ecosystesm service tos of the and are commonly divided into Mustajoki et al. (2020)

Using a systematic literature review approach, Torres, Tiwari, and Atkinson (2021) distinguished and categorized 8 major key themes and 22 approaches in the ES field. Key themes represent underlying meanings or ideas that are widely used, trending or rising in the ecosystem services research field. Key approaches include methods (Harrison et al. 2018), tools, frameworks, perspectives and management strategies to analyze, assess, and quantify ecosystem services.

Efforts have been made in the literature to classify the methods used to assess ecosystem services based on 27 case studies. Ecosystem service assessment methods were classified into four broad categories: biophysical, socio-cultural, monetary, and integrative.

The loss in value associated with biodiversity loss and the related loss of ecosystem services is often invisible and does not influence decision makers. It is difficult to provide information about pressure from industrial systems in corporate information systems. EE uses valuation techniques to reveal the value of nature and develops ways to overcome the current technical and ethical challenges to valuation, for example, by broadening the dominant monetary perspective on the value of nature by nonmonetary and deliberative approaches influence decision makers.

- Hoy en dia es necesario tener en cuenta no solo un factor technic-econonomic en el momento de evaluar soluciones en amount. Tambien, es necesario estavlecer cuales serain las implicationes y los impactos para el territoirio desde el punto de vista de servicios ecosistemicos

2.1 Ecosystems services in the industrial systems: towards a reconciliation of two capitals for humanity.

The economic valuation of ecosystem goods and services gives an elegant framework highlighting their importance for society and human welfare. However, there is a need to explicitly account for their contribution when designing and developing products and services (Diwekar et al. 2021). The engineering discipline developed the implicit assumption that ecological systems have nearly endless capacity to provide resources and adsorb wastes. This blindness in the engineering vision can be explaining by the fact that at the beginning of the technological industrialization, the human activites' impacts on the earth remained marginal. This scenario is not true today. Engineering within ecological constraints need to acknowledge the capacity of relevant ecosystems to supply the demanded goods and services while the ecosystems and natural capital must be protected, restored and developed to be capable of continuing to supply those services that industry (and society) relies on (**ref?**). According to the Milleniums 15 out of 24 ecosystems services examined are degraded or being used in an unsustainable manner (MEA 2005). Likewise, using the planetary boundaries framework, it is argued that anthropogenic activities already exceed the biophysical limits of the "safe operating zone" in terms of carbon and nitrogen cycles, and biodiversity loss (Rockström et al. 2009; O'Neill et al. 2018). Among the root causes of ecological degradation is ignorance about the exceedance of the ecological carrying capacity in many desicions (Liu and Bakshi 2019). Another crucial issue is that current design approaches based on life cycle characterization and footprint methods focus on continuous improvement by reducing life cycle impacts per unit of product, encouraging improvements by doing "less bad," which need not translate into keeping human activities within ecological constraints. Ideally, it is needed to (re)designed industrial activites to reduce the demand for the demand of ecosystems services creating for a local '*island of sustainability*' which is that the demand should not exceed the supply at the local scale (Gopalakrishnan, Bakshi, and Ziv 2016). Therefore, it's urgent to expand the boundaries for engineering design from the lowest molecular level to the process level, and from individual process to the higher levels of value chains, ecosystems and the planet (Martinez-Hernandez 2017).

Ceschin and Gaziulusoy (2016) putted forward the evolution of *Design for Sustainability (DfS)* framework showing the different approaches that have evolved from a product innovation level to socio-technical systems level. They pointed out that engineering interventions at only technological unit operation/product level are necessary, but not sufficient condition for sustainability.

A framework for assessing and encouraging synergies between technological and ecological systems has been developed to consider systems at multiple spatial scales ranging from local to global.44 This theoretical framework for Techno-Ecological Synergy (TES) aims to encourage synergies for small systems such as a house and its yard, a manufacturing process and its site, as well as larger scale systems that extend to consider the entire life cycle. This article relies on the idea of TES and develops ways of enhancing synergies between a local scale manufacturing process and the land around it.

The key point for bussiness and government sectors in terms realize an integrated valuation and comprehensive account of both the negative impacts on ES from business activites and the positive contributions of ES to business and households (Costanza et al. 2017). More general, the critical issues relies on the importance of ES to challenge the conventional approaches to growth and development, towards a perspective more focalized on the prosperity and wellbeing. The loss in value associated with biodiversity loss and the related loss of ecosystem services is often invisible and does not

3 Methodology

The purpose of this article is to propose a conceptual approach to evaluate the synergy of prospective industrial filière considering the technological and ecological spheres.

Four steps were proposed as illustrated in figure XX .

The goal of *Asessments* step is to identify the bounddaries for the technoological and ecological systems to be evaluated. In the *Planning* step, the main aim is to jeopordize the key ecosystems services and the respective scales that are going to be included in the analysis. These elements will be a intersection of the technological and geographihcal issues based on a analysis of each systems. In the *Evaluation* stage, the main purpose is to establish the demand and supply of ES based on respective inventory and models. This include the specific allocation Finally, ini the last step *Management*, the main goal is to establish scenarios of evaluation based on the 'Bussiness-as-usual' and Synergy frameworks. This will enable to take a more informed decision to stakeholder at the evaluation of prospopective projects.

An application of the framework will be presented in Section XX using as case study of the distributed recycling chain via additive manufacturing.. In the following sub-sections, each stage of the methodology is explained.

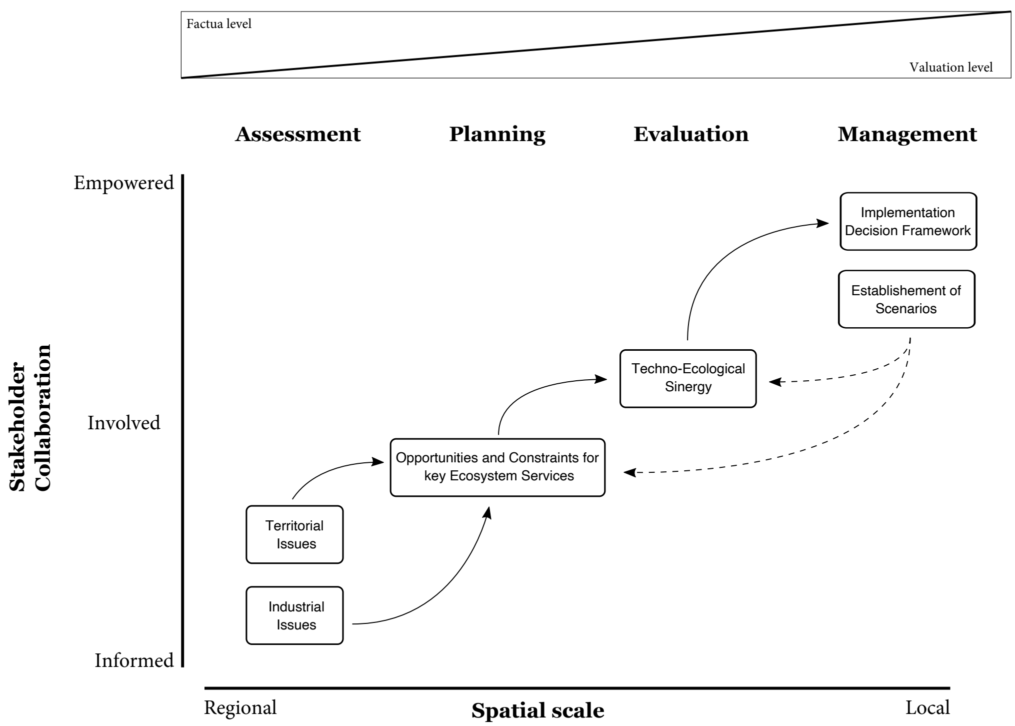

Figure 1: Operational framework for evaluatig the ecosystem services of industrial systems

3.1 Assessment

3.1.1 Definition of the Tech- and Eco- Spheres

It is needed to define two types of boundaries: technological and ecological. Regarding the technological sphere, it involves choosing the human activites that can be a single process, life cycle, or economic network. Concerning the ecological sphere, it relies on specifying the geographical regions that the activity is implemented.

4 Case study: Distribuuting recycling via Additive Manufacturing

4.1 Indicators in Ecosystem Services Distributed recycling The

References

Bruel, Aurélien, Nadège Troussier, Bertrand Guillaume, and Natalia Sirina. 2016. "Considering Ecosystem Services in Life Cycle Assessment to Evaluate Environmental Externalities." *Procedia CIRP* 48: 382–87. https://doi.org/10.1016/j.procir.2016.03.143.

Ceschin, Fabrizio, and Idil Gaziulusoy. 2016. "Evolution of design for sustainability: From product design to design for system innovations and transitions." *Des. Stud.* 47 (November): 118–63. https://doi.org/10.1016/j.destud.2016.09.002.

Costanza, Robert, Ralph D'Arge, Rudolf de Groot, Stephen Farber, Monica Grasso, Bruce Hannon, Karin Limburg, et al. 1997. "The value of the world's ecosystem services and natural capital." *Nature* 387 (6630): 253–60. https://doi.org/10.1038/387253a0.

Costanza, Robert, Rudolf de Groot, Leon Braat, Ida Kubiszewski, Lorenzo Fioramonti, Paul Sutton, Steve Farber, and Monica Grasso. 2017. "Twenty years of ecosystem services: How far have we come and how far do we still need to go?" Elsevier B.V. https://doi.org/10.1016/j.ecoser.2017.09.008.

Diwekar, U., A. Amekudzi-Kennedy, B. Bakshi, R. Baumgartner, R. Boumans, P. Burger, H. Cabezas, et al. 2021. "A perspective on the role of uncertainty in sustainability science and engineering." *Resour. Conserv. Recycl.* 164 (January): 105140. https://doi.org/10.1016/j.resconrec.2020.105140.

Ekins, Paul, Sandrine Simon, Lisa Deutsch, Carl Folke, and Rudolf De Groot. 2003. "A framework for the practical application of the concepts of critical natural capital and strong sustainability." *Ecol. Econ.* 44 (2-3): 165–85. https://doi.org/10.1016/S0921-8009(02)00272-0.

Gopalakrishnan, Varsha, Bhavik R. Bakshi, and Guy Ziv. 2016. "Assessing the capacity of local ecosystems to meet industrial demand for ecosystem services." *AIChE J.* 62 (9): 3319–33. https://aiche.onlinelibrary.wiley.com/

doi/full/10.1002/aic.15340%20https://aiche.onlinelibrary.wiley.com/doi/abs/10.1002/aic.15340%20https://aiche.onlinelibrary.wiley.com/doi/10.1002/aic.15340.

Gómez-Baggethun, Erik, Rudolf de Groot, Pedro L. Lomas, and Carlos Montes. 2010. "The history of ecosystem services in economic theory and practice: From early notions to markets and payment schemes." *Ecol. Econ.* 69 (6): 1209–18. https://doi.org/10.1016/j.ecolecon.2009.11.007.

Harrison, Paula A., Rob Dunford, David N. Barton, Eszter Kelemen, Berta Martín-López, Lisa Norton, Mette Termansen, et al. 2018. "Selecting methods for ecosystem service assessment: A decision tree approach." *Ecosyst. Serv.* 29 (February): 481–98. https://doi.org/10.1016/j.ecoser.2017.09.016.

Honeck, Erica, Louise Gallagher, Bertrand von Arx, Anthony Lehmann, Nicolas Wyler, Olga Villarrubia, Benjamin Guinaudeau, and Martin A. Schlaepfer. 2021. "Integrating ecosystem services into policymaking – A case study on the use of boundary organizations." *Ecosyst. Serv.* 49 (June): 101286. https://doi.org/10.1016/j.ecoser.2021.101286.

Liu, Xinyu, and Bhavik R. Bakshi. 2019. "Ecosystem Services in Life Cycle Assessment while Encouraging Techno-Ecological Synergies." *J. Ind. Ecol.* 23 (2): 347–60. https://doi.org/10.1111/jiec.12755.

Martinez-Hernandez, Elias. 2017. "Trends in sustainable process design—from molecular to global scales." *Curr. Opin. Chem. Eng.* 17 (August): 35–41. https://doi.org/10.1016/j.coche.2017.05.005.

MEA. 2005. "Ecosystems and Human well-being: Synthesis." www.islandpress.org.

Mustajoki, Jyri, Heli Saarikoski, Valerie Belton, Turo Hjerppe, and Mika Marttunen. 2020. "Utilizing ecosystem service classifications in multi-criteria decision analysis – Experiences of peat extraction case in Finland." *Ecosyst. Serv.* 41 (February): 101049. https://doi.org/10.1016/j.ecoser.2019.101049.

O'Neill, Daniel W., Andrew L. Fanning, William F. Lamb, and Julia K. Steinberger. 2018. "A good life for all within planetary boundaries." *Nat. Sustain.* 1 (2): 88–95. https://doi.org/10.1038/s41893-018-0021-4.

Pedersen Zari, Maibritt. 2019. "Ecosystem services impacts as part of building materials selection criteria." *Mater. Today Sustain.* 3-4. https://doi.org/10.1016/j.mtsust.2019.100010.

Rockström, Johan, Will Steffen, Kevin Noone, Åsa Persson, F. Stuart Chapin, Eric F. Lambin, Timothy M. Lenton, et al. 2009. "A safe operating space for humanity." https://doi.org/10.1038/461472a.

Torres, Angélica Valencia, Chetan Tiwari, and Samuel F. Atkinson. 2021. "Progress in ecosystem services research: A guide for scholars and practitioners." *Ecosyst. Serv.* 49 (June): 101267. https://doi.org/10.1016/j.ecoser.2021.101267.