Towards smart and suitable management of roadsides: System dynamics in the era of industry 4.0

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Towards Smart and Suitable Management of Roadsides: System Dynamics in the Era of Industry 4.0

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Abstract: Within the aim of supporting territories to create more sustainable systems, road infrastructure plays a paramount role, not only because road shoulders represent a non-negligible land area, including their own biodiversity, but also because this represents the interface with the territory's ecosystems. For this reason, future road management systems should include all the different dimensions of sustainability. However, sustainable management of roadsides can be considered a complex and dynamic process. It requires access to data, from communities, maintenance services, suppliers of mowing equipment, and the roadsides themselves (physiognomy of the terrain, the composition of the soil, biodiversity, the composition of the area to be mowed and pruned, etc.). Therefore, the current development of Industry 4.0 opens opportunities to capture, aggregate, and analyze the information needed to support decision-making by territory planners and to provide the network's various stakeholders with complete visibility. Although generic models for decision-making in big data environments have been proposed in the scientific literature, they fail to deal with the specific characteristics and data requirements of such a system. In this context, this paper proposes the integration of a process based on the dynamic systems theory and the Industry 4.0 paradigm to achieve sustainable management of roadside processing. It will enable us to identify and manage in a proper manner the varying and heterogeneous amount of data that this type of system entails. The proposed model will support territory policy-makers to take sustainable actions in order to ensure efficient decisions with a long-term view, to assess the current situation and future opportunities, and then to contribute to the evolution of territories towards a circular economy.

Keywords: *Roadside Management, Sustainability, Industry 4.0, Dynamic System Theory*

1 Introduction

In a context where transport infrastructure is confronted with territorial, social, political, and technological changes, it becomes essential to review its place in society. To cite an example, the French transport infrastructure network has grown from 926,500 km of roads in 1990 to 1,073,500 km in 2014, an increase of 15.9% in 25 years [1]. Therefore, the construction and maintenance of transport infrastructure involve assessment elements related to the economic role of transport, public safety, and the living environment, as well as the preservation of the environment [2]. All this capital, distributed throughout a territory, must be managed in a sustainable way, not only to support economic development but also to mitigate the environmental impact by reducing the extraction of natural resources and the discharge of waste, while maintaining the quality of life of citizens [3]. Indeed, the consequences of the choices made, particularly in terms of spatial planning, have repercussions in the long term. It is time to make infrastructure management strategies more resilient and responsive to the new conditions imposed by the planet.

The roadsides consist of the entire public road domain except for the pavement and the hard roadside. Maintenance of these structures includes all the activities carried out or controlled, usually in a subdivision, aimed at preserving the safety of the user and keeping the road annexes in good condition [4]. Thus several economic issues (creation of local value, job creation, the attractiveness of the local

areas, etc.), technological issues (development of biomass, promotion of energy transition and reduction of the carbon footprint), social issues (road safety, prevention of floods and fires), and environmental issues (preservation of biodiversity, improvement of water, air and soil quality, etc.) are integrated [4]. Therefore, sustainable management of roadsides can contribute to the evolution of territory towards a circular economy, which is a huge opportunity to integrate sustainability into the vision of companies and territories [5]. For policy-makers, sustainable action means taking a very long-term view and giving a different signal to stakeholders who wish to assess the current situation and future opportunities [6]. Assessing current and future situations requires a variety and diversity of public data, in order to realize territorial diagnostics, measure and monitor the evolution towards the circular economy, and optimize the use of resources for providing services to the public (waste collection, energy…). However, for that purpose, the challenge is twofold. First, it lies in accessing, collecting, and processing massive and heterogeneous information on characteristics such as the potential of unused roadside resources (wood, grass, waste), the roles of and synergies between the different actors (politicians, user associations…), the diversity of work on resource estimation, the knowledge of flows (wood, biomass), and the geographical dispersion of activities, all of which makes sustainable roadside management challenging and complex. Second, the management of roadsides is a responsibility of the territories and nowadays represents a significant cost. At present, there are no management tools enabling stakeholders to make appropriate decisions and thus control the various externalities of roadside management. Such a decision support tool must therefore understand the complexity inherent in roadside management in order to benefit from it.

To confront these difficulties, the current spread of digital technologies (Big Data, Open Data, Blockchain…) related to the new challenges of Industry 4.0 offers the opportunity to shift from classic roadside management to a form that is based on a circular economy [7], [8]. In particular, embedded intelligent technologies make it possible to fully observe the states of production, machines, and materials by making information available in real time [9], [10] for decision-making purposes. However, in order to leverage the opportunity of Big Data, the implementation of those data-driven approaches requires organizations to adapt their organizational decision-making process [11], perceived as complex because of the significant role played by many factors on roadside management strategies. Therefore, Industry 4.0 technologies have the potential to unlock a circular economy through the tracking of materials and systems to be managed (here, green waste and green dependencies) by integrated sensors [7]. [12] proposed a model called Decision-Making Process in a Big Data Environment (DMP-BDE), which aims to be generic and is based on the four phases of the decision-making process proposed by [13]. However, it fails to deal with the specific characteristics and data requirements of such a system. Indeed, contrary to the industrial standardized environment, roadsides include dimensions, so metrics that are less commonly measured and then mastered (biomass valorization, biodiversity maintenance, fire prevention, driving security, management of allergenic plants, among other things) [14]–[17].

In this article, special attention is paid to the decision-making process and the modeling of different roadside management strategies. Thus, we seek to integrate system dynamics into the decision-making process because this modeling approach allows the decision-maker to identify the different components of a complex system and to visualize the most likely consequences of his decisions [18]. This article presents a dynamic simulation modeling of the roadside management and highlights the data to be collected to assist decision-makers in their decision-making. A system-dynamics-based model is proposed to allow decision-makers to understand the influences between the different variables and therefore the impact of each roadside management strategy. This system-dynamics-based model forms the basis of a future roadside management tool. To illustrate our proposal, the results obtained for reasoned management with biomass valorization will be presented as part of a circular economy project. Thus, the first objective is to establish the characteristics of the sustainability of roadside management strategies and to apply the methodology of system dynamics to identify the data to support decision-making. Based on this analysis, a discussion will be proposed to

identify how Industry 4.0 can lead to collective, sustainable, and intelligent management of roadside dependencies.

This article is structured as follows. In the first section, a review of the literature on the management of roadsides and Industry 4.0 in the service of territorial intelligence is presented. The system dynamics methodology is detailed and the formalization of a roadside management model is given. Finally, a digital architecture for the management of roadsides is proposed to highlight how Industry 4.0 can promote the deployment of a circular economy around roadsides.

2 Scientific Context

The circular economy is a broad concept bringing together different approaches that refer to new ways of organizing and managing human activities at the level of companies and territories. It integrates a set of approaches such as waste management (recycling), the extension of the duration of use and responsible consumption, sustainable extraction/exploitation and purchasing practices, and eco-design, as well as the approaches of the economy of functionality and industrial ecology [19]. The implementation of circular economy approaches is intended to strengthen the resilience of the territory by limiting its dependence on incoming resources flows. The looping of territorial resources flows enables the use of materials and energy to be optimized for the benefit of the local economy.

The management of roadsides can be fully integrated into a circular economy approach because the raw material resulting from mowing and pruning can be integrated into energy supply chains. It is therefore part of the waste management pillar of the circular economy.

2.1 Green dependencies and management strategies

Road infrastructure is typically composed of four main elements [20]: (i) the paved roadway on which vehicles travel (ii), the berm or roadside, located near the road (iii), the ditch, intended for the collection and circulation of the water that runs over the adjacent elements (roadway, berm, and embankments), and (iv) the embankment or slope which generally provides the transition between the road infrastructure and the neighboring environment (Figure 1).

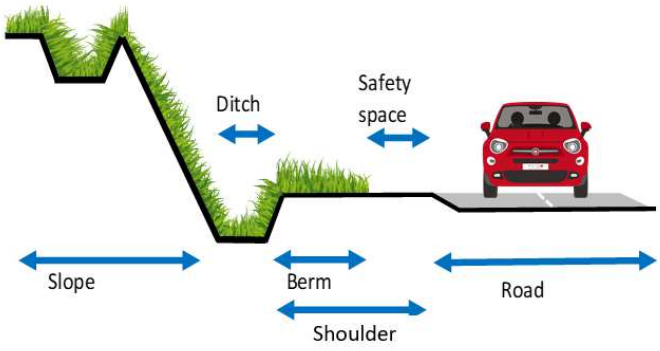

Figure 1: Definition of the roadside

Roadsides are also known as “green dependencies,” and are defined as all the surfaces forming part of the infrastructure right of way except for the direct supports of the structures. They are subdivided into two categories: those that are directly associated with the operation of the structure (roadside, ditches, etc.) and those that accompany the structure (embankments, abandoned areas, etc.) [21]. Subsequently, the terms “roadsides” and “green dependencies” will mainly be used and will include the embankment and the roadside.

The maintenance of roadside infrastructure is the scope of work usually carried out to preserve the safety of the user and keep the roadside annexes in good condition [4], and this includes mowing and pruning.

Green dependencies play a variety of roles [4]:

- Technical: draining water from the platform, storage of snow during snow removal, support for information and signage, location of underground networks, access to riverside properties, etc.
- Roads: safety (possibility of stopping off the road), guidance (on curves and at junctions), visibility of road equipment, etc.
- Ecological: as a screen, a filter for nuisances (pollution, noise…), a refuge for the flora and fauna, reduction of erosion, and restoration of surfaces denuded by earthworks
- Landscapes: a staging of the regions crossed, creation and enhancement of landscapes specific to the route

2.1.1 Green dependencies, a complex and dynamic system

A system is a set of elements considered in their relations within a whole functioning in a unitary manner [22]. The complex system, on the other hand, is a set made up of many entities whose interactions produce an overall behavior that is difficult to predict, while each entity can act on a group and modify the system [23]. Finally, dynamic systems are the mathematical notions which allow the modeling of phenomena that evolve. It is made up of phase space, the space of possible states of the phenomenon suitably parameterized, provided with a law of evolution which describes the temporal variation of the state of the system [24].

Green dependencies can be seen as a complex and dynamic system, functioning not only as a social interface between farmers and road maintenance workers but also as an interface between the agricultural world in general, rural areas, and road users. This dual nature of the interface, which separates two environments while creating a continuity, here vegetal, may reflect the complexity of the relationships that societies have with nature [25].

2.1.2 The management of green dependencies

There are three general types of roadside management, commonly referred to as (i) intensive or conventional management, (ii) reasoned or differentiated management, and (iii) reasoned management with biomass valorization.

Intensive management is considered to be the classic management method, most commonly used in places where road safety and visibility are the dominant priorities (bends, intersections, narrow roads, etc.). In this case, the aim is to carry out as many cuts as necessary according to the growth of the vegetation [26]. This management in three (or more) passages remains theoretical and, in reality, the agents constantly adapt to the conditions of the terrain, in terms of weather conditions, vegetation growth, and the work period, as well as the constraints of equipment and personnel. Vegetation left on the spot during intensive mowing enriches the soil, resulting in faster grass regrowth and more frequent passes over the mowing area, which also makes it necessary to clean nozzles and ditches. Enrichment also leads to pollution of the aquatic environment and a general loss of biodiversity in the natural environment [27].

Reasoned or differentiated management adapts in principle to the type of environment in which it is practiced [28]. It was formalized in the 1990s with the rise of sustainable development. This management method aims to adapt maintenance practices to the type of green space in order to respond to environmental issues while taking into account social, cultural, and economic issues [29]. It is characterized by a de-intensification of practices to promote biodiversity, rationalization of the

resources allocated to management, improved public perception of these areas, and late mowing or even a halt to the use of phytosanitary products. Reasoned management is a method that consists of allowing vegetation to grow spontaneously and cutting it down only once a year, between August and November. This allows most plants to complete their life cycle and thus maintain or even increase plant diversity. To guarantee visibility, late mowing is not applied at intersections.

Lastly, reasoned management with biomass valorization combines economy and biodiversity conservation and is part of a circular economy strategy. It seeks to promote the use of grass and "harvested" wood [27], [30]. This valorization of biomass can be in the form of composting, biogas production, or energy production.

2.2 Industry 4.0 at the service of territorial intelligence

The transition to a circular economy aims to integrate sustainability into roadside management activities and thus requires a structural change in the traditional management model. Therefore, the circular economy model offers an alternative to the linear economy, decoupling economic value creation from resource consumption, keeping resources in use for as long as possible, extracting maximum value during use, and recovering and regenerating products at the end of their useful life [31]. Reasoned management with biomass recovery is part of the circular economy because the waste extraction from roadside mowing (grass and wood) could provide beneficial feedstock for use in biogas systems, anaerobic digestion, composting, or combustion [32]. However, the implementation of circular economy strategies can be impaired by a lack of information regarding the status, availability, and location of raw materials (grass and wood considered as a waste product of roadside management). The emergence and increasing adoption of technologies based on Industry 4.0 principles is one way of overcoming some of these barriers to full implementation of circular economy principles.

Industry 4.0 was initially introduced during the Hanover Fair in 2011 and was officially announced in 2013 as a German strategic initiative [33]. The term Industry 4.0 emerged to frame the Fourth Industrial Revolution. According to [34], it can be defined as "real-time, intelligent and digital networking of people, equipment and objects for the management of business processes and value-creating networks." It aims to connect the physical and virtual worlds in industrial production [35]. From a technical perspective, Industry 4.0 can be seen as an umbrella of various digital concepts and new technologies such as the Internet of Things and Services, Cyber-Physical Systems, Industrial Automation, Intelligent Robotics, Big Data Analytics, Data Analytics, Digital Twin, Digital Shadow, HRC, etc. [36]. It makes it possible to materialize novel potentials to cope with future challenges in the production environment, as well as to offer many opportunities and business models that can be consolidated with these technologies and concepts.

2.2.1 Industry 4.0 and green dependencies

The advancements in and adoption of digital technologies are the key factors for the economic and social development of a territory. It can radically improve public services and improve the quality of life of individuals, and can cope with multiple-environmental, social, and economic challenges. Indeed, the interest in innovative, creative, and digital territories is growing. A great deal of research is being carried out on these subjects in a wide variety of fields, e.g. Intelligent Transportation Systems (ITS), Smart Cities, and Smart Roads, among others.

For the purpose of using real-time and inline data to achieve more efficiency and effectiveness in the logistic process, Industry 4.0 becomes unavoidable in a transportation management system. Intelligent transportation systems have yielded new and innovative ways to improve the safety, operation, and environmental impact of transportation systems—for instance, Smart roadside servers for driver assistance and traffic safety warning [37], planning, and synchronization between different transport

modes during the various logistic operations [38]; the use of big data analysis for demand forecasting and improving inventory planning, warehousing fulfillment, and distribution [39]; connected vehicles to improve operational performance on road links and intersections, leading to increased mobility and improved operations [40]; and an intelligent monitoring system of traffic accidents to collect and process sensor data [41], among other things.

To the best of our knowledge, research on Industry 4.0 does not appear to have extended to the management of roadsides. However, it appears that the digitalization of their management process can be beneficial for territories and communities. Indeed, the management of roadsides is an important but necessary cost center for territories (especially in terms of safety). Like transport systems, management of roadsides requires the use of real-time data to be efficient and adapted to the territories and the particularities of the road network (accident-prone areas for example). Appropriate management of roadsides considers, among other things, the planning of mowing operations, the synchronization of modes of transport (in the case of management with biomass recovery), the anticipation of mowing and pruning needs (these activities take place from April to September in all territories), the frequency of mowing by zone, and the availability of recovery facilities. Thus, in the context of green dependency management, one of the most important challenges is the massive and heterogeneous data from communities, maintenance services, suppliers of mowing equipment, and the roadsides themselves (physiognomy of the terrain, composition of the soil, composition of the area to be mowed and pruned, etc.). Indeed, management of green dependencies is a complex process, in which multiple actors, sensors, and devices should constantly communicate, exchange, and generate new data. In this regard, the collection, integration, storage, processing, and analysis of data between the multiple entities is a major challenge for an effective sustainability management of green roadsides.

Otherwise, Industry 4.0 involves digital capabilities, unprecedented dissemination of the Internet of Things, interoperability, and powerful technologies to aggregate, process, and analyze the very large volume of heterogeneous data which is supplied. Moreover, it allows for the selection and prioritization of the information that will be most relevant for the decision-making process, and provides the network's various stakeholders with complete visibility. Furthermore, the real-time capability visibility enabled by Industry 4.0 and the overwhelming amount of digital data, analytics, and information can be used to manage collaborative decisions in real-time [42].

However, the Industry 4.0 paradigm can be promising for the support of possible innovations that can be applied to manage the networked ecosystems [43] and to improve the traditional Business Model for Roadside Management. In addition, the advancement and adoption of intelligent management of green dependencies can support decision-makers in dealing with the massive volume of data from which relevant information can be provided and shared through the Internet of Things (IoT) systems to ensure sustainable collaborative management. Also, regarding the different stakeholders involved in the roadside management process, digital transformation and the use of intelligent and cooperative systems will make the roadside management process more transparent and more efficient, thereby significantly increasing the decision-making quality and flexibility.

2.2.2 The importance of data in the decision-making process

The challenge for decision-makers is to be able to identify and understand the complexity of the roadsides that they have to manage. In a context of economic intelligence where the environment is uncertain, strategic decision-making always requires important information and is based on a complex process.

In the literature, many decision-making models represent the different phases of the decision-making process [13], [44]–[48]. Simon's model will be the basis of our study, as it is the most famous and most referenced model in research [49].

This model, called the IDC model, contains four phases [12]:

- Intelligent phase: this refers to searching the environment for conditions (a problem or opportunity) calling for a decision
- Design phase: refers to developing and analyzing alternative solutions to the problem or opportunity
- Choice phase: refers to choosing one or more of the available alternatives developed in the previous phase
- Implementation phase where the chosen solutions are implemented

The objective of this research is to help decision-makers make the best use of Big Data to implement the most appropriate roadside management strategy. Several analyses have already attempted to integrate Big Data into the decision-making process [12], [50], [51]. Our thinking is based on the model proposed by [12] because it integrates the Decision Model and Notation (DMN) standard to simplify communication between decision-makers and Big Data analysis teams during the decision-making process. This standard enables human decision-making to be modeled in an understandable way by providing a common notation [52].

The DMN standard leads to two levels of modeling, used jointly or independently [52]:

- decision requirement diagrams, which include a set of elements and the relationships between them. These sets define the decision that will be made and how it depends on other decisions (policy or regulatory), knowledge, and inputs
- the decision logic, which specifies the logic used to make individual decisions [53]

Therefore, [12] propose a model called Decision-Making Process in a Big Data Environment (DMP-BDE) (Figure 2), which is based on the four phases of the decision-making process proposed by [13].

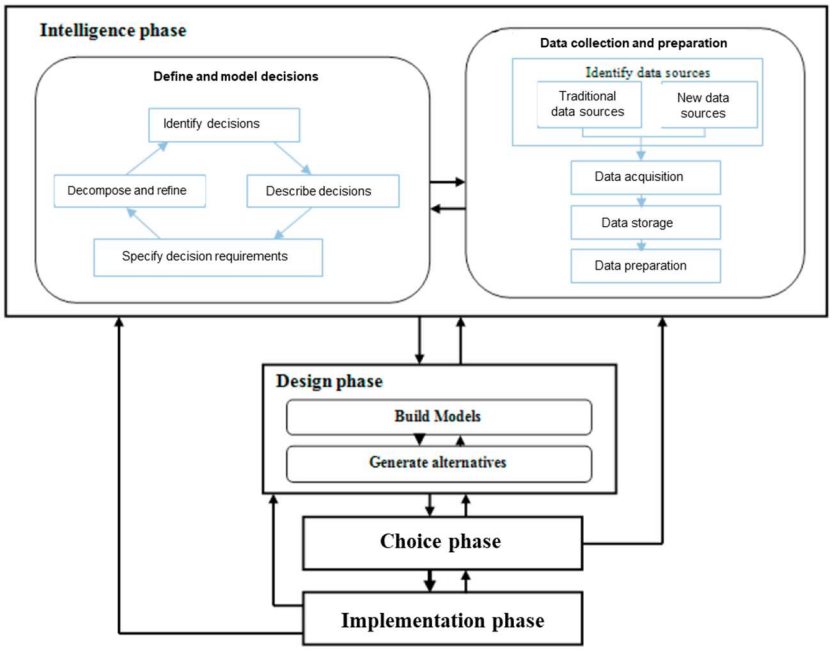

Figure 2: Decision-Making Process in a Big Data Environment Model [12]

In this model, the first step consists of scanning the environment to identify and understand the decision to be made, i.e. the choice of the roadside management strategy in our case. The decision requirements are defined and include needed data, the knowledge to be extracted from this data that is capable of supporting this decision, and the outputs of the other decisions necessary to make this decision. The second phase of the decision-making process is the design phase, where possible courses

of action are developed and analyzed to handle the situation that requires the decision. The following phase is the choice phase, then these alternatives are evaluated to know the impact that each of them will have on the ecosystem.

However, this model fails to deal with the specific characteristics and data requirements of such a system. Indeed, contrary to the industrial standardized environment, roadsides include dimensions, or metrics, that are less commonly measured and then mastered (biomass valorization, biodiversity maintenance, fire prevention, driving security, management of allergenic plants, among other things) [14]–[17]. Therefore, in order to provide territorial decision-makers with a realistic vision of the management costs of their roadsides and thus highlight the economic, social, ecological, and technological benefits of reasoned management with biomass valorization, it is important to integrate and represent the dynamics generated by the different strategies in the decision-making process.

3 System dynamics for decision-making in a Big Data environment

3.1 System dynamic methodology

System dynamics is a practice aimed at creating complex models and providing an overview of the system [54]. It is a methodology that combines analysis and synthesis, which facilitates the distinction of feedback mechanisms [55]. It allows us to understand the behavior of complex systems over time. It can be used to study markets and production capacities [56], industrial behaviors [57], or political strategies [58], among other things. The approach of [25] is of particular interest because it takes all the dimensions of sustainability into account and considers data collection and the selection of mathematical relationships between the different variables. System dynamic models are based on ordinary non-linear differential equations, solved numerically in a digital integration process [59]. On this basis, this article describes and applies the dynamic system methodology to understand the effect of roadside management decisions on the territory through the prism of sustainability.

The methodology of system dynamics involves three general steps: the articulation of the problem or conceptualization, formulation of dynamic hypotheses, verification, and analysis [60]; these are divided into activities to enable the decision-maker to understand the process to be followed and thus obtain the quantitative model representing the system (here, a roadside management system) (Figure 3).

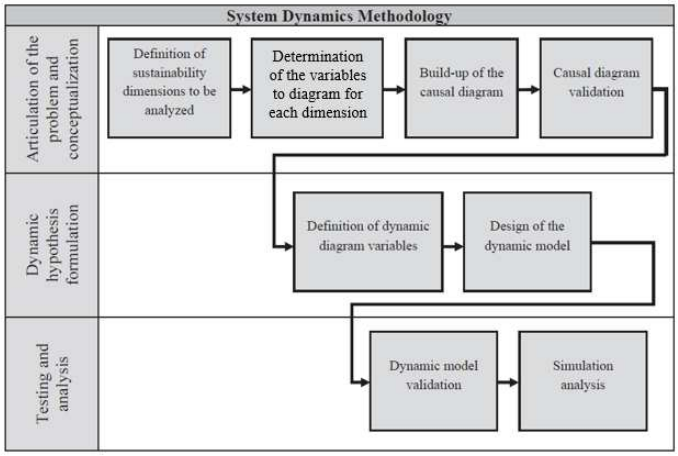

Figure 3: System dynamic methodology, based on [25], [60], [61]

Articulation of the problem and conceptualization

The first stage seeks to analyze the sustainability of the roadside management system through the description of the technological, political, social, and economic dimensions. The second stage aims to

define the variables representative of each of these dimensions. These relationships can be theoretical or provided by stakeholders in the system. In our research, these two steps are based on an evaluation methodology proposed by [62] to define more precisely the specific decisions for a green dependency management project (Figure 4).

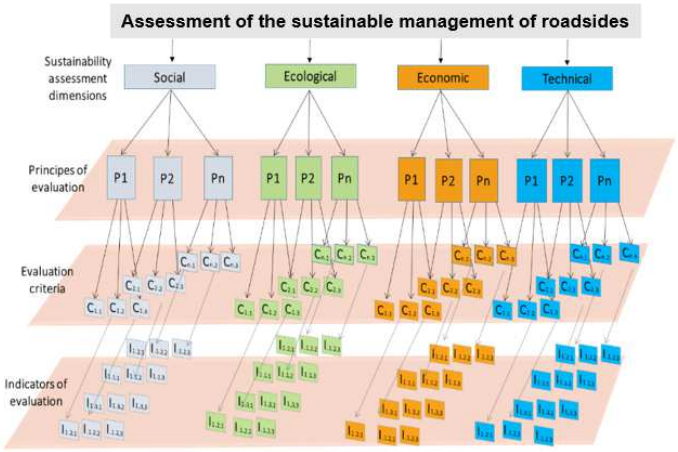

Figure 4: Assessment of the sustainable management of roadsides

In each dimension, different principles have been identified, with which several criteria are associated. From a review of the literature [63] and meetings with experts during workshops, a series of indicators were identified to measure the level of implementation of the criteria in the social, ecological, economic, and technological dimensions, with which it is possible to define the impact of a type or strategy of roadside maintenance. These indicators are validated by experts and will serve as a basis for decisions because they are based on data and knowledge essential for decision-making.

The last two steps in this first phase consist of constructing causality diagrams, which can be interpreted using these variables and relationships, and then having them validated by experts to check that the model meets the assumptions of the mental maps of those linked to the system.

The data used in the definition of the indicators were collected through a literature review and interviews with experts (decision-makers, suppliers of management tools, etc.). To control the indicators defined previously, formulas are developed and help to provide quantified elements to concretely evaluate the impacts of each decision. From these data, causality cycles were identified. Causality cycles can be understood in terms of flows between processes and expressed in mathematical language. In general terms, they are relationships that are established between events, variables, or states. It is generally assumed that the chronological order of cause precedes effect.

Dynamic hypothesis formulation

Each parameter identified in the causality loops was formalized mathematically. In this way, an initial model for roadside management was formalized. The model consists of two types of indicators, exogenous and endogenous. The exogenous indicators or variables are variables external to the model and can be defined by the user of the model. They are also technical parameters that are validated by consulting experts or literature. The endogenous variables are quantifiable by the model and result from calculations integrating the exogenous variables. The objective of this modeling phase is to obtain a conceptual model based on dynamic hypotheses.

In this research, the modeling of the roadside management system was carried out on the Stella© software. This makes it possible to simplify the modulation of complex systems, to look at their evolution, and to act on some parameters to test different scenarios. It enables a similar approach to be used for objects that are a priori very different. Stella© allows you to build “stock and flow” diagrams. Stocks are like reservoirs, accumulators that are filled and emptied. Flows are taps, connections that let

the elements of the stocks in or out. Connectors can be added to indicate what the flows depend on. With the help of a few simple equations, this model can be made quantitative; it then calculates the evolution of the system from the initial conditions, and through the disturbances that can be caused to it. Mathematically, Stella© allows us to program the resolution of differential equations [64].

Testing and analysis

The validation of the model and the roadside management system is based on expert opinion to assess the quality of the model through interviews. Indeed, an initial validation of the model was carried out thanks to a Delphi method [65], [66] to reach a consensus. On the basis of a questionnaire, 10 experts including companies specializing in biomass recovery, mowing and pruning, biomass collection, technical services, and territorial public institutions discussed the relevance of each indicator and the availability of information in order to validate that this model could work. In addition, the results of the model have compared with results from a field study realized in another French region [67]. Moreover, validation with the real world is carried out to ensure that each element of the model has its equivalent in the real world. Currently, a validation of the model is being carried out on a given territory in order to validate the results provided by the model for each of the strategies. Afterwards, the model will be validated and improved by means of Industry 4.0 technologies (embedded sensors, the Internet of Things…).

3.2 The role of system dynamics in the decision-making process in the Big Data Environment model

Therefore, the systems dynamic approach allows an in-depth study of the roadside management system and proposes a first draft of the model supporting the decision-making process. Table 1 highlights how we use a system dynamic approach within the decision-making process in a Big Data Environment, provided by [12] to better understand the role of system dynamics in the design of a decision-making process.

Table 1: Comparison of the system dynamics approach and the DMP-BDE model

<table>
<tr><th colspan="3">Decision-Making Process in a Big Data Environment</th><th colspan="3">System Dynamics Methodology</th></tr>
<tr><th>Phase</th><th>Step</th><th>Role</th><th>Phase</th><th>Step</th><th>Role</th></tr>
<tr><td rowspan="6">Intelligence phase</td><td>Identify decisions</td><td>Identify decisions that can be made to solve a problem</td><td colspan="3"></td></tr>
<tr><td rowspan="2">Describe decisions</td><td rowspan="2">Specify the content of each of the decisions to identify the objectives of each one.</td><td rowspan="2">Articulation of the problem and conceptualization</td><td>Definition of sustainability dimensions</td><td>Analyze the sustainability of the system</td></tr>
<tr><td>Determination of the variable for each dimension</td><td>Describe in detail each of the decisions considering each of the decisions</td></tr>
<tr><td>Specify decision requirements</td><td>Represent the decisions in a clear, simple, and unambiguous way</td><td rowspan="4">Dynamic hypothesis formulation</td><td rowspan="2">Build up and validate the causal diagram</td><td rowspan="2">Identify the decision logic by looking at cause and effect</td></tr>
<tr><td rowspan="2">Decompose and refine</td><td rowspan="2">Show the dependency between decisions, specify the necessary data and define the decision logic</td></tr>
<tr><td rowspan="2">Design phase</td><td>Definition of dynamic diagram variables</td><td>Describe the contents of the decisions in the shape of mathematical formalization</td></tr>
<tr><td>Build models</td><td>Develop a model from data sets identified in the previous step</td><td rowspan="2">Design of the dynamic model</td><td rowspan="2">Develop a model from data sets identified in the previous step and propose several scenarios to facilitate decision-making</td></tr>
<tr><td>Generate alternatives</td><td>Propose several scenarios to facilitate decision-making</td></tr>
</table>

This comparison underscores that a system dynamics approach can be integrated into the model proposed by [12] by achieving the objectives expected within the DMP-BDE. Furthermore, it can be seen that a system dynamic approach makes it possible to detail all decisions more precisely. It should be noted, however, that the "Identify decisions" step is missing in a system dynamic approach.

Therefore, in the context of a roadside management project, we propose to integrate the steps of the dynamics of a system approach into the DMP-BDE model to consider the complexity of the system and its sustainability. Indeed, in the context of a circular economy, it is important to have a global vision of the system to identify the contributions of an alternative strategy such as reasoned management of roadsides with biomass valorization.

Thus, for our research, the following model will be used (Figure 5).

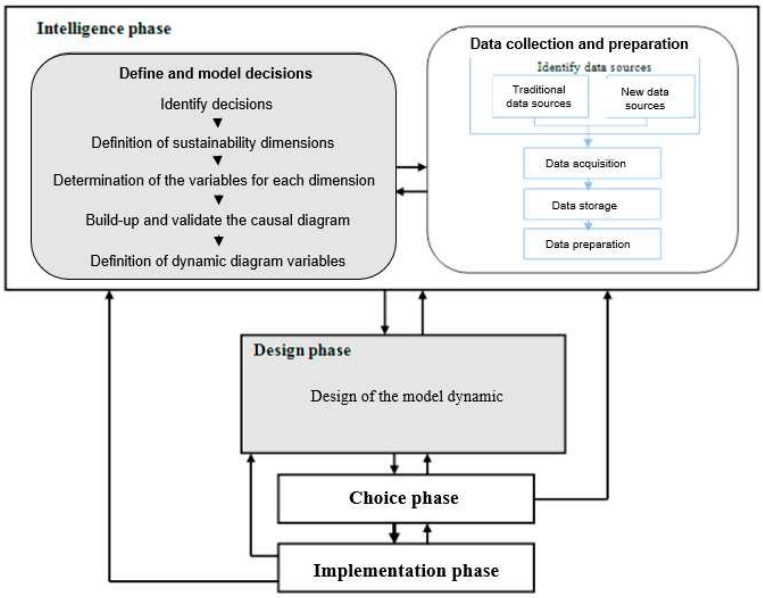

Figure 5: The decision-making process model based on a system dynamic approach (our proposal in the gray boxes)

4 Formalization of a roadside management model

The results of the "Define and model decisions" and "Design phase" stages are presented in this section of our research. The phase "Data collection and preparation" is addressed in Section 5.

4.1 Identify Decisions

As part of our study, three management strategies were studied for comparison. However, particular attention was paid to reasoned management with biomass valorization, as this is an alternative strategy that is still underdeveloped and is part of a circular economy strategy. Therefore, our approach will be illustrated with the results of this management strategy.

4.2 Definition of Sustainability Dimensions

The main decision in a roadside management project is a strategic one: what type of management is to be adopted? This choice will lead to other decisions specific to the chosen strategy. Three strategies are possible (see section 2.1.2) and each has different impacts on the ecosystem.

To assess the impacts of decisions within a roadside management project, four dimensions were identified which are common to each strategy:

- Social, integrating concerns about road safety (reduction of accidents), health (concerning allergenic plants), reduction of natural risks…
- Ecological, including concerns related to the enhancement of biodiversity, habitat preservation, restoration of ecological corridors…
- Economic, including concerns related to the valorization of biomass, the creation of local value, the bio-economy…
- Technical integrating concerns related to cost control, issues related to different types of mowing…

Only the most important principles for the circular economy have been described in this article. Therefore, social principles concerned with improving the health of citizens [66]—[69] and the balance between security and biodiversity [68], [73], [74] as well as ecological principles integrating ecosystem services [70], [74]—[78] and the preservation of water and soil [72] will not be detailed here. Particular attention is paid to waste management and recovery integrated into economic and technological principles.

From an economic point of view, roadside management contributes to territorial attractiveness, local value creation, and the bio-economy [75], [79]—[82] and promotes the recovery of biomass and waste resulting from the management of mowing residues, which is in line with a strategy of circular economy where potentially recyclable waste is incorporated into local recycling chains. Thus, bioenergy is produced from the valorization of mowing residues (grass and wood) through technologies such as mechanization, gasification, and biofuels. Biomass can also be valorized through composting [85].

From a technological point of view, roadside management promotes the advantages of reasoned and innovative mowing, while considering road safety, environmental, and economic issues through rationalization of operations, frequencies, cutting height, organization of mowing, and pruning and management of residues from mowing and pruning which can potentiate the valorization of grass and wood residues [26], [76], [77], [86]. Therefore, the development of biomass valorization technologies contributes to the implementation of the circular economy strategy.

4.3 Determination of the variables

A set of indicators has been identified to measure the level of implementation of the criteria in each of the dimensions to determine the impact of decisions on roadside management strategies (Appendix A).

4.4 Build up and validate the causal diagram

These indicators have been organized in the form of a causal cycle to represent the impacts of successive decisions specific to each of the strategies. Only the strategy of reasoned management with biomass valorization is detailed here because it is integrated into the circular economy (Figure 5).

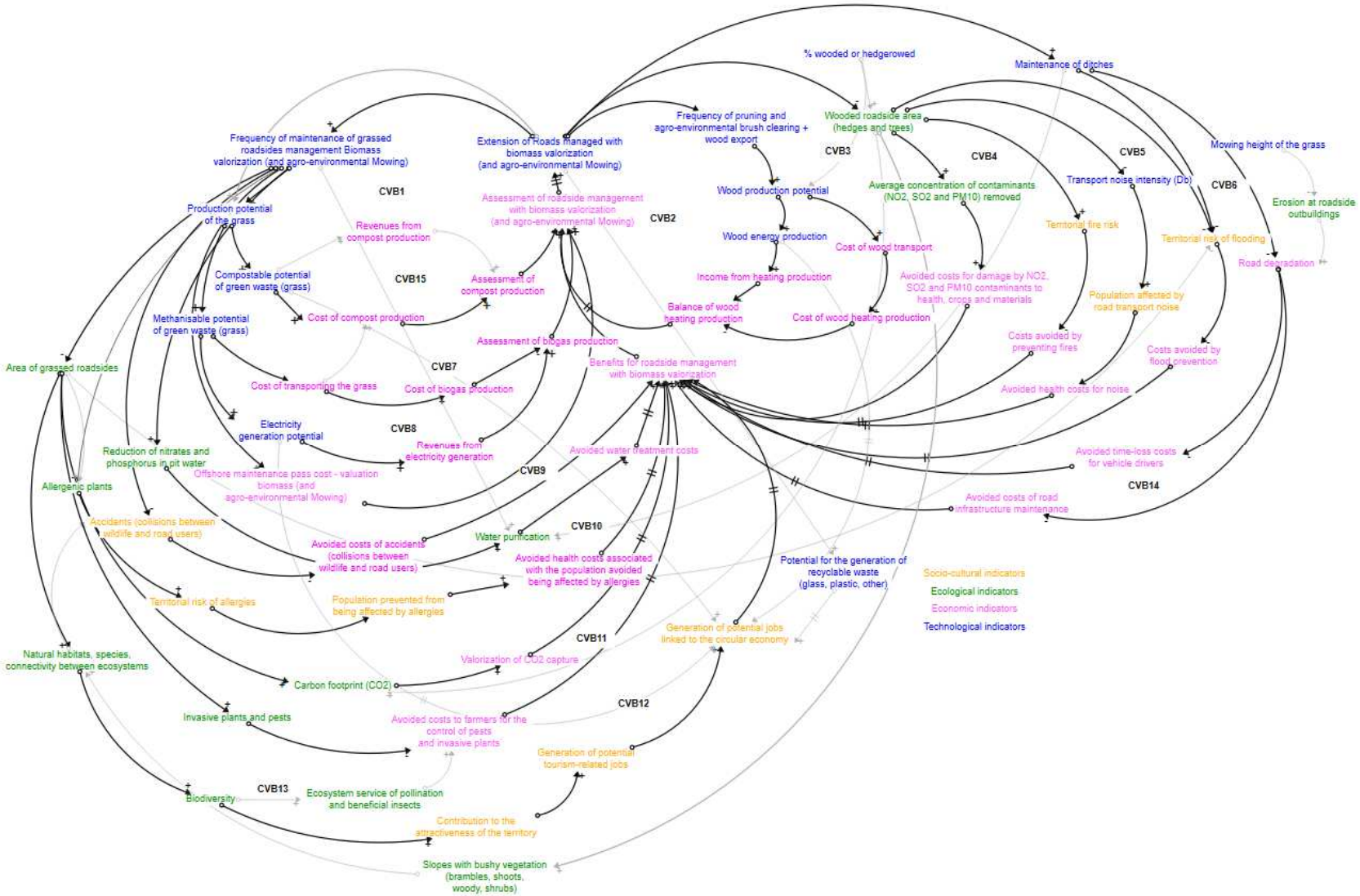

Figure 6: Causality diagram of rational management with biomass valorization

This type of roadside management strategy assumes that cutting frequencies, cutting height, and cutting periods, among other aspects, follow the guidelines set out in the CVB1. By removing cut grass and woody material from the site, roadside "naturalization" processes are promoted. In this sense, studies show that the flora and fauna of these areas are gradually enriched with native species, thereby improving biodiversity (CVB13), also in terms of pollinator species and species beneficial for the control of crop pests; when the biomass is removed, the seeds of invasive and allergenic plants (CVB10) are also removed, thus favoring a reduction in the population affected by allergies, and more beautiful areas and landscapes that favor tourism in these territories. Similarly to that mentioned above in reasoned management, the ecosystem services of reducing flood (CVB5) and fire (CVB4) risks, reducing atmospheric pollutants (CVB3), as well as slope stability, are increased, which together generate the synergy of reducing the rate of road degradation (CVB6) and reducing road maintenance costs (CVB14).

Another benefit of removing cut plant material from the site is a reduction in this type of material reaching the pits and access roads, thus preventing the pit from becoming clogged, requiring less pit maintenance and cleaning, and generating fewer costs associated with these activities. Another advantage of removing the cut plant material is that it reduces water pollution, particularly the reduction of nitrate and phosphorus concentrations (CVB9).

Biomass produced by the road maintenance process can be used as a raw material in the production process of compost (CVB15), biogas (CVB7), heat (CVB2), and electricity (CVB8), producing energy and economic benefits. It also generates jobs related to this local bio-economy (CVB12).

4.5 Definition of Dynamic Variables

Based on these diagrams, several variables have been defined and will be an integral part of the future model. 456 variables were identified, all roadside management strategies combined. Therefore, Table 2 lists some of the endogenous variables defined within the framework of this project, with particular attention being paid to variables that are relevant in a circular economic context.

Table 2: Presentation of some dynamic variables for roadside management

Dimension	Variable	Units
Technological	Total area to be mowed	Km²/ year
	Mowing grass potential	Ton/year
	Potential for electricity production from biogas from grass mechanization	kWh/year
Economic	The selling price of electricity from biomass	€/year
	Gross income from biomass valorization	€/year
	The cost associated with the valorization of biomass	€/year
	The cost associated with routine maintenance in reasoned management with biomass valorization	€/year
	The cost associated with mowing the grass	€/year
	Gross direct employment caused by the valorization of biomass	Employment/year

4.6 Design of the model dynamic

Indeed, the construction of the model was based on data collected "manually" at first to be able to build the first models and thus determine the data to be collected afterwards.

The model obtained is divided into 27 sectors, of which 11 are specific to the circular economy and are presented synthetically in Appendix B.

A sector of the model is presented in Figure 7 as an example.

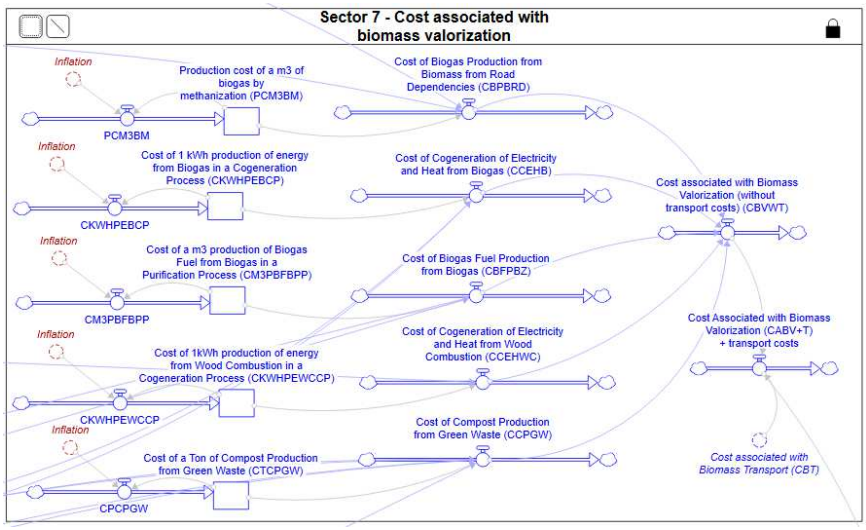

Figure 7: Sector 7—Cost associated with biomass valorization

5 Towards a digital architecture for the management of roadsides

Currently, in our research, data are collected manually from experts and specialized literature. Our vision is to digitize the data collection, processing, and division process by taking advantage of Industry 4.0 concepts. The real-time capability, the interconnection between the Internet and objects, and the data mining process provided by the Industry 4.0 paradigm can be exploited to interact with the information from Open Data. Data-driven intelligence is rapidly becoming a pervasive feature for the economy, where data generated through mobile, social, machine, and product networks are being leveraged through data analytics to create new forms of value [87] and to exploit public data with field data from mowing machines crisscrossing the territory, connected to roadside equipment (smart sensors) and real-time private and public road applications, as well as to allow a territorial anchoring through the facilitation of exchanges between stakeholders for the establishment of local value splay.

In this section, we propose a framework based on the Industry 4.0 paradigm and dynamic systems theory for data management roadside processing (Figure 8).

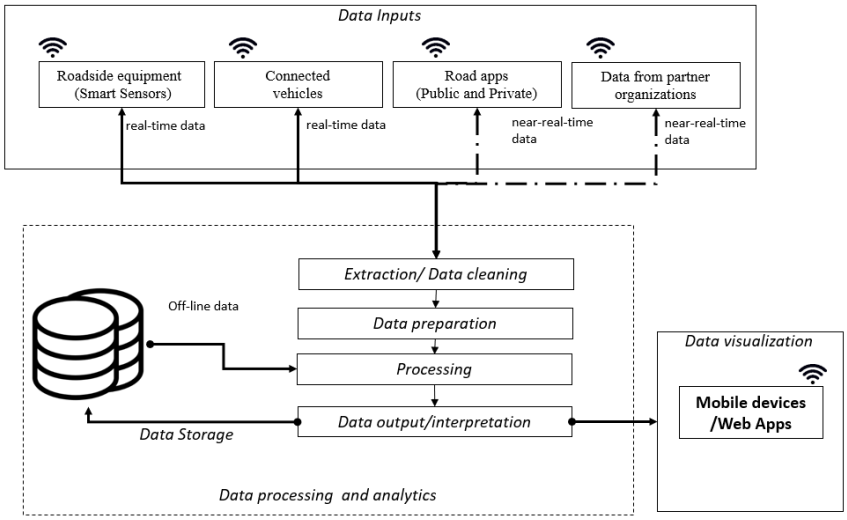

Figure 8: A proposed framework to manage roadsides

The proposed framework involves several steps: real-time data acquisition, data processing and storage, and information and analysis visualization:

- Real-time data acquisition and collection from different sources in the ecosystem, private and public applications of the environment, security systems applications. For instance, data traffic accidents, forest fires, dangerous obstacles on the road, etc. Also, data from the vehicles of the people who manage the roads and shoulders, by means of external and internal sensors to collect the information, and connected equipment. This collection and acquisition will ensure that the data obtained are accurate and well-defined, to ensure the validity of the data.
- Data cleaning and preparation, exploitation of the data into a form suitable for further analysis and processing, as well to ensure that the data contains vital information, and can be easily processed. The preparation process will involve sorting filtering procedures applied to data, to be ultimately used as input.
- Processing: The processing stage refers to the concept of the actual execution of instructions. Technically, it will be based on the dynamic system approach proposed above, and technical exploitation using artificial intelligence algorithms to produce an idea of the data.
- Data storage: In this stage, the pertinent instructions and information, as well as the data collected, prepared, processed, and interpreted, are maintained for future purposes.
- Data visualization: Visualize interpretations and technical information, and to refine and display information to the different stakeholders. The output and interpretations will be presented in multiple reporting forms such as audio, video, graphical, or document viewers.
- The data displayed and visualized can help local governments and users refine their systems, provide complete, up-to-date information to the various stakeholders, such as the municipal department, the planning technician, and the operator of the mowing machine, and analyze the impact of road management strategies in different scenarios.

For example, this data can be used to generate a visualization that shows:

- Environmental conditions: climatic and meteorological conditions, vegetation type (density, high, invasive plants, allergenic plants, presence of biodiversity).
- An economic evaluation of the benefits of roadside management in possible scenarios (environmental, economic, and social).
- Safety conditions on the road: the condition of signs, the stability of the embankment, condition of ditches, the average increase in traffic speed on the road section.
- The detection of cracks or damage in asphalt, in general of infrastructure, roads, and roadsides, which allows preventive interventions.
- Configurator of road management strategies to quantify the ecological, economic, and social impact.
- The embedded application for tuners, which manages in real-time the maintenance of the territory's roadsides.
- The presence of mowing equipment.
- Living areas of invasive plants or infrastructure damage.

6 Conclusion and Perspectives

How does "Big Data" management affect roadside management and its integration into circular economies? Several data collection methods exist, such as field inventories, integrated GPS/GIS mapping systems, aerial/satellite photography, ground laser scanning, or driving an instrumented vehicle while directly collecting a 3D precision point, for example [88].

The integration of Big Data within roadside management can bring together the territory's actors (local authorities, waste treatment companies, farmers…) in innovative collaborations to find ways of using waste from one as raw material for another, thus forming an industrial symbiosis and constituting a fundamental aspect of the circular economy and a driver of green growth. To stimulate the circular economy and the exchange of flows at the level of a territory, it is still necessary to be able to "source" potentially available waste. Indeed, one of the interests of the circular economy is the most efficient and comprehensive use of resources, in this case, green waste. However, the recovery of

green waste from mowing and pruning of roadside outbuildings is struggling to develop due to a lack of information on potentially available waste.

The digitalization of roadside management will therefore make it possible to harmonize management processes and policies and give local authorities a broader vision of the impacts of their decisions. At present, the management of roadsides is considered for the most part as a cost center that is difficult to cut from territorial budgets for safety reasons. However, the system dynamics approach has shown that an alternative strategy for managing roadsides, centered on the use of biomass, could be a source of revenue for local authorities and contribute to the functioning of local authorities. Indeed, the biomass that is recovered and transformed can be reused by local authorities in another form (composting, energy…). However, this requires some reflection on the coordination of the actors in the territory and on new business models. As a result, Big Data can provide the necessary information to accompany these changes in policies and operations by collecting data at each stage (decision-making [1], mowing/pruning [2], green waste collection [3], waste valorization [4], and reintegration of the results of the valorization process in service to the territory [5]) (Figure 9).

Figure 9: Roadside management in the era of Industry 4.0

Consequently, the continuation of this research lies in the creation of a platform that allows a territorial anchoring by facilitating exchanges between the actors concerned for the implementation of local supply chains, operating in a closed loop. The interest would then be to make the information resulting from open data interact, allowing access to public data with data from mowing machines crisscrossing the territory to facilitate sustainable decision-making.

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Appendix A: Identification of indicators specific to a circular economy strategy

D	Indicators		References
Economic	Green economy jobs (eco-activities)		[87]—[90]
	Revenues from rational management with biomass export	Income from the sale of electricity	[30], [91]—[94]
		Income from the sale of heat	
		Income from the sale of biogas fuel	
		Income from the sale of compost	
		Revenue from the sale of wood	
	Cost associated with mowing the grass		
	Associated cost of wood pruning		
	Cost associated with routine maintenance		
	Cost associated with the transport of biomass		
	Cost associated with the valorization of biomass		
Technological dimension	Grass mowing potential		[30], [91]—[94]
	Wood pruning potential		
	Biogas production potential		
	Electricity generation potential		
	Heat generation potential		
	Biogas fuel production potential		
	Compost production potential		

Appendix B: General indicators of the model and the sectors describing it

Technological dimension	
Sector	**General indicators**
Sector 1—Road extension and roadside mowing and pruning area	Area to be mown by type of road Total area to be mowed Surface to be pruned by type of road depending on the case study Total area to be pruned
Sector 2—Wood potential	Potential of wood pruning according to the type of road Total potential of wood pruning
Sector 3—Grass potential	Grass mowing potential according to the type of road grass potential
Sector 4—Biogas, electricity, heat and biogas fuel production potential	Biogas production potential from grass methanization Potential for electricity production from biogas from grass methanization Potential for electricity generation from wood combustion Potential for heat production from biogas derived from grass methanization Potential for biogas production fuel from biogas derived from the methanization of grass
Sector 5—Compost and digest production potential	Potential for compost production from wood Potential for compost production from grass, wood, and compost (digest) from methanization
Economic dimension	
Sector	**General indicators**
Sector 6—Sale of electricity, heat, biogas fuel, compost and wood	Sale of electricity produced from biogas (from grass) and wood combustion Sale of heat produced from biogas (grass) and wood combustion Sale of biogas fuel produced from biogas from the methanization of grass Sale of compost produced from grass Sale of compost produced from wood Sale of compost produced from the methanization of grass (digest) Sale of wood Gross Income Biomass Valuation
Sector 7—Cost associated with biomass valorization	Cost of biogas production from biomass from roadsides Cost of cogeneration of electricity and heat from biogas Cost of biogas production fuel from biogas Cost of cogeneration of electricity and heat from wood combustion
Sector 8—Cost Associated with the Transport of Biomass	Labor costs associated with biomass transport Truck rental cost for transport Cost of fuel and lubricant for the transport truck
Sector 9—Pruning and mowing costs	Labor costs associated with wood pruning Material costs associated with wood pruning Cost associated with wood pruning Cost associated with wood pruning with collection by recovery Labor costs associated with grass mowing Material costs associated with grass mowing Cost associated with grass mowing with collection by recovery
Sector 10—Unwanted waste management costs	Average amount of roadside waste to be managed per year Cost of managing undesirables, first mowing Cost of managing undesirables, second mowing
Sector 11—Gross direct employment that can be created due to the valorization of biomass	Biomass potential mobilized for valorization Gross direct employment that can be created due to biomass valorization Benefits in terms of minimum gross net salary due to biomass valorization