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Holonic self-organized and multicriteria control of the Circular Supply Chain

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Abstract. The circular economy transforms the supply chain by introducing three types of feedback loops that operationalize the 10 action levers of circularity. This model aims to preserve the use value of artefacts and limit the extraction of new resources, while reducing environmental impact. The control of these circular flows, which are more complex and uncertain than in a linear approach, requires an adapted and decentralized logistics organization able of adjusting in real time. A holonic approach to control this circular supply chain aims to maximize the profitability and service life of artefacts, using a self-organized, multicriteria approach.

Keywords: Circular Supply Chain, Circular Economy, Holonic Paradigm, Self-Organization, Multicriteria Decision Aid.

1 Context and key issues in Circular Supply Chain control

Following a study carried out in 2023 by Citwell and Soroa with the support of the Institut National de l'Économie Circulaire (INEC) [1], the question of how to manage flows in a circular economy has recently been raised in France. The study shows that the practical implementation of the circular economy – an emerging approach - must rely on the skills of the supply chain sector. However, while the supply chain is set to become a central lever, optimizing the whole system in line with both public and private objectives, thanks in particular to legislative and tax incentives, it is no less true that it will have to reinvent itself to meet the new imperatives imposed by the Circular Economy [2]. With a view to meeting the United Nations' Sustainable Development Goal No. 12 ("Do more and better with fewer resources"), logistics systems need to incorporate the new imperatives of the circular economy, while seeking greater resilience and circularity. This is an important field of research for the circular economy, even if it is not addressed by [3].

This paper sets out to show how the circular economy approach, viewed from the flow angle, can be translated into a structuring model from the logistics point of view: we refer to this as the Circular Supply Chain (CSC) [4]. The aim is to highlight the main structuring lines that will enable the CSC to play a central operational role in promoting high levels of circularity [5]. The objective of the control flow is to ensure, as far as possible, the maximum preservation of the value of products and materials during their use, to optimize the efficiency of use of products and materials, and to limit the loss of value at the end of their life, whatever the products or their state.

To do this, we first propose to characterize the flows in a circular economy, by analyzing the interactions between the 10 action levers of the Circular Economy. We will then briefly present the SCC pyramid model, which is a dynamic and ecological model for sustainable and circular production. We will then carry out a qualitative analysis of the flows within the CCS pyramid. We will conclude that current control approaches of linear supply chain are no longer suitable for CCS. We will therefore propose an approach based on self-organized, multicriteria and holonic control, showing its advantages. Finally, we will describe the holonic structure involved and the multicriteria decision support structure used to control the CCS.

2 Flow characterization in a circular economy

In a Circular Economy, the flows of artefacts are more complex.

2.1 New flows linked to circularity

The Circular Economy calls into question the strictly linear process: 'extraction of resources', 'production of raw materials', 'manufacture and assembly of products', 'storage and distribution', 'use and disposal' [6]

The circular economy consists of setting up return loops aimed at Repairing, Reusing, Repurposing, Retrofitting or Remanufacturing objects when they need to be upgraded (the era of 'R'), or Recycling and/or Regenerating materials perceived as waste (the era of 'D') [7, 2]. The aim of these different flows is to preserve the use value of products as much as possible.

In the era of 'D', the complexity or mixing of materials often leads to "downcycling": recycled materials lose quality and are therefore less suitable for reuse in subsequent production processes [4]. Using waste from "urban mines" [8], the aim is to produce virgin base materials that can replace those obtained from extraction, although their properties (purity, strength, etc.) may be less good. It is important to note that, according to the ISO 59004 standard [9], recycling only comes in eleventh place out of thirteen prioritized actions in a circular economy policy, after actions such as extending life, reusing without modification, or refurbishing/remanufacturing, which involve

replacing certain components or recovering parts for new manufacturing processes. These actions relate to the era of 'R' [7, 2].

Implementing these practices requires an appropriate logistics organization able of supporting the development of this new economy. To date, such a circular supply chain exists only in a partial or embryonic form. A key issue in the transition to circular supply chains lies in the power of circularity: the aim is to maximize the service life of an artefact, optimizing its profitability by extending or intensifying its uses over time [10, 5]. This profitability can be measured by the cumulative sum of the cumulative use values of the artefact, compared with the total cost of the operations required to manufacture, maintain and adapt it. It is essential to consider all the potential uses of a product, made possible by circularity actions, beyond its initial form.

To support these changes, the supply chain needs to be adapted to incorporate a circular and global approach, with a diversity of supply and processing channels that encourage the regeneration and conservation of resources [11]. The circular economy involves a multitude of interconnected loops, constantly evolving according to temporal and spatial variables. All of these flows must aim for efficiency, in order to reconcile economic performance with a reduction in environmental impact.

This circularization must be based on the various action levers of the Circular Economy.

2.2 The 10 action levers of the Circular Economy

Upstream of the actual life of the artefact (its use), it is necessary to deploy eco-design strategies, based on reducing the resources and materials used to make the product and strengthening control of the various use and end-of-life levers. These different levers are contained in the '10R' model [12], which sets out the possible flows to be considered in order to retain as much as possible of the value invested in the initial manufacture of products. These levers are divided between eco-design and circularization of uses. This gives us the following questions, recommendations and guidelines:

R0: Refuse - a. usefulness of the artefact - b. right sizing of the artefact - c. removal of unnecessary options - d. refusal of virgin/raw, dangerous materials,

R1: Rethink: make the use of the artefact more intensive by - a. sharing its use over time (sequential) - b. sharing its use in the moment (simultaneous) - c. increasing its duration of use by extending its lifespan,

R2: Reduce: reduce - a. the quantities of materials used to build the artefact or the energy consumed in its operation - b. the variety of materials used in its production - c. reduce losses due to non-quality,

R3: Reuse - a. direct reuse of the artefact for an identical purpose by a third party user, with a view to sharing the use,

R4: Repair - a. repair of minor faults by the end user, - b. replacement of faulty components by a specialist or the artefact supplier,

R5: Reconditioning - a. renovation of the artefact, keeping its overall structure and replacing certain degraded elements so that it functions as new - b. retrofitting by refurbishing and modernizing part of the artefact from a re-used base, enabling it to perform better than it did initially,

R6: Remanufacturing - a. remanufacturing new artefacts from components of artefacts that are no longer in use - b. disassembling artefacts, checking their components and requalifying them so that they can be reinserted into the same artefact model, replacing initial components that have failed,

R7: Redirect - a. reallocation of artefact components, verified and certified for a given function, to a new context of use different from that initially considered,

R8: Recycle - recycle the waste from the artefact, once all the possibilities of the era of 'R' have been exhausted,

R9: Energy recovery - incineration or mechanization of waste.

Around these different levers gravitate different stakeholders, who are more or less specialists in the different stages or modes of transformation-processing-value-addition of the artefact, whether it is a product, a component or a material. The different inter-organizational flows need to be identified in order to understand how they are structured and how to control them effectively.

3 Circular Supply Chain Pyramid

3.1 General structure of the CSC pyramid

Some of the levers directly concern the use of the artefact, the intensification of its use or the conservation of its use value. There are also precedence or preference relationships between these levers. For example, it is preferable to repair rather than recycle, but reconditioning and remanufacturing can feed off each other.

Inspired by the graphic model of the circular pyramid [13], where value is built up by climbing up one side and, at the end of its useful life, gradually descends on the other side through different stages to slow down the loss of value before final disposal, the Circular Supply Chain Pyramid represents flows according to three levels of circularity loops (Fig. 1). In each loop, specialized stakeholders are responsible for conserving as much of the artefact's use value as possible.

Higher-level loops, associated with the era of 'R', aim to preserve the use value of the product, by intensifying or maintaining its use. They encourage pooling, sharing, reuse and repair, thanks to appropriate circularity loops. The economic efficiency of the business model depends on the speed of these processes. For example, in the economy of functionality, it is essential to put in place short, responsive loops to quickly put a product back into service with a new user after the previous use has come to an end. This involves control operations (checking that the product is working properly, identifying any repairs), preparation (cleaning, disinfecting) and appropriate logistics to recover the product from the previous user and deliver it to the next.

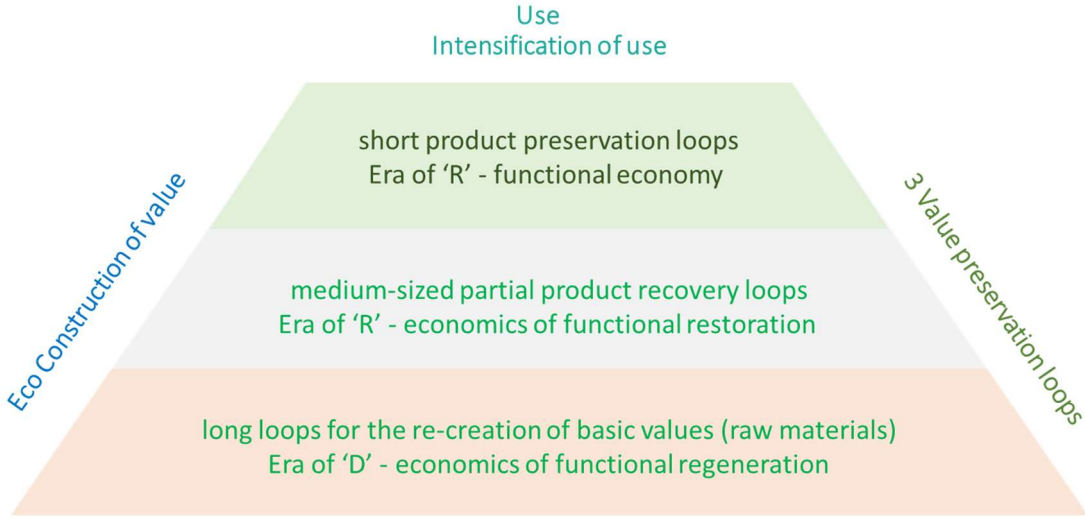


Fig.1 . CSC Pyramid: general structure

Intermediate-level loops come into play when the product has partial failures and loses part of its value in use, requiring more complex interventions than simple repair. The aim is to restore a value in use, which may differ somewhat from the initial value. We are still in the era of 'R', with actions such as reconditioning, remanufacturing or redirecting. In these cases, the product may be completely or partially dismantled, and the various parts from the initial product are used to reconstitute the use value of new products. This approach involves using specific logistics to match needs (for example, a product requiring function X to regain its use) and available resources (a component offering function X).

The lower level loops, known as long loops, or 'D' loops, concern the recovery of materials. They are based on industrial processes that enable new basic materials to be regenerated from end-of-life products. This model is similar to traditional mass production, provided that sufficient waste can be collected to ensure the viability of the operation. In addition, the logistical organisation must ensure regular supplies and the continuity of material sources.

3.2 Circular action levers in the CCS pyramid

The hierarchy of actions in the circular economy leads us to favour higher-level loops: the use value of a product is higher than the sum of the use values of its components, which themselves have a higher value than that of the materials that make them up. Thus, seeking to retain as much of the initial value as possible limits the effort required to preserve it: the more the use value is degraded, the more resources and energy will have to be mobilized to restore it.

Figure 2 completes the structure of the CCS pyramid.

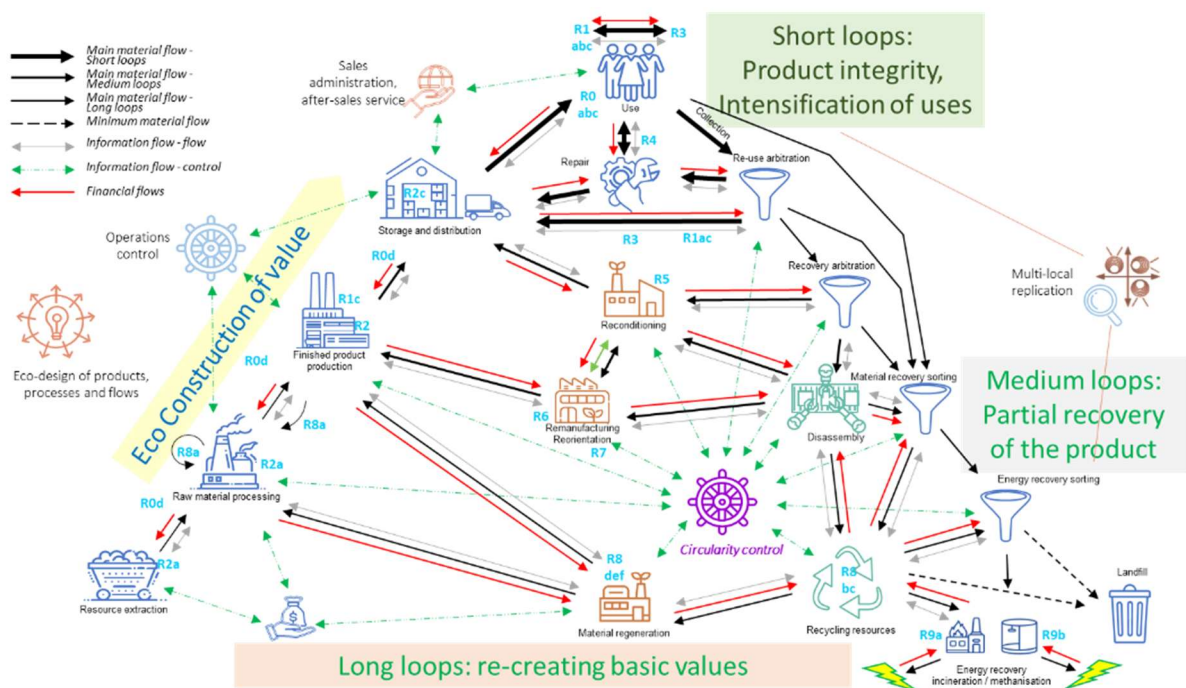


Fig.2 . CSC pyramid with levers for circular actions

We find the different levers (in cyan blue) associated with each of the 3 loops mentioned in the previous paragraph. We show the inter-organizational relationships that link the different stakeholders, for the 3 loops. This conceptually represents an industrial ecosystem, with each of the levers mentioned being provided by one of the companies with the skills and operational capacity to do so. There is therefore competition and collaboration between the stakeholders.

The flow control system within the SCC pyramid must be able of managing the future of each artefact, despite the wide variety of evolution possibilities available to each of them.

4 Proposal for a holonic self-organised multicriteria control system for CCS

The solutions used to control linear supply chains are no longer appropriate. We are going to see what the new constraints are and what approaches can be chosen to control Circular Supply Chains, the main objective of which is to conserve the value of artefacts.

4.1 Characterization of flow control in the CCS pyramid

In the Circular Supply Chain pyramid, each flow contributes to a part of the circular industrial ecosystem. These flows are implemented by various logistics service providers (LSPs), who ensure their operation through storage and transport actions between the various economic actors and industrial sites, depending on the treatments to be applied to the products, their components and their raw materials. This means that a number of solutions are needed (several transport companies, repair companies, remanufacturers, recycling companies, etc.), each of which characterizes different flows. Each of these flows is subject to much more complex dynamics than in a Linear Supply Chain (LSC). In LSC, the flows are generally organized in a stable way and their management can be based around a central actor, called a "pivot", which plays the role of high-level integrator [14]. This pivot coordinates the skills, capabilities and resources of the various partners in the chain. This allows to optimize interfaces between actors, reduce lead times and costs, and ensure harmonious overall management of flows, based on a statistical view of market demand and a predictive optimization approach.

In the Circular Supply Chain, the uncertainty of consumption (which is greater) is compounded by the uncertainty of supply, amplified by the effects of the geographical dispersion of products during their use phase. The Circular Supply Chain is confronted with two uncorrelated types of uncertainty:

- The random nature of demand forecasting (sales): demand is erratic and no longer depends solely on predictable standard use, which is subject to the product/consumption supply model. It is also influenced by competition from new products, which may be more attractive technically or economically, by the more or less widespread sharing of product use, by the more or less abundant supply of repair, reuse and re-employment opportunities, by improvements in potential use (e.g. increased robustness, which reduces the need for renewal), and by consumer expectations, which are subject to marketing influences (fashions, costs, attractiveness of innovation, risk of shortages, etc.).

- Non-predictability of sourcing: to maximize the 'conservation of use value' effect, sourcing is done primarily through circular return flows, which are not necessarily regular, or of homogeneous characteristics due to the effects of use (ageing, deterioration, etc.), and are scattered throughout the territory (in their areas of use). These

flows come from the three types of value conservation loops (short, medium and long loops), with totally uncorrelated temporal and volume dynamics.

This double uncertainty obliterates any control solution that is intended to be predictive and optimizing: the uncertainties are far too great for the solutions thus obtained to be robust in the face of the actual situation of the CSC. This is why we are proposing a radically different approach: a holonic self-organized and multicriteria control of the Circular Supply Chain.

4.2 The benefits of self-organised, multicriteria holonic control

The specific features of CCS mean that control is more complex, and must be much more flexible, responsive and opportunistic than in a conventional linear chain. This leads us to favor a decentralized, non-predictive control system, based on real-time self-organization and the search for compromises between several criteria [15]. The concept of self-organization of a CCS implies, on the one hand, the use of a decentralized decision-making structure at the level of each CCS actor, and on the other hand, considering the specific behavior of each of these actors.

For such an organization to function, it is necessary to share a common objective; in the case of CCS, this is naturally to maximize the preservation of the use value of the artefacts concerned. This objective can be expressed in different ways, depending on the characteristics of the industrial actors involved, and is reflected in terms of coordination, cooperation and the search for multicriteria compromises.

In addition, the solution for operating and controlling all the industrial actors and associated flows is obtained gradually by emergence: it is not the result of a global calculation, but is built up through a succession of coherent decisions and multicriteria compromises, considering various objectives and constraints (lead times, costs, environmental impact, etc.). This self-organization is developed in real time, depending on the actual state of the industrial actors (available capacities, committed loads) and the flows to be managed (volumes to be processed, availability of processing circuits, buffer stocks, etc.), in a highly variable environment that is difficult to predict. This approach is particularly relevant when centralized, predictive management is not appropriate [16].

Self-organized real-time control has several advantages: it focuses on the short term, which considerably simplifies the management of the tasks to be coordinated, while integrating the constraints and situation of each industrial actor. The result is control solutions that are immediately operational and better adapted to the reality of the CSC. This approach relies on multicriteria decision support, which facilitates the search for the best compromise among a set of possible alternatives [17].

5 Formal framework for holonic self-organized multicriteria control for CCS

We will use the holonic paradigm to formally describe CCS, and then we will look at multicriteria decision support.

5.1 Holonic stakeholder modeling

We define a holon as a conceptual entity based on the combination of a real structure and an information and processing system that gives it decision-making intelligence enabling it to interact with other holons [18]. Our approach is one of edge computing [19], where each holon is equipped with a state machine: this enables it to manage itself and access contextual processing, such as event perception, information requests to other holons or multicriteria decision support, and this allows it to make decisions and evolve in its state graph.

We will use 3 types of holons: Product holons, Resource holons and Order holons.

The Holons Resources (RH) concern all the stakeholders and industrial actors in CCS. We will therefore find all the companies specializing in the levers of circularity (repairers, retrofitters, disassemblers, etc.), as well as all the LSPs that will provide the necessary transport within CCS. All of them will have to be able of responding to load demands, and will have to be able to do so in terms of technical capacity, operational availability, costs and environmental impact.

The Product Holons (PH) are in fact the artefacts that are the focus of the maximum research into the conservation of use value. In fact, this is the specific objective of each Product holon. When it is in a high circular loop, its function of use will be its main concern: it will make sure that it is properly checked before any new use is made of it, imposing a repair if necessary. If its function of use is lost, it can move into an intermediate circular loop, and why not disappear after creating product holons corresponding to each component resulting from total or partial disassembly.

Each Holon Order (OH) represents a task in progress in the CSC. This may concern a single batch of several PHs, but if at any one time some PHs require repair and others do not, this OH will be duplicated in as many copies as necessary to keep track of all the situations. It is the OH that acts as the link between the PHs and the RHs, and ultimately drives the flow within the CSC.

Overall, the operation of this whole set of holons constituting the different facets of CSC remains consistent with the basics set out in [18], and certain aspects of the logistics operation can be found in the examples described in [17]. This is particularly the case for the choice of LSPs once the artefact has determined which flow it is going to take: it knows where it is and where it needs to go, and its OH can organize *ad hoc* transport.

In the proposed control solution, the innovative aspect specific to circularity concerns the ability of the PH's to ability to retain its value within the CSC pyramid. In particular, it must validate the fact that it is shifting down one level in the pyramid, resulting in a reduction in its value. The various choices will be made using a multicriteria decision support approach, using the AHP [20] and ANP [21] methods.

5.2 Multicriteria decision-making structure

The aim here is to explore the decision-making conditions for the choice of flows to be followed, with the objective of preserving as much of the use value as possible, as well as that of reusable components... and therefore considering that recycling remains the last resort before energy recovery or, worse still, landfill.

These decisions mainly concern the arbitration stages during the descending phase of the CSC pyramid. The aim is to retain as much use value as possible, without degrading it, or by degrading it as little as possible. To achieve this, we need to identify the criteria that can influence and inform this choice. In all cases, the question arises as to whether it is possible to maintain the current level of circularity loops, or whether we should consider moving down a level. In all cases, we are faced with different industrial flow solutions aimed at preserving the value of use at the time of sorting, and different industrial flow solutions at the lower level, the latter degrading this value in the process. For example, as long as the product is in a high loop covered by the functionality economy, we need to ask ourselves whether it can continue to be used at this level, whether it can be repaired (these different possibilities will of course be prioritized) or whether it can be switched to a medium loop with a view to being disassembled to recover the value of its components. These are all possible logistical flows, and when the time comes, it will be necessary to arbitrate and make choices that will trigger transport activities in the CSC.

This necessarily multicriteria issue raises the question of how to assess performance from the point of view of circularity. We have conducted a literature review of the performance indicators used to characterize circularity / sustainability, in order to identify those that could be useful in the self-organized, multicriteria control of the CSC [15]. This is useful for understanding how decisions are made to steer flows with a view to conserving use value. In addition, the proposed multicriteria decision-making structure (Figure 3) also integrates various aspects linked to the business model. This is an initial version that will be refined after the first experiments.

It is not a question of circularizing for the sake of circularizing, but of circularizing in order to transform economic activities: the market must also be the vector and attractor of any approach to circularizing manufacturing activities.

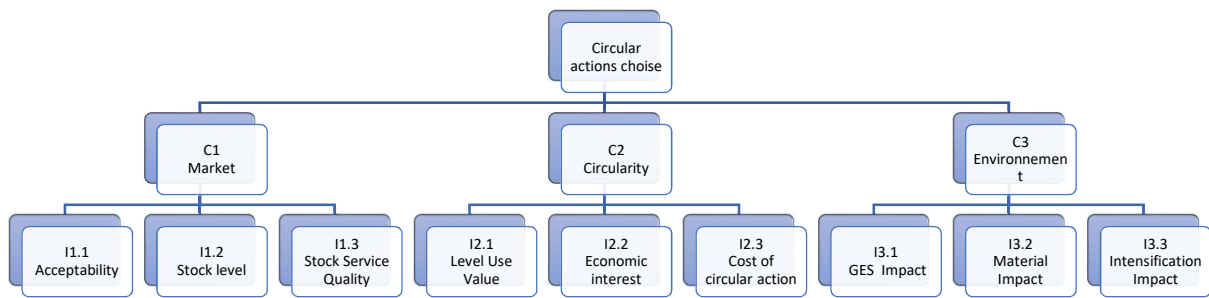


Fig. 3. AHP structure for the choice of circular actions

This AHP structure will be implemented to produce a PoC. Various scenarios will be tested to assess the performance of the holonic, self-organized and multicriteria control system. The indicators will be calculated using formulas and data specific to the various concerned product, resource and order holons.

6 Conclusion

The circular economy requires a profound transformation of supply chains, moving from a linear logic to a complex circular organization, based on the maximum conservation of the use value of artefacts through a hierarchy of actions favoring repair, reuse and remanufacturing before recycling and disposal. This transition requires the implementation of interconnected and adapted circularity loops, involving numerous specialized actors and flexible logistics. However, the control of these circular flows comes up against a double uncertainty - that of demand and that of supply - which renders traditional forecasting models obsolete. Faced with this complexity and uncertainty, we propose the adoption of a more decentralized, reactive and opportunistic holonic self-organised and multicriteria control, able of adapting in real time to changes in flows and effectively supporting the transition to a truly circular economy.

References:

1. Citwell, Soroa, INEC. (2023). *La supply chain circulaire, pivot de la réindustrialisation verte*, Institut Nationale de l'Economie Circulaire. <https://institut-economie-circulaire.fr/wp-content/uploads/2023/04/Plaidoyer-Supply-Chain-Circulaire-mars-2023.pdf>
2. W. R. Stahel, F.-M. Lambert (2025). *Economie Circulaire – les défis à relever pour atteindre une économie de performance*. Dunod.
3. Kirchherr, J., Urbinati, A., & Hartley, K. (2023). Circular economy: A new research field?. *Journal of Industrial Ecology*, 27(5), 1239-1251.
4. Dull, D. (2021). *Circular supply chain*, ISBN: 9798463191410

5. P. Pujo, F. Ounnar, A. Leblanc, F.M. Lambert, (2024). Structuration de la Supply Chain Circulaire et positionnement vis-à-vis des filières REP. *1^{er} CIEC*, Montpellier.
6. Stahel, W. R. (2019). *The circular economy: A user's guide*. Routledge
7. Stahel, W. R. (2017, February). Analysis of the structure and values of the European Commission's Circular Economy Package. In *Proceedings of the Institution of Civil Engineers-Waste and Resource Management* (Vol. 170, No. 1, pp. 41-44). Thomas Telford
8. Wallsten, B., Carlsson, A., Frändegård, P., Krook, J., & Svanström, S. (2013). To prospect an urban mine-assessing the metal recovery potential of infrastructure "cold spots" in Norrköping, Sweden. *Journal of Cleaner Production*, 55, 103-111.
9. International Organization for Standardization. (2023). *ISO 59004:2023 - Sustainable and traceable cocoa bean production*. Geneva, Switzerland.
10. De Angelis, R., Howard, M., & Miemczyk, J. (2018). Supply chain management and the circular economy: towards the circular supply chain. *Production Planning & Control*, 29(6), 425-437.
11. Farooque, M., Zhang, A., Thürer, M., Qu, T., & Huisingh, D. (2019). Circular supply chain management: A definition and structured literature review. *Journal of Cleaner Production*, 228, 882-900.
12. Kirchherr, J., Reike, D., & Hekkert, M. (2017). Conceptualizing the circular economy: An analysis of 114 definitions. *Resources, conservation and recycling*, 127, 221-232.
13. Achterberg, E., J. Hinfelaar, and N. M. P. Bocken. M. P. Bocken (2016). Master circular business models with the Value Hill. *White paper*, (September)
14. Fabbe-Costes, N. (2005). La gestion dynamique des supply chains des entreprises virtuelles. *Revue française de gestion*, 156(3), 151-166.
15. Ounnar, F., Boissée, S., Lambert, F.M., & Pujo, P. (2025). Pilotage multicritère des flux dans la Pyramide de la Supply Chain Circulaire, *2th CIEC*, Amiens.
16. Ounnar, F., Pujo, P. (2010). Isoarchic and Multi-criteria Control of Supply Chain Network. In: *Artificial Intelligence Techniques for Networked Manufacturing Enterprises Management*. Springer Series in Advanced Manufacturing. Springer, London. https://doi.org/10.1007/978-1-84996-119-6_6.
17. F. Ounnar. (2025). Pilotage adaptatif intra/inter organisationnel de systèmes logistiques pour la transformation écologique, articulant décisions stratégiques et opérationnelles. AMU.
18. Pujo, P. (2012). *Pilotage isoarchique des systèmes de production*. Éditions Universitaires Européennes.
19. Cao, K., Liu, Y., Meng, G., & Sun, Q. (2020). An overview on edge computing research. *IEEE access*, 8, 85714-85728.
20. Saaty T.L. (1980). *The Analytic Hierarchy Process*. New York, McGraw- Hill.
21. Saaty, T. L. (1996). *Decision Making with Dependence and Feedback: The Analytic Network Process*. RWS Publications, Pittsburgh, PA.