Supplementary Material for Review:

Model full description and analysis of the paper entitled:

"Consideration of complexity in the management of construction and demolition waste flow in French regions: an agent-based computational economics approach"

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This document presents the complete version of the model described in the main text of the article of the same title. Our model is an agent-based model or ABM (Le Page et al., 2013). In particular, because our application is economics, our model is an agent-based computational (ACE) model i.e. a model studying economic processes represented as dynamic systems of interacting agents (Tesfatsion, 2006; Nardone, 2019). It will be formulated according to the ODD protocol (Grimm et al., 2010) and more precisely ODD + D (Müller et al., 2013), an extension of ODD to represent human-decision making. This protocol is being recognized by the community more and more as a means of building and communicating ABMs (Railsback & Grimm, 2019) in a comprehensible way by users who may not have scientific understanding.

I. Description of the model (by following the ODD + D protocol)

I.1 Overview

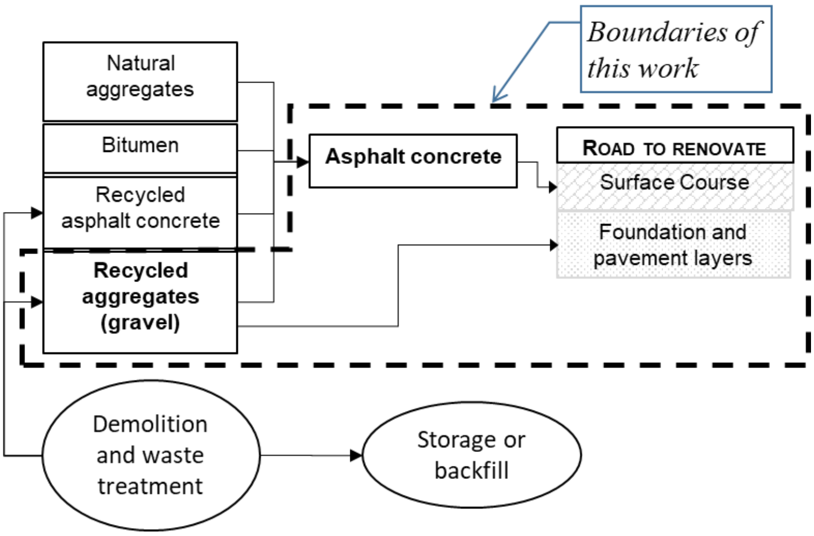
I.1.1 Purpose

I.1.1.1 Context

In accordance with the French "Loi Notre" of August 7, 2015 (JORF NOTRE, 2015) on new organization of French Republic territories, the Decree applying from June 17, 2016 (JORF PRPGD, 2016) asked the 18 French regions to implement a regional prevention and management plan for waste (From the French plan régional de prévention et de gestion des déchets, PRPGD), a plan that is reviewed every 6 years. This waste includes that from work sites (construction, renovation) whether buildings or public work (e.g. roads).

If we focus only on cases of road renovation, a principal post-consumer use of recycled gravel (called "gravel" in the rest of the document) as a road base (Figure 1), the following questions recur: *(Q0 – demand) What is the annual renovation rate of roads in the region? (Q1 – supply) What are the material needs for gravel, natural aggregates and asphalt? And (Q2) How might the situation change over time?*

Figure 1: Boundaries of the work: focus on gravel and asphalt flows, used for road renovation applied to the PACA region



To implement the PRPGD plan in the Provence Alpes Côte d'Azur (PACA), the stakeholders of that region conducted various cooperative workshops (Atelier Mai PACA, 2017; Atelier Sep PACA, 2017) that were to, among other things, to answer questions *(Q0)* and *(Q1)*. Future scenarios *(Q2)* have not been taken into account. As results, the answer to *(Q1)* is global gravel and asphalt production estimated from the 2015 survey and other sources (Frtppaca, 2017) . This production is split as follows:

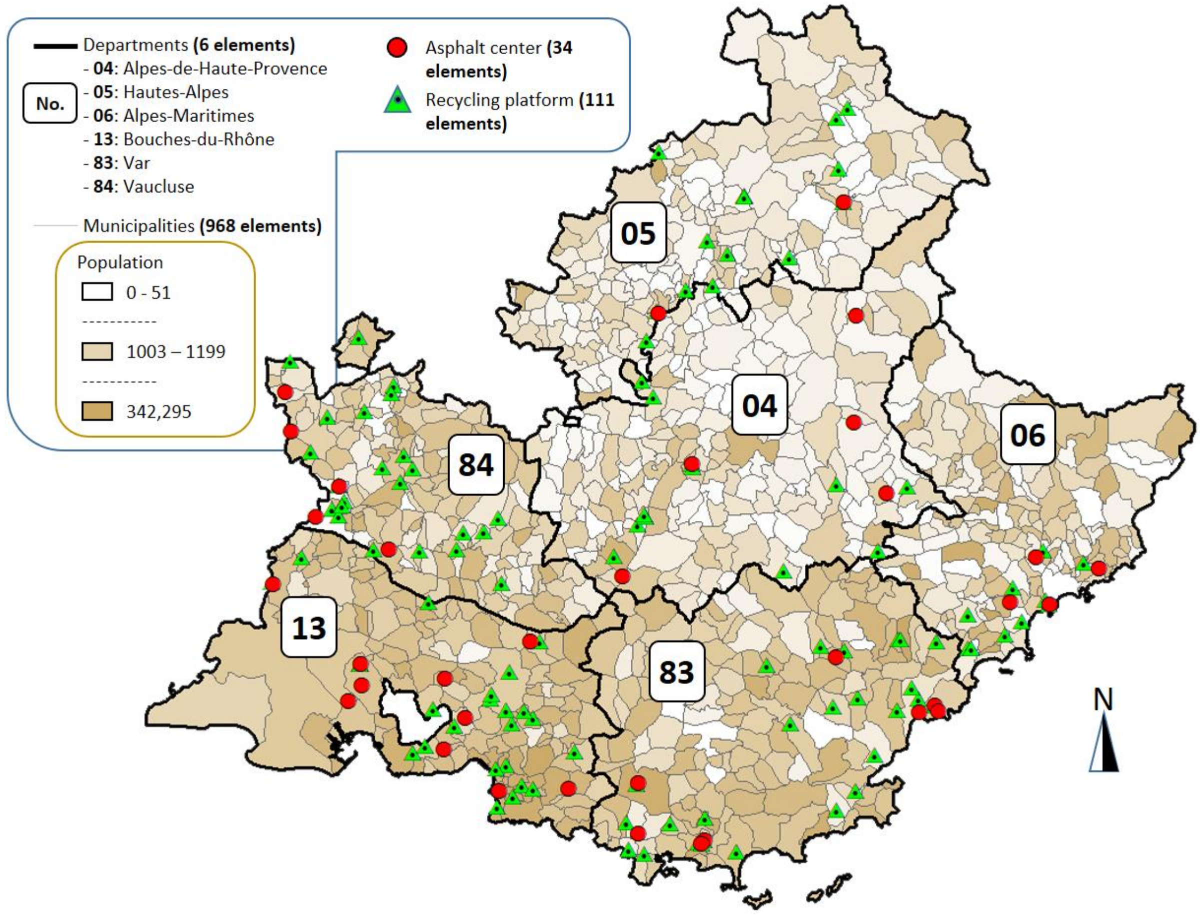
- Gravel production = 1,393,579 mt
- Asphalt production = 2,508,694 mt

From this production, and knowing the surface area in the region's roads (IGN Carto Admin, n.d.; Frtppaca, 2017), the workshops estimated a global road renovation rate of about 3.7% (answer to *(Qo)*).

Beyond this global study, these workshops also integrated the results of a survey on a more detailed scale (sites) conducted in 2017 with operators in the region. These surveys related to 2015 management of inert waste activity from demolition in construction and the production and consumption of asphalt and of recycled gravel. The response rate was 75% - *which also means that 25% of sites did not respond about their production and flows*.

The work presented in this article extends the initial global model from PACA workshops to a more refined and more complex model (multi-scale and heterogeneous on one or more scales) that Figure 2 shows better.

Figure 2: PACA region presented, with (a) the 2015 locations of inert waste management sites (recycling platforms) and asphalt plants, according to the survey, and (b) the administration (Region, Department, municipality) and population distribution per municipality (IGN Carto Admin, n.d.)



The model used answers the same question (*Qo)* that we answered for the regional scale, but at a lower scale, as follows *(Qo'): for 2015, what would the possible geographic distribution (hypothesis) per municipality and per Department, of the quantity behind this global road renovation rate of 3.7 % for PACA?*

I.1.1.2 Intended Audience

This model is intended for the administration of the Provence-Alpes-Côte d'Azur (PACA) region to help in the development of its regional plan for waste prevention and management (PRPGD).

I.1.2 Entities, state variables and scales

I.1.2.1 Preliminary notations

Before describing the model, Table 1 presents a set of notations that will be used within.

Table 1: Various notations used during the description of the model

Notation	Meaning
`e.sm()`	The entity `e` calls to its submodel (or method) `sm`.
`x{}`	Indicates a set of elements of type `x`
submodel / `n`	Introduces a submodel of level `n`, which can be called by a submodel of level `n-1` if `n` > 1
Exo	Indicates, in a column of a table describing the properties of an entity, whether the property located in the current line is an exogenous variable or not
Endo	Indicates, in a column of a table describing the properties of an entity, the equation initializing the property (which is therefore endogenous) located in the current line
`Parameters`	Introduces the parameters of an equation. Not mentioned if the equation does not have it
`Returns`	Introduces the return value of an equation. Not mentioned if the equation does not have it
`Body`	Introduces the body of an equation. Not mentioned if the equation does not have parameters or a return value
`//`	Introduces a comment in an equation
`var`	Introduces a local variable to an equation
`this`	Refers to the object 'itself'
`SymG2A`	Indicates symmetrical reasoning for an equation on the asphalt from an equation on the gravel

I.1.2.2 The entities

Table 2 gives here the list of the model's entities and, if necessary, its spatial form (point or polygon or n/a if the entity has no spatial form).

Table 2: list of the model's entities

Type of entity	Name of the entity in the model	Description	Name of an instance of the entity in the model	Spatial form
Parties in the model	`region`	Describes the unique administrative entity "PACA"	`reg`	Polygon
	`MacroManager`	Is the synchronizer of interactions, globally. Also contains all of the system's global variables, which are not in the entity `region`. These are generally variables for mathematical use.	`mm`	n/a
	`Department`	Describes an administrative entity "Department"	`dept`	Polygon

Type of entity	Name of the entity in the model	Description	Name of an instance of the entity in the model	Spatial form
	`Municipality`	Describes an administrative entity “municipality”	`comm`	Polygon
	`PM`	Is the project manager responsible for the renovation of a road in a municipality.	`pm`	n/a
	`Recycler`	Supplies gravel for road renovation. Is a material supplier	`rec`	Point
	`AsphaltProducer`	Supplies asphalt for road renovation. Is a material supplier	`prod`	Point
Other entities	`Site`	Generic name given to the objects: a localized recycler (a recycling platform) and a producer (an asphalt plant)		Point
	`Distance`	Stores in its structure the information necessary for measuring the distance between two sites or two municipalities		n/a
	`GravelOrder`	Stores in its structure the information necessary to make a gravel order		n/a
	`AsphaltOrder`	Stores in its structure the information necessary to make an asphalt order		n/a

I.1.2.3 The attributes

Before describing the attributes, note that all the spatial entities implicitly have properties (`x`, `y`) and polygon properties, a set of (`x`, `y`){} that describes the contour.

The region

Table 3: the attributes of the entity `region`

Symbol	Meaning	Type	Unit	Exo	Endo
`χG2015`	Regional gravel production for 2015	double	t	✓	
`χE2015`	Regional asphalt production for 2015	double	t	✓	

The macro manager

Table 4: the attributes of the entity `MacroManager`

Symbol	Meaning	Type	Unit	Exo	Endo
`qG0`	The default value of gravel stock from a recycler that did not complete the survey	double	t	✓	
`qE0`	The default value of asphalt stock from a producer that did not complete the survey	double	t	✓	
`cEvM`	The total number of PM having finished the evaluation of their material needs for the renovation	integer			Eq 13

Symbol	Meaning	Type	Unit	Exo	Endo
κRecs	The structure that encompasses all the orders from recyclers, in the form of a queue (FIFO model)	GravelOrder{}			Eq 5
κProds	The structure that encompasses all the orders from asphalt producers, in the form of a queue (FIFO model)	AsphaltOrder{}			Eq 5
ρGpv	The ratio of gravel necessary per lane	double	t/lane/m	✓	
ρEpv	The asphalt ratio necessary per lane	double	t/lane/m	✓	
ρEGpv	The connection between quantity of gravel and of asphalt	double	%		Eq 7
μOD	The buffer radius threshold below which an orthodromic distance between two points is returned even if the points belong to two different municipalities	integer	km	✓	
μBR	The maximum buffer for the material suppliers search	integer	km	✓	
ρM0	The production rate for sites that did not complete the information (whose stock values are assigned by default)	double	%	✓	
ρRenovC{}	The renovation rate list for each municipality	double{}			Eq 1
ρRenovD{}	The renovation rate list for each Department	double{}			Eq 1
ΔProd	The difference between the actual production sold and the simulated production (globally)	double	%		Eq 2

The PM

Table 5 : the attributes of the entity PM

Symbol	Meaning	Type	Unit	Exo	Endo
comm	The municipality where the PM does his renovation work	Municipality		✓	
clRec	The closest recycler	Recycler			Eq 11
clProd	The closest asphalt producer	Producer			Eq 12
βRec	The gravel need	double	t		Eq 6
βProd	The asphalt need	double	t		Eq 6
ΔRec	The gravel quantity available for the renovation	double	t		Eq 15
ΔProd	The asphalt quantity available for the renovation	double	t		Eq 19
υRec	The quantity of gravel used in the end for the renovation, given the available asphalt	double	t		Eq 18
υProd	The quantity of asphalt used in the end for the renovation, given the available gravel	double	t		Eq 18
οRec	Flag indicating 'true' when a recycling offer reaches this PM, whether or not this offer is zero	boolean			Eq 15, Table 27
οProd	Flag indicating 'true' when an asphalt producer offer reaches this PM, whether or not this offer is zero	boolean			Eq 19, Table 27

Symbol	Meaning	Type	Unit	Exo	Endo
oNZRec	Flag indicating 'true' when a recycling offer reaches this PM, and this offer is null	boolean			Eq 16, 18
oNZProd	Flag indicating 'true' when a producer's offer reaches this PM, and this offer is null	boolean			Eq 18, 20
χRecs	Flag indicating 'true' when all the recycling platforms (within the range of this PM) are exhausted	boolean			Table 27
χProds	Flag indicating 'true' when all the asphalt plants (within the range of this PM) are exhausted	boolean			Table 27

The Department

Table 6: Attributes of the entity `Department`

Symbol	Meaning	Type	Unit	Exo	Endo
#	The Department's code	string		✓	
ρRenov	The Department's average renovation rate	double	%		Eq 1
σς	The list of municipalities in the Department	Municipality{}		✓	

The municipality

Table 7: Attributes of the entity `Municipality`

Symbol	Meaning	Type	Unit	Exo	Endo
cIns	The unique identifier code of the municipality as provided by INSEE[1]	integer		✓	
λσAut	The total length of freeways (always 4 lanes) passing through the municipality	double	km	✓	
λσDep4v	The total length of 4-lane "Départementales" passing through the municipality	double	km	✓	
λσDep2v	The total length of 2-lane "Départementales" passing through the municipality	double	km	✓	
λσRNat	The total length of "Nationales" (aways 4 lanes) passing through the municipality	double	km	✓	
λσRComm	The total length of "Municipales" (aways 4 lanes) passing through the municipality	double	km	✓	
ρGRenov	The renovation rate of the municipality if the material necessary was gravel only	double	%		Eq 16
ρERenov	The renovation rate of the municipality if the material necessary was asphalt only	double	%		Eq 20
ρRenov	The renovation rate of the municipality	double	%		Eq 18
δC{}	List of distances between this municipality and all the other municipalities	Distance{}		✓	
Rec{}	List of recyclers in the municipality	Recycler{}		✓	
Prod{}	List of asphalt producers in the municipality	Producer{}		✓	

[1] INSEE is the Institut Français de la Statistique et des Etudes Economiques (French national institute for statistical and economic studies)

The site of a municipality

Table 8: Attributes of the entity `Site`

Symbol	Meaning	Type	Unit	Exo	Endo
`municipality`	The municipality where the site is found	Municipality			Eq 10
`χ`	Flag indicating if the site is exhausted (out of stock) or not	boolean			Eq 9

A gravel order

Table 9: Attributes of the entity `GravelOrder`

Symbol	Meaning	Type	Unit	Exo	Endo
`rec`	The recycler that receives the order	Recycler			Eq 5
`qty`	The quantity ordered	double	t		Eq 14

An asphalt order

Table 10: Attributes of the entity `AsphaltOrder`

Symbol	Meaning	Type	Unit	Exo	Endo
`prod`	The asphalt producer that receives the order	Producer			Eq 5
`qty`	The quantity ordered	double	t		SymG2A Eq 14

The distance between municipalities

Table 11: Attributes of the entity `Distance`

Symbol	Meaning	Type	Unit	Exo	Endo
`comm`	The municipality designated by the INSEE code	Municipality			Eq 11, 12
`cInsD`	The INSEE code of the other far-away municipality	integer			Eq 10
`δVal`	The value of the distance	double	km		Eq 10

The recycler

Table 12: Attributes of the entity `Recycler`

Symbol	Meaning	Type	Unit	Exo	Endo
`#`	The recycling site code	string			
`γs`	The total gravel stock produced by this recycler	double	t	✓	
`γc`	The total gravel stock used by this recycler	double	t		Eq 14, 21

The asphalt producer

Table 13: Attributes of `AsphaltProducer`

Symbol	Meaning	Type	Unit	Exo	Endo
`#`	The code for the asphalt production site	string			
`γs`	The total stock of asphalt produced by this recycler	double	t	✓	

Symbol	Meaning	Type	Unit	Exo	Endo
γ_C	The total asphalt stock used by this producer	double	t		SymG2A Eq 14, 21

I.1.2.4 Space

The model's space is an explicit geographic space. This space is necessary because of the transport distance calculation but also for feedback to user of the geographic distribution of the renovation rate. The data correspond to the actual territory in PACA. It comes from a GIS and is presented in the form of irregular polygons or points (See Figure 2).

I.1.2.5 Scales for space and time

The PACA region our model relates extends over a surface area of 31,400 km² with:

- From west to east at the farthest points, a distance of about 250 km
- From north to south at the farthest points, a distance of about 230 km

The step for time simulation is the year. As this is only 2015, the model only covers 1 time step.

I.1.3 Process overview and scheduling

I.1.3.1 Preamble on the sequences

Table 14 lists the principal model's level 1 submodels (See Table 1 for this notation) and the entities that call them. The level 2 and subsequent submodels are directly detailed in section I.3.4 'Submodels', starting from page 22.

Each submodel corresponding to a sequence has a reference. The description of all of the sequences is split across different figures, some referring to the others. Table 14 also shows how the references and figures of the detailed description correspond. If the reference value is empty, this means that the figure has been described within Figure 3.

Table 14: list of level 1 submodels

Call	Name	Meaning	Reference	Detail of the reference
PM	Renovate()	Road renovation		Figure 3
MacroManager	HandleEvalMaterialsDemandOK()	Notification of end of materials evaluation for the renovation		Figure 3
Recycler	ProposeGravel()	Gravel proposal by the producer	#Og	Figure 4
AsphaltProducer	ProposeAsphalt()	Asphalt proposal by the producer	#Oa	Figure 4
MacroManager	HandleGravelNextOrder()	Treat the next gravel order	#Hgno	Figure 4
MacroManager	HandleAsphaltNextOrder()	Treat the next asphalt order	#Hano	Figure 4
PM	DecideAboutGravelProposal()	Decision on the gravel proposal	#Dago	Figure 5
PM	DecideAboutAsphaltProposal()	Decision on the asphalt proposal	#Daao	Figure 6
Recycler	DecideAboutUnusedGravel()	Decision on the unused gravel proposal (because no corresponding asphalt)	#Danug	Figure 7

Call	Name	Meaning	Reference	Detail of the reference
AsphaltProducer	DecideAboutUnusedAsphalt()	Decision on unused asphalt proposal (because no corresponding gravel)	#Danug	Figure 7

Table 15 then summarizes the conditions that will be used in the figures describing how the sequences proceed (Section I.1.3.2).

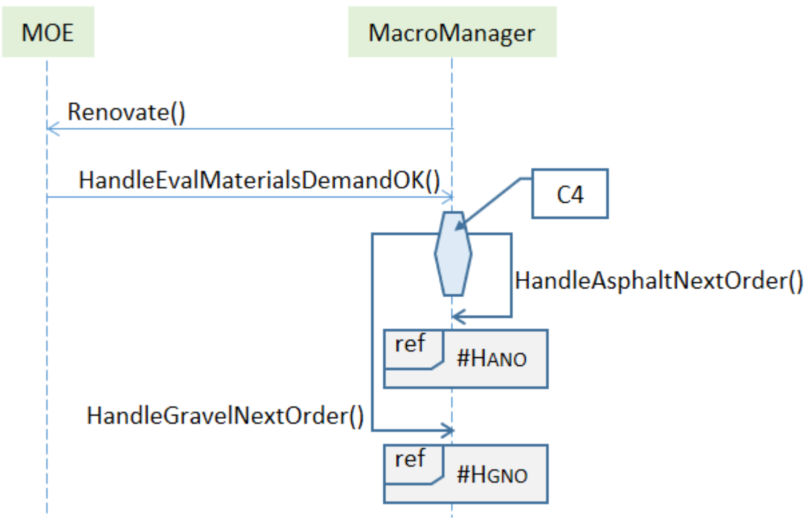
Table 15: table of conditions used in the figures describing the sequences

#condition	Call	Summary description
C4	MacroManager	Tests whether all the PM have notified the MacroManager that their evaluation of material needs for the renovation is completed
C5	PM	Tests (a) whether a recycler has sent a proposal for the demand and (b) whether all the recyclers in the model have exhausted their stock.
C6	PM	Like C5 but for asphalt

I.1.3.2 How sequences occur

The sequence starts with renovation in each municipality. To do this, PM's evaluate their respective material needs (gravel and asphalt) and does so from the length of the different types of roads in the municipality (freeway, 2-lane Departmental, 4-lane Departmental, national), and gravel and asphalt ratios that are used in a road to be renovated. Next, PM's look for in a given radius the respective closest suppliers (recycler and asphalt producer) (reasoning by proximity), and that are not exhausted (i.e. stock unused from prior orders). If they find both sites at the same time, they then prepare their orders for the respective materials and send it to the MacroManager. So there are two order queues: one for gravel and one for asphalt. If the project does not find two sites at once, it means there was no renovation for this PM's municipality. In that case, no material order is made. The PM does notify the MacroManager of the situation. Once all the notifications have arrived, the MacroManager processes the first order in the queue (Figure 3).

Figure 3: sequence for renovation and associated materials orders



The concerned recycler reviews the order that he/she receives and makes a proposal to the ordering PM. The asphalt producer does the same. The PM reviews the proposals and decides what he/she will do with them (Figure 4). To do that, the PM uses the following questions:

- Have both the proposals arrived?
- If there are no proposals, (which means that other orders of this material ended up being made before this one `PM`), is another site still available?

This other site should be normally farther away from the `PM` than the initial site because of the proximity rationale. If no site has been found, the `PM` returns the other material that was still available to its producer, because it is useless: both are needed for the renovation.

Figure 4: sequence on how to consider a PM's material orders and the corresponding proposal for the respective materials

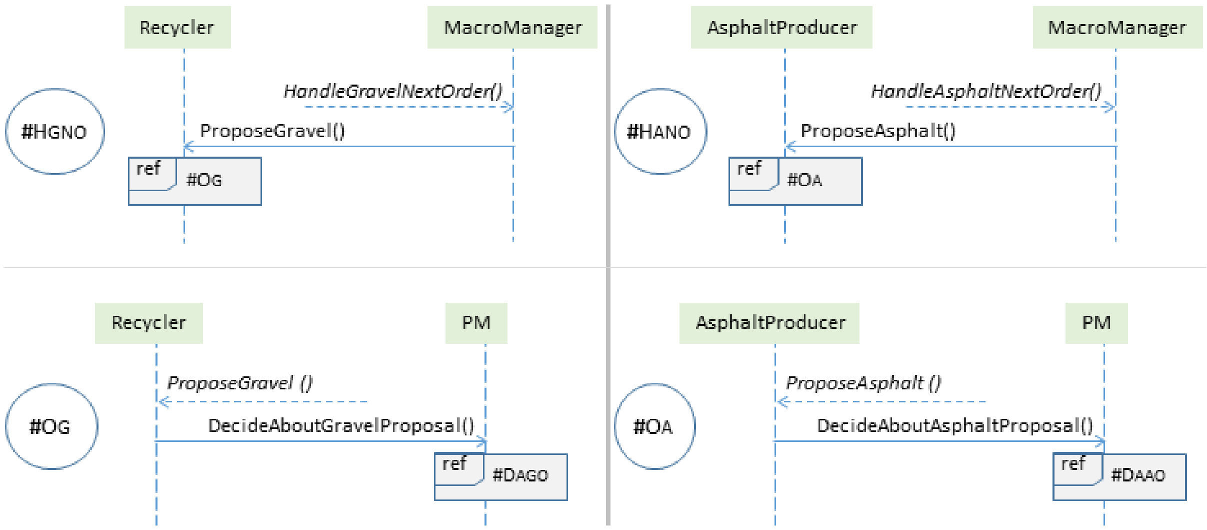


Figure 5 Shows how a `PM` behaves on receiving a gravel proposal.

Figure 5: sequence on how a PM behaves on receiving a gravel proposal

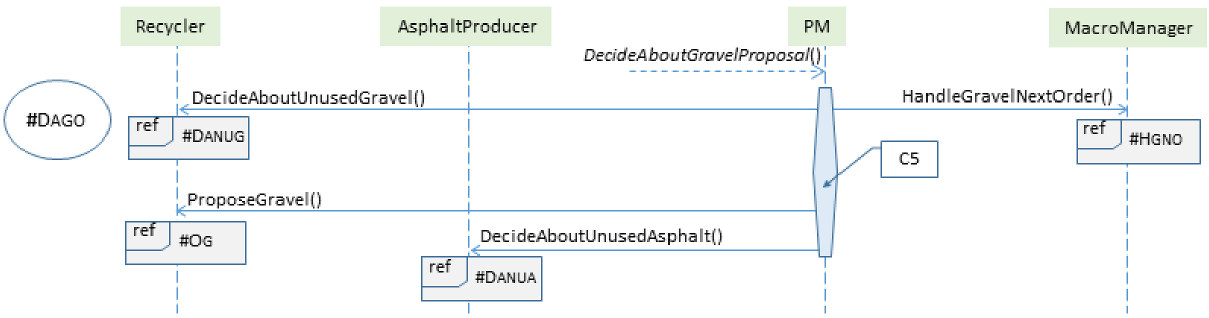
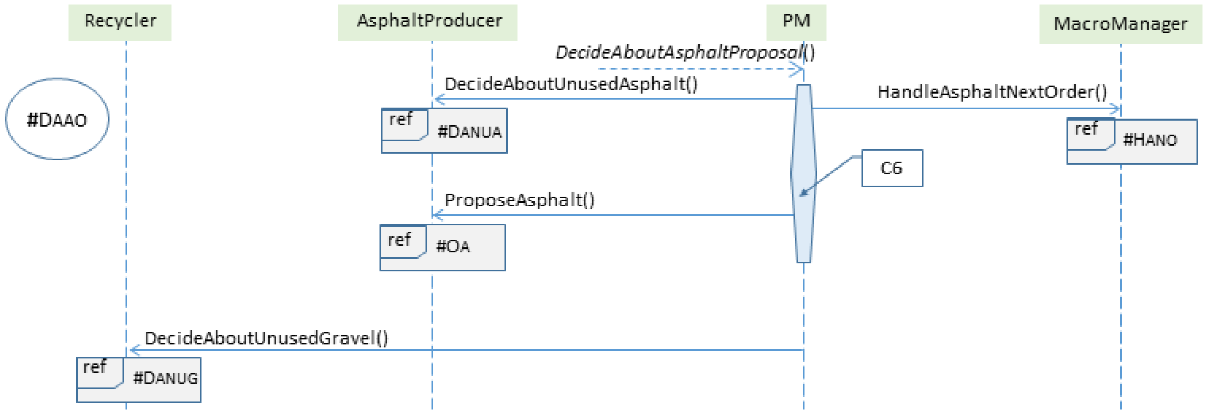


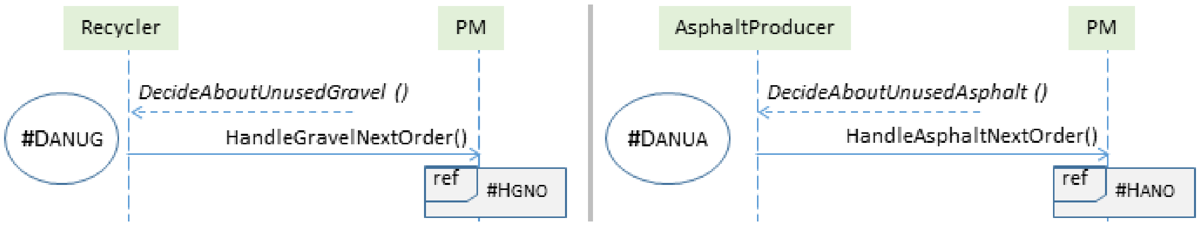
Figure 6 is a mirror image of Figure 5 for asphalt.

Figure 6: sequence on how a PM behaves on receiving an asphalt proposal



When suppliers receive an unused material from the `PM` (because they did not receive the other material), they add it to the stock, for sale, and notify the `MacroManager`. They then process the next order (return to Figure 4).

Figure 7: sequence on receiving materials not used by a PM



I.2 ODD + D: Design concepts

I.2.1 Theoretical and Empirical Background

I.2.1.1 Data source and evaluation

As was set out in section I.1.1 "Purpose," a survey on operators in PACA have been conducted. This survey is on their 2015 production activity and inert waste management from deconstruction. The response rate was 75% - which also means that 25% of sites did not respond about their production and flows. This is this survey that was used to develop our model on a finer scale.

More precisely, for the model to be able to identify the location of these operators' sites (whether they responded or not), the results of the survey were then coupled with the layers of the corresponding geographic information system (GIS). These layers have been provided by the PACA "Direction Régionale de l'Environnement, de l'Aménagement et du Logement" (DREAL PACA, n.d.). Concerning the 25% of sites who did not respond to the survey, the production by default for the respective materials was determined using pattern-oriented modeling or POM (Grimm & Railsback, 2012). Here, the value of the default production (the same for a given type of material) at sites (municipality scale) that have not answered was calibrated so that global production for the entire region, per type of material, approaches the actual data for PACA in 2015.

Moreover, for reasons of simplification, we also consider the data calculated when the system was initialized system as exogenous even though they are calculated. Indeed, these calculations only aim for the dynamic creation of an instance and of its association with the object that it created (such as for instance `PM` ↔ `Municipality`).

Finally, the transport data used by the model is presented in the form of matrix of distances, elaborated from the compilation of the Route 120® national data (IGN Carto Route 120, n.d.) but delineated over PACA. This matrix attributes, for each municipality in the region (968 in all - see Figure 2), the road distance towards all other municipalities of the region. For each municipality, the list of distances is sorted in increasing order. The reference point is the municipality capital (generally the location of the town hall). Accordingly, all of the tables in the entire PACA region contains about 940,000 entries. Table 16 shows a (very) partial view of this matrix of distance for Department 04. This table for 04 actually contains about 190,000 entries.

Table 16: (Very) partial view of the matrix of distances between municipalities in Department 04 (this is the end of the list for Braux and the start of the list for Montclar). For each municipality, the list of distances is sorted in increasing order. This table for 04 actually contains about 190,000 entries.

From municipality capital…	To municipality capital	Minimum distance (in km)
(…)	(…)	(…)
Braux (04032)	Lamotte-Du-Rhone (84063)	229.47
Braux (04032)	Lapalud (84064)	231.75
Braux (04032)	Saintes-Maries-De-The-Mer (13096)	246.80
Montclar (04126)	Selonnet (04203)	3.93
Montclar (04126)	Seyne (04205)	7.74
Montclar (04126)	Saint-Vincent-Les-Forts (04198)	7.96
Montclar (04126)	Saint-Martin-Les-Seyne (04191)	8.55
Montclar (04126)	Le Lauzet-Ubaye (04102)	13.57
Montclar (04126)	La Breole (04033)	14.96
Montclar (04126)	Le Vernet (04237)	18.07
Montclar (04126)	Rousset (05127)	20.66
Montclar (04126)	Espinasses (05050)	21.35
Montclar (04126)	Meolans-Revel (04161)	21.66
Montclar (04126)	Le Sauze-Du-Lac (05163)	21.79
Montclar (04126)	Verdaches (04235)	21.92
Montclar (04126)	Auzet (04017)	23.92
Montclar (04126)	Theus (05171)	24.90
Montclar (04126)	Remollon (05115)	26.18
(…)	(…)	(…)

Table 17 summarizes the various types of data sources used by the model.

Table 17: Types of data sources used by the model

Action (source)	Form and use in the model	Name of the data in the model	Name given in the model (sub-category)
The coupling of (a) the survey on waste production and flows (survey of PACA parties involved) and (b) the corresponding GIS layers (DREAL PACA, n.d.)	GIS initialization layer for instances of the type `Recycler`	GIS WASTE FLOW (GIS WFL)	GIS WFL REC
	GIS initialization layer for instances of the type `AsphaltProducer`		GIS WFL PROD
Delineation of administrative layers (IGN Carto Admin, n.d.) for PACA	GIS initialization layers for the unique instance `region`	GIS ADMIN (GIS ADM)	GIS ADM REG

Action (source)	Form and use in the model	Name of the data in the model	Name given in the model (sub-category)
	GIS layers for initialization of `Department` instances		GIS ADM DEP
	GIS initialization layer for `Municipality` instances		GIS ADM COM
Data compilation Route 120® (IGN Carto Route 120, n.d.) delineated in PACA and only keeping the minimum distance between the municipality capitals of two municipalities	Initialization table of distances between a `Municipality` instance and its surroundings, in a given radius	TAB TRANSP	TAB TRANSP
Pattern-oriented modeling (Grimm & Railsback, 2012): calibration of materials production at sites so that the global production approaches the actual data for PACA.	Real (double) or integer value for initialization of the stock of instances of `Recycler` and `AsphaltProducer` (value not provided by the survey)	POM PACA	POM PACA
Estimation of materials needs for renovation projects (Dialog workshop between PACA stakeholders)	Real (double) or integer value for initialization of different coefficients of different entities	WSP PACA	WSP PACA
Data calculated upon system initialization: simple connection of instance	Object type value (for instances of objects) created dynamically upon initialization by another entity	INIT INST	INIT INST

I.2.1.2 Hypothesis, assumptions of simplifications (conceptual model evaluation)

Above all, this work aims to be an extension 'Scientific research at a finer scale' of workshops conducted in 2017 by the PACA stakeholders. The choice of the models and hypothesis chosen in this work will occur before anything else in accordance with these workshops (apart from on transport). However, as the work tackles a more complex scale, to achieve it will take longer; indeed not all of the parameters for the PACA model necessary for the development of PRPGD are not yet taken into account.

Because of this, this hypotheses we pose:

- Even though asphalt also contains natural aggregates and bitumen, flows for these materials are not yet followed by the model.
- The availability of gravel and nearby asphalt plants (Figure 2) are the only factors considered to determine renovation of roads. In reality, this renovation also depends on any other factors
- The regions and Departments in the model do not yet have decision-making rules. Their role is limited here to aggregating and recreating results on their level.
- The supplier search radius is the same for everyone at this time. We imagine that in reality, each asphalt recycler and producer has their own radius.
- Price is not yet taken into account in the model except to justify the choice of supplier in terms of transport
- All 2015 production in the model goes towards renovation because it is a regular annual process (strong hypothesis). In reality, a part of the gravel and asphalt may also go towards road construction. But these are very occasional roadwork projects.

Regarding the management of material orders, and without more information from the field, the model chosen for the `PM`, the FIFO theory (Katre, n.d.). The order covers both materials at the same time so that each `PM` has the chance of obtaining both together. In terms of materials sale, the model chooses a version (without price for now) of the theory for maximum profit (Nitisha, n.d.) where the gravel and asphalt producers liquidate their stock as fast as possible.

I.2.2 Individual Decision-Making

Table 18 gives the list of decision-making entities for the model and the goals to be met in making those decisions (one factor may require several decisions in different contexts). By contrast with Figure 2, where we show the elements manipulated (e.g. recycling platform), the ACE approach shows the agents behind this instead (e.g. recyclers).

Table 18: list of decision-making factors and goals

Subject (agent)	Decision scales	Objectives	Object or Subject of the decision
Recycler (waste consumer)	Sites	Transform the maximum of waste into "gravel" materials (stored and intended for sale)	Waste
	Municipalities	Sell maximum gravel	Stored gravel
Asphalt producer (waste consumer)	Municipalities	Sell maximum asphalt	Stored asphalt
Project manager (PM)	Municipalities	Conduct roadwork (here road renovation)	French Roads of different types: - freeway - "Departmentale" (roads managed at a departmental level only) - "nationale," (roads managed at a national scale only) - "municipale") (roads managed at a municipality scale only)
	Sites	Identify the appropriate materials quantity for renovation	Gravel and asphalt
		Minimize the cost of transport with the supplier	Asphalt producer and Recycler

The rationality of these decision-making entities is limited in the sense that they do not know what strategy the other entities are using. To know it, they have to interact with them. Additionally, there are no time limits for decision making.

The mathematical translation of decision-making rules and the corresponding rational is explained little by little as the submodels (Section I.3.4) are developed.

Finally, the model does not contain a mechanism for adaptation and not cultural or social factors are taken into account. Uncertainty is not explained in the decision-making rules either.

I.2.3 Learning

The model does not contain a mechanism for learning either individually or collectively.

I.2.4 Individual Sensing

All the entities are supposed to directly aware of all the properties of `MacroManager` (See Table 4).

An instance of a `PM` entity knows geographically:

- the municipalities around their own, located within the supplier's search radius given by the `MacroManager µBR` property.
- the recyclers and producers in that municipality.

All the other information is private and are only accessible through messages (See I.2.6 'Interaction')

I.2.5 Individual Prediction

There are no predictions in the model.

I.2.6 Interaction

All the interactions, if necessary, are made directly by exchange of messages (See the details in section I.1.3 'Process overview and scheduling') excepting those that aim to collect results (See section I.2.10 'Observation'), and those that aim to find the closest supplier geographically (See Equation 9).

A message contains the sender, the receiver and the contents. The contents can be:

- Either an order (an instance of `GravelOrder` – See Table 9 - or of `AsphaltOrder` – See Table 10)
- or empty if this is a simple notification message.

All interactions other than results collection are located on the micro level.

No global coordination of interactions exists for the theme. The only global coordination is instead computational, conducted by the `MacroManager` to ensure that the messages exchanges are synchronous.

I.2.7 Collectives

In reality, an administrative hierarchy exists implicitly between the region, the Departments and the municipalities. However, as our model does not (yet) see the region and the Department as a decision-making entity, the entities do not at this time belong to any collectivity or group.

I.2.8 Heterogeneity

Heterogeneity exists on these aspects.

In terms of structure, no entity of the same type is located at the same location. Material needs are not the same from one `PM` to another.

In terms of behavior, a specific rule also exists in the initialization of the sites that did not respond to the survey (See Equation 4)

I.2.9 Stochasticity

The model does not contain a process implemented randomly.

I.2.10 Observation

Table 19 shows the list of variables to sample at output and how to use them. Two types of use exist here:

- The one that is used to answer questions asked by users.
- The one that is used to evaluate the model's global mathematical margin of error (indicator of model validation).

Table 19: List of variables to sample at output and how to use them

Entity	Symbol	Meaning	Type	Unit	Use	Endo
`MacroManager`	ρRenovC{}	The renovation rate list for each municipality	double{}		Answer the question asked by the user for the municipal scale	Eq 1
`MacroManager`	ρRenovD{}	The renovation rate list for each Department	double{}		Answer the question asked by the user on the Departmental scale	Eq 1

Entity	Symbol	Meaning	Type	Unit	Use	Endo
`MacroManager`	`ΔProd`	The difference between the actual production sold and the simulated production (globally)	double	%	Analyze the model's global margin of error	Eq 2

The list of renovation rate by municipality (`mm.ρRenovC`) and by Department (`mm.ρRenovD`) respectively is obtained via Equation 1.

```
Parameters:
comms // list of municipalities in PACA
depts // list of Departments in PACA

mm // macromanager

Body:
// calculation of the average renovation rate for each Department
for each dept in depts
{
	var trd = 0.0;
	for each comm in dept.σς)
		trd += comm.ρRenov

	// take the average here
	dept.ρRenov = trd / comm.Count;

	mm.ρRenovD.Add(dept.ρRenov) // store in mm
}// for each dept


// collection of the renovation rate for municipalities
for each comm in comms
	mm.ρRenovC.Add(comm.ρRenov)
```
(1)

The difference between global actual and simulated production sold (`mm.ΔProd`) is obtained via Equation 2.

```
Parameters:
reg // PACA
recs // all recyclers in PACA
prods // all producers in PACA


Body:
// for collecting gravel consumed
var collG = 0
for each r in recs
{
       // add what is consumed by the recycler
       collG += r.γc
}// end for each 1

// percentage unused gravel (no client found)
var ΔGnc = (1- (collG / reg.χG2015)) * 100

// for collecting asphalt consumed
var collE = 0
for each p in prods                                                              (2)
{
       // add what is consumed by the producer
       collE += f.γc
}// end for each 2

// percentage unused asphalt (no client found)
var ΔEnc = (1- (colleE / reg.χE2015)) * 100

// application of the balance principle (need=proposal)
// therefore by transposition of the equation 7
⇒ a) collG = collE * mm.ρEGpv // (a)

// And as in Table 21, we see that:
⇒ b) reg.χG2015 = reg.χE2015 * mm.ρEGpv

Where a) and b) give the unique margin of error:
ΔGnc = ΔEnc = (1- (collE / reg.χE2015)) * 100

// a unique name mm.ΔProd for gravel and asphalt
ΔGnc = ΔEnc = mm.ΔProd
```

I.3 ODD + D: Details

I.3.1 Implementation Details

I.3.1.1 Implementation Language

The model is implemented in the Is@Tem simulation platform (Andriamasinoro et al., 2010), an agent-based platform dedicated to the mineral resource sectors over the entire value chain, including the secondary materials circuit (recycling, etc.). Developed in Microsoft Visual Studio© C#, the platform can display maps from vectorial GIS data in ESRI© format, either static as in Figure 2 (simulation input) or dynamically as in Figure 10 (simulation output). The ESRI `shp` format initializes the location properties while the `dbf` format initializes the other properties. Scripts can also initialize the entities that do not depend directly on these GIS maps per program. These are the 'INIT INST' variables explained in Table 17.

The rules for converting a value in a color to display it in a visually different way (Table 29) are the same as for the Is@Tem platform.

I.3.1.2 Place of download/availability

Because of the intellectual property value of BRGM's Is@Tem simulation platform, this platform is not currently available for download. It is not therefore practical that all of the application program files to implement the model are also provided because they will not work.

In terms of the scientific objective of model reproducibility, we do think however that the specifications (described in a very detailed way) in this document should be sufficient.

I.3.1.3 Verification of Implementation

In the model's current state of implementation, no logical error was detected. The development was debugged line by line by the corresponding tool in Visual Studio©. The alternative was to put the statement 'print' in the lines of code containing doubts. This statement was used to make sure that the code executes at the place in question and then display the expected result. These pieces of code were then left as comments once the doubts were raised.

The result corresponds to what is expected.

The program also executes without a runtime error.

I.3.2 Initialization

In all that follows, the initialization sources are for the most part presented in the form of abbreviation: those defined in Table 17.

I.3.2.1 The instances

Table 20 gives the initial number of instances for each type of the model's entities, or stakeholders. Other types of entities are generally initialized in an endogenous way (namely in the equations).

Table 20: Number of initial instances for each type of party

Type of entities	Number of initial instances	Type of source	Source	Name of dbf file
`Region`	1	Import of GIS layers (shp/dbf)	GIS ADM REG	nouvelles_regions.dbf
`Department`	6		GIS ADM DEP	PACA_departements.dbf
`Municipality`	968		GIS ADM COM	PACA_communes.dbf
`Recycler`	111		GIS WFL REC	PACA_2015_plateformes0.dbf
`AsphaltProducer`	34		GIS WFL PROD	PACA_2015_enrobes0.dbf
`MacroManager`	1	Others	Hypothesis (1 instance suffices)	
`PM`	968		INIT INST (same number as municipalities)	

I.3.2.2 Exogenous properties

The tables that follow show how exogenous variables are initialized for each type of entity. However, for entities whose initialization sources are importing layers (Table 20), only the initialization of variables in other ways than by these layers will be explained (the properties of an instance of entities may be initialized by different sources). This choice was made for reasons of simplification in writing this document.

Table 21 shows how exogenous `region` variables are initialized.

Table 21: Initialization of exogenous variables of the `region` entity

Symbol	Meaning	Value	Unit	Source
χG2015	Regional gravel production for 2015	1,393,579	t	WSP PACA
χE2015	Regional asphalt production for 2015	2,508,694	t	WSP PACA

Table 22 shows how exogenous `MacroManager` variables are initialized.

Table 22: Initialization of exogenous variables of the `MacroManager` entity

Symbol	Meaning	Value	Unit	Source
qG0	The default value of gravel stock from a recycler that did not complete the survey	9,750	t	POM PACA
qE0	The default value of asphalt stock from a producer that did not complete the survey	105,000	t	POM PACA
ρGpv	The ratio of gravel necessary per lane	0.375	t/lane/m	WSP PACA
ρEpv	The asphalt ratio necessary per lane	0.675	t/lane/m	WSP PACA
µOD	The buffer radius threshold below which an orthodromic distance between two points is returned even if the points belong to two different municipalities	2	km	Hypothesis
µBR	The maximum buffer for the material suppliers search	105	km	Hypothesis for all the applications are satisfied
ρM0	The production rate for sites that did not respond to the survey	100	%	Hypothesis (before sensitivity test)

The last two properties are those that are analyzed for sensitivity (Table 28).

Table 23 shows how exogenous `PM` variables are initialized.

Table 23: Initialization of exogenous variables of the `PM` entity

Symbol	Meaning	Value	Unit	Source
comm	The municipality where the `PM` does his renovation work	1 instance		INIT INST

Table 24 shows how exogenous `Municipality` variables are initialized.

Table 24: Initialization of exogenous variables of the `Municipality` entity

Symbol	Meaning	Value	Unit	Source	Corresponding dbf field (PACA_communes.dbf)
cIns	The unique identifier code of the municipality as provided by INSEE[2]	See Source column		GIS ADM COM	'INSEE_COM'
λσAut	The total length of freeways (always 4 lanes) passing through the municipality	See Source column	km	GIS ADM COM	'DENS_AUTOR'

[2] INSEE is the Institut Français de la Statistique et des Etudes Economiques (French national institute for statistical and economic studies)

Symbol	Meaning	Value	Unit	Source	Corresponding dbf field (PACA_communes.dbf)
`λσDep4v`	The total length of 4-lane "Départementales" passing through the municipality	See Source column	km	GIS ADM COM	'DENS_DEPAR'
`λσDep2v`	The total length of 2-lane "Départementales" passing through the municipality	See Source column	km	GIS ADM COM	'DENS_DEPAR'
`λσRNat`	The total length of "Nationales" (aways 4 lanes) passing through the municipality	See Source column	km	GIS ADM COM	'DENS_NATIO'
`λσRComm`	The total length of "Municipales" (aways 4 lanes) passing through the municipality	See Source column	km	GIS ADM COM	'DENS_COM'
`δC{}`	List of distances between this municipality and all the other municipalities	1 instance		TAB TRANSP	

Table 25 shows how exogenous `Recycler` variables are initialized.

Table 25: Initialization of exogenous variables of the `Recycler` entity

Symbol	Meaning	Value	Unit	Source	Corresponding dbf field (PACA_2015_plateformes0.dbf)
`#`	The recycling site code	See Source column		GIS WFL REC	'CODEREGION'
`γs`	The total gravel stock produced by this recycler	See source column or Eq 3 if not initialized	t	GIS WFL REC	'STOCK'

If the recycler corresponds to a site that was not completed by the survey, the GIS WFL REC data source will (naturally) contain no value. In this case, the total stock was initialized using Equation 3.

```
Parameters:
mm // macromanager

// no stock calculated because site was not completed?
// mm.ρM0 is the production rate
if(this.γs == 0)
       this.γs = mm.qG0 * (mm.ρM0/100)
```
(3)

Table 26 shows how exogenous variables for `AsphaltProducer` are initialized.

Table 26: Initialization of exogenous variables for the `AsphaltProducer` entity

Symbol	Meaning	Value	Unit	Source	Corresponding dbf field (PACA_2015_enrobes0.dbf)
#	The code for the asphalt production site	See Source		GIS WFL PROD	'CODEREGION'
γs	The total stock of asphalt produced by this recycler	See source or Eq 4 if not initialized	t	GIS WFL PROD	'STOCK'

If the producer corresponds to a site that did not respond to the survey, the GIS WFL PROD data source will (naturally) contain no value. In this case, the total stock was initialized using Equation 4.

```
Parameters:
mm // macromanager

// if no calculation because the site's information was not
completed ⇒ default value
// mm.ρM0 is the production rate
if(this.γs == 0)
       this.γs = mm.qE0 * (mm.ρM0/100)
```
(4)

I.3.3 Input data

The model does not use input from external sources such as data files or other models to represent processes that change over time. This version of the model does not change over time.

I.3.4 Submodels

This subsection describes all the submodels in detail, regardless of their level: there are level 1 submodels, already introduced in Table 14 and submodels for levels 2 and 3, called by the parent submodels.

Moreover, instances of entities in the equations will use the corresponding notations described in Table 2.

I.3.4.1 Submodel/1: pm.Renovate()

This `pm` submodel, described by Equation 5 (See Figure 3 as well), concerns renovation. To trigger this process, the `pm` identifies the material demands, i.e.:

- They first determine the material needs (call to `this.GetAllMaterialsNeedsValue()` submodel)
- They then decide on materials suppliers (gravel and asphalt respectively), who will supply (call to `pm.DecideAboutBothProviders()`) submodel.

If both suppliers have been found, the submodel prepares and places (`Inqueue()` function) the respective gravel and asphalt orders at the head of the orders queue. The gravel (`this.βRec`) and asphalt (`this.βProd`) quantity ordered respectively is that from Equation 6. These quantities are passed implicitly into parameters via `this`, which is why they are not seen in Equation 5 (which sends the orders).

```
Parameters:
mm // macromanager

// add the gravel order to the macromanager's queue
mm.κRecs.Inqueue(new GravelOrder (this.clRec, this))

// add the asphalt order to the macromanager's queue
mm.κProds.Inqueue(new AsphaltOrder (this.clProd, this))

// notify the macromanager
mm.HandleEvalMaterialsDemandOK()
```
(5)

If one or other of the suppliers is not found, this means that there is no renovation to do in this municipality. In both cases, a message is sent to `MacroManager` stating that the identification of materials needs (=o in the 'no renovation' case) was made (call `mm.HandleEvalMaterialsDemandOK()`). All the municipalities have to have declared their situation before the `MacroManager` can start processing orders (for those that have orders to make).

I.3.4.2 Submodel/2: pm.GetAllMaterialsNeedsValue()

This `pm` submodel, described by Equation 6, determines the material needs for the renovation of roads in a municipality. To do this, it calls the `this.GetNeedsValueForMaterial()` function described in Equation 8 twice: once for asphalt (with as a parameter `mm.ρEpv`) and once for gravel (with as parameter `mm.ρGpv`).

```
Parameters:
mm // macromanager

pm.βRec = GetNeedsValueForMaterial(mm.ρGpv) // gravel need
pm.βProd = GetNeedsValueForMaterial(mm.ρEpv) // asphalt need
```
(6)

From Equation 6, and for a given portion of road, we can deduce the relation between the gravel and asphalt needs (Equation 7).

```
Parameters:
mm // macromanager

mm.ρEGpv = mm.ρGpv / mm.ρEpv
pm.βRec = pm.βProd * mm.ρEGpv
```
(7)

To estimate the needs of a given material type, the `GetNeedsValueForMaterial()` function in Equation 8 takes into account the 5 types of road in the municipality (See Table 7) and takes as parameters the necessary ratio of this material per lane (See Table 4).

```
Parameters:
rmpw // the ratio of material per lane (en t/lane/m)
comm // the municipality that is asking for the materials

Returns: the total materials need

Body:
var λAut = comm.λσAut * 1000; // 1000 means km → m
var λDep4v = comm.λσDep4v * 1000;
var λDep2v = comm.λσDep2v * 1000;
var λRNat = comm.λσRNat * 1000;
var λRComm = comm.λRComm * 1000;

// now calculate the materials need per road type
var βAut = rmpw * 4 * λAut; // 4 means 4 lanes
var βDep4v = rmpw * 4 * λDep4v;
var βDep2v = rmpw * 2 * λDep2v;
var βRNat = rmpw * 4 * λRNat;
var βRComm = rmpw * 4 * λRComm;

// the total need
return βAut + βDep4v + βDep2v + βRNat + βRComm;
```

(8)

The rationale behind this submodel is simply to determine the material needs using the available coefficients provided during the workshops in PACA.

I.3.4.3 Submodel/2: pm.DecideAboutBothProviders()

This `pm` submodel decides from which supplier asphalt and gravel are provided, respectively. Here the decision is to find the closest supplier (reasoning by proximity).

The rationale behind this proximity submodel for finding suppliers is that proximity is generally the first identification criterion for a material supplier in France because of high transport costs (Rodriguez Chavez et al., 2010). The `PM` (who is the client here) will therefore make this choice to reduce costs.

To do this, the `pm` submodel calls two respective functions:

- `this.DecideAboutRecyclerProvider()` to find the closest recycler whose stock is not exhausted
- and `this.DecideAboutAsphaltProvider()` to find the closest asphalt producer whose stock is not exhausted.

These two functions are described in equations 11 and 12 respectively.

Beforehand, these two functions call the `this.GetClosestSite()` function described in Equation 9 and that looks for the closest site, in a generic way. This function then calls the `this.GetDistance()` function described in Equation 10 that calculates the distance between a `PM`'s municipality and a site (platform or asphalt plant).

```
Parameters:
cPM // PM's municipality
sites // the set of municipality sites from which to find the
closest one

Returns:
clSite // the closest site that is not exhausted

Body:
var clDist // the closest distance from a site
var clDist = +∝ // initialize with a far away distance

for each lSite in sites
{
 if (lSite.χ)// site already exhausted
 {
 continue; // pursue the search
 }
// else
// get the distance from this site
var lSDist = GetDistance(pMunicipality, lSite);

 if (lSDist < clDist)
 {
 clDist = lSDist;
 clSite = lSite;
 }
 }// end for each

return clSite;
```

(9)

To calculate the distance this.GetDistance() between a PM's municipality and a site (platform or asphalt plant) (Equation 10), the barycenter of the two shapes is used. The distance between the two points is the orthodromic distance if (a1) both points are in the same municipality or if (a2) the distance between the barycenter of the two municipalities is less than a maximum radius mm.µOD (Table 4). The distance is provided by the transport table (Table 16) if the value is less than the maximum supplier search buffer mm.µBR. This distance is infinite in the other cases. Moreover, the this.GetCentroid() function in Equation 10 is the function that actually returns the barycenter of a municipality (a polygon) or the coordinates of the point of a site (a point).

How to implement a barycenter function will not be explained here but can be found in various libraries in the literature.

```
Parameters:
mm: macromanager
cPM // PM's municipality
site // the site where the PM may want to go if it is the closest

Returns: the minimum distance (km) between the two areas above

Body:
var lDx = site.GetCentroid().X - cPM.GetCentroid().X;
var lDy = site.GetCentroid().Y - cPM.GetCentroid().Y;
var lOD = Sqrt(lDx * lDx + lDy * lDy);// orthodormic distance
lOD /= 1000;// convert m → km

var comm = site.Municipality
// a1) if the same municipality
if (cPM.cIns == comm.CIns)
{ return lOD; }

// a2) if between two differents municipalities, but the
orthodromic is below a threshold
if (lOD ≤ mm.µOD)
 { return lOD; }

// b) return the distances between the chef-lieu of the two
municipalities if inside the macro manager buffer
for each lD in comm.δC{}
{
 if (lD.cInsD == comm.CIns)
 { return lD.δVal; }
}

return +∝ // c) otherwise, return a distance very far away
```
(10)

The body of the function `this.DecideAboutRecyclerProvider`(), which looks for the closest recycler who has stock, is described in Equation 11.

```
// first, search the closest recycler inside the PM municipality
comm = this.comm
this.clRec = GetClosestSite(comm, comm.Rec{})

if(this.clRec != null)
{ return; }

// if not found, search in other municipalities
for each lδ in comm.δC{} // loop until finding a recycler
{
      this.clRec = GetClosestSite(comm, lδ.comm.Rec{})
      if (this.clRec != null)// a recycler has been found
      {
       return; // before the loop ends
      }
}// end for each
```
(11)

The body of the function `this.DecideAboutAsphaltProvider`(), which looks for the closest asphalt producer who has stock, is described in Equation 12.

```
// first, search for the closest producer inside the PM's
municipality
comm = this.comm
this.clProd = GetClosestSite(comm, comm.Prod{})

if(this.clProd!= null)
{ return; }

// if not found, search in other municipalities
for each lδ in comm.δC{} // loop until finding a producer
{
 this.clProd = GetClosestSite(comm, lδ.comm.Prod{})
 if (this.clProd!= null)// a producer has been found
 {
 return; // before the loop ends
 }
}// end for each
```
(12)

I.3.4.4 Submodel/1 : mm.HandleEvalMaterialsDemandOK()

This `mm` submodel, described by Equation 13 (see Figure 3 as well), is called when it senses a message from a `PM` indicating that the evaluation of materials needs (See Equation 5) is complete. The submodel ensures that all the `PM` have sent this message before the `MacroManager` sends the next message, which processes the orders. In Equation 13, the `Fromqueue`() function takes the order at the head of the queue, mirrors the `Inqueue`() function of Equation 5.

```
Parameters:
sender // who sent the message
mm // macromanager
pms // all project managers

Body:
if(sender is a PM)
{
       mm.cEvM++ // another PM has notified
}

if(mm.cEvM == pms.Count) // all PMs have notified
{
       // take the gravel order at the top
       var cG = mm.κRecs.Fromqueue()
       cG.rec.HandleGravelNextOrder()

       // take the asphalt order at the top
       var cE = mm.κProds.Fromqueue()
       cE.prod.HandleAsphaltNextOrder()
}
```
(13)

The rationale behind this submodel is to ensure via the `MacroManager` that the actions of all the agents, in evaluating material needs for the renovation, are synchronous.

I.3.4.5 Submodel/1: rec.ProposeGravel()

This `rec` submodel, described by Equation 14 (see Figure 4 as well), decides the quantity to propose relative to the gravel order obtained. The submodel looks at the maximum stock available that could meet the order and propose it to the ordering `PM`. Then any ordered stock is immediately considered to be consumed. If, subsequently, part of this stock is not consumed by the `PM` (in particular because the asphalt equivalent was not found), then the unused part is returned to stock via the `rec.DecideAboutUnusedGravel`() submodel, described by Equation 21.

Note that the proposal is always sent to the `PM` even if there is none (= 0, site out of stock). This case occurs when several orders arrive at the same time at a given site (which is generally the case) and that all the stock is then exhausted by those that arrive first.

```
Parameters:
cG // the gravel order

Body:
// the ordering party and the quantity ordered
var pm = cG.sen

// take what is available in stock and add it to the quantities to
be used
var δs = min(this.γS, cG.qty)
this.γS -= δs
this.γc += δs

// send to ordering party
pm.DecideAboutGravelProposal()
```
(14)

The rationale behind this submodel is profit maximization by selling as much stock as possible (Nitisha, n.d.).

I.3.4.6 Submodel/1: prod.ProposeAsphalt()

This `prod` submodel is symmetrically identical to `rec.ProposeGravel`() described by Equation 14 (see Figure 4 as well), except that it is about asphalt and not gravel. The rational is the same.

I.3.4.7 Submodel/1: pm.DecideAboutGravelProposal()

This `pm` submodel, described by Equation 15 (See Figure 5 as well) aims to treat a proposal received from the recycler. When the proposal is received, the `pm` updates the quantity available for renovation.

```
Parameters:
qG // gravel quantity proposed

Body:
// acts as the recycler's proposal (which is 'this.clRec')
this.oRec = true

// records the quantity available
this.ΔRec = qG
```
(15)

If a recycler site is exhausted (quantity of gravel = 0), the submodel calls the `pm.DecideAboutRecyclerProvider`() function described in Equation 11 again; it looks for a supplier while implicitly avoiding the exhausted sites. This means that the new site found should be normally located farther from the `pm` than the first site found (reasoning by proximity).

As the rule above also applies to asphalt (i.e. again calls `pm.DecideAboutAsphaltProvider`() for this material – Equation 12), in the end this creates proposal asynchronism where the `pm` has one given material but not the other. Consequently, they must wait to know whether any is available (because both types are needed for the renovation). Because of this asynchronism, PMs will not always be certain which type of material corresponds to the first proposal that arrives. Therefore both cases of proposals must be planned: gravel first and asphalt first.

The decisions to take if the gravel arrives first are described in Table 27. This table is the continuation of Equation 15 and corresponds to condition C5 of the conditions table (Table 15). The schematic version of the process is summarized in Figure 5.

Table 27: decision-making rules of a pm on what should be done with the proposal from the recycler (the value of this.oRec in Table 5 is here 1 meaning true)

#case	oRec	oProd	χRecs	χProds	Decision	Next function called
A	**1**	0	0		If the quantity of proposed gravel is = 0, look for other non-exhausted recycling sites	`this.DecideAboutRecyclerProvider()`
					Next, do nothing. Wait for the asphalt producer's answer (See #case C or D).	
B	**1**	0	1		If all the platforms are exhausted before the producer answers, then tell the `MacroManager` to process the next gravel order (that is normally no longer related to this `pm`)	`mm.HandleGravelNextOrder()`
					Next, wait for the asphalt producer's answer (See #case E).	
C	**1**	1	0	0	Are all the materials available? If so, start renovation	`this.GetRateInMunicipality()`
D	**1**	1	0	1	Are all the plants are exhausted? If so, return the gravel received to the recycler so they can make it available to others	`rec.DecideAboutUnusedGravel()`
					Also tell the `MacroManager` to process the next asphalt order (that is normally no longer related to this `pm`)	`mm.HandleAsphaltNextOrder()`

#case	oRec	oProd	χRecs	χProds	Decision	Next function called
E	**1**	1	1		Are all the platforms exhausted? If so, return the asphalt received to the producer so they can make it available to others.	`prod.DecideAboutUnusedAsphalt()`

After following the rules in Table 27, and where the gravel proposal is not zero, it is then possible to determine the municipality's renovation rate. The process is described by Equation 16 and explained below.

```
this.oNZRec = true

// first the rate if gravel only
var ρ = GetRenovationRateIfMaterial(this.βRec, this.ΔRec)
this.comm.ρGRenov = ρ //

// next the final rate (gravel + asphalt)
GetRenovationRateInMunicipality()
```
(16)

In Equation 16, the final renovation rate for the municipality is calculated using the `this.GetRenovationRateInMunicipality()` function, shown in Equation 18. Before this final rate, we must determine the rate as if the renovation required gravel only. This uses the `this.GetRenovationRateIfMaterial()` – function shown in Equation 17 – and uses gravel needs (`βRec`) and available gravel (Δrec)`ΔRec`) as parameters.

The rationale behind this intermediate rate is to save the renovation rate associated with each material in isolation first (the same principle applies to asphalt). The final renovation rate then corresponds to the rate that includes both materials at the same time: the minimum of both rates (Equation 18).

I.3.4.8 Submodel/2: pm.GetRenovationRateIfMaterial()

This `pm` submodel evaluates the renovation rate of the municipality if the renovation only asks for a single material (only gravel or only asphalt).

```
Parameters:
βM // need in this material for the renovation
ΔM // quantity available for this material

Returns:
The renovation rate associated with this material

Body:
var ρM = 0 // initialization of the return variable

if(βM ≥ ΔM) // the proposal does not meet all needs
{
        ρM = ΔM / βM // → part of the need met by the proposal
}
else
{
        ρM = 1 // all needs are met
}

return ρM
```
(17)

I.3.4.9 Submodel/2: pm.GetRenovationRateInMunicipality()

This `pm` submodel evaluates the municipality's final renovation rate (what we are looking for through the model, in the end) taking account simultaneously of both materials, gravel and asphalt.

```
// do not continue if at least one of the materials has not yet
responded (and is non null)
if (this.oNZRec == false || this.oNZProd == false)
{
        return;
}

// simple reinitialization for other uses
this.oNZRec = false;
this.oNZProd = false;

// the final renovation rate is the minimum of both rates (gravel
and asphalt) in isolation
var ρ = Min(this.comm.ρGRenov, this.comm.ρERenov)
this.comm.ρRenov = ρ * 100; // since it is  %

this.υRec = this.βRec * ρ;
this.υProd = this.βProd * ρ;

ηG = Math.Max(0, this.ΔRec - this.υRec);
ηE = Math.Max(0, this.ΔProd - this.υProd);

// send the unused to their source
this.clRec.DecideAboutUnusedGravel(ηG);
this.clProd.DecideAboutUnusedAsphalt(ηE);
```

(18)

I.3.4.10 Submodel/1: pm.DecideAboutAsphaltProposal()

This `pm` submodel, described by Equation 19 (See Figure 6 as well) mirrors the `pm.DecideAboutGravelProposal()` submodel. This means that to understand it, switching the terms 'gravel' and 'asphalt' suffices.

The decision-making rules are also symmetrical with those of Table 27, i.e. in the description, the terms `rec` and `prod` must be swapped. Finally when the asphalt proposal is received, the `PM` updates the quantity available for the renovation.

```
Parameters:
qE // the asphalt quantity proposed

Body:
// acts as the producer's proposal (which is 'this.clProd')
this.oProd = true

// records the quantity available
this.ΔProd = qE
```

(19)

In the same way as for gravel, when the asphalt proposal is not null, it is then possible to determine the municipality's renovation rate. The process is described by Equation 20, knowing that the intermediate rate, if the renovation only needed asphalt, is found by calling the `this.GetRenovationRateIfMaterial()` – function shown in Equation 17 – and uses asphalt needs (`βProd`) and available asphalt (Δprod)`ΔProd`) as parameters.

```
this.oNZProd = true

// first the rate if asphalt only
ρ = GetRenovationRateIfMaterial(this.βProd, this.ΔProd)
this.comm.ρERenov = ρ //

// next the final rate (gravel + asphalt)
GetRenovationRateInMunicipality()
```
(20)

I.3.4.11 Submodel/1: rec.DecideAboutUnusedGravel()

This `rec` submodel, described by Equation 21 (See Figure 7 as well), processes the gravel not used in the end by the `PM`, because no asphalt was found. The unused quantity is then returned to stock at the recycler concerned. If the site is exhausted, then it will no longer be considered during the next search for gravel suppliers (Equation 9).

```
Parameters:
qηG // the quantity of gravel unused by the PM
mm // macromanager

Body:

this.γs += qηG // add to stock the unused quantity
this.γc -= qηG // remove from gravel used

if(this.γs == 0) // → no more stock? the site is exhausted
{
       (this as site).χ = true
}

// move to the next gravel order
mm.HandleGravelNextOrder()
```
(21)

The rationale behind this submodel is profit maximization by selling as much stock as possible (Nitisha, n.d.).

I.3.4.12 Submodel/1 : mm.HandleGravelNextOrder()

This `mm` submodel, described by Equation 22 (See Figure 4 also), processes the next gravel order located at the head of the order queue. The corresponding recycler will then prepare the proposal via the `rec.ProposeGravel`() submodel already described in Equation 14.

```
Parameters:
mm // macromanager

Body:
// take the gravel order at the top

var cG = mm.κRecs.Fromqueue()
cG.rec.ProposeGravel(cG)
```
(22)

The rationale behind this submodel is to follow the FIFO mechanism (Katre, n.d.) for gravel orders.

I.3.4.13 Submodel/1 : prod.DecideAboutUnusedAsphalt()

This `prod` submodel (See Figure 7 as well) mirrors `rec.DecideAboutUnusedGravel`() described by Equation 21, except that this is for asphalt and not gravel. The rationale is the same.

I.3.4.14 Submodel/1 : mm.HandleAsphaltNextOrder()

This sub-model `mm` (See also Figure 4) on asphalt is symmetrically identical to `mm.HandleGravelNextOrder`() described by Equation 22, which was on gravel. The rational is the same.

II. Simulation and results

II.1 Sensitivity analysis

Table 28 lists the input variables chosen to analyze the model's sensitivity. This choice comes because these are exogenous variables whose the source of initialization is the model's hypothesis (POM included) and not the field hypothesis.

Table 28: List of input variables chosen to analyze the model's sensitivity

Entity	Symbol	Meaning	Type	Unit
`MacroManager`	µBR	The maximum buffer for the material suppliers search	integer	km
`MacroManager`	ρM0	The production rate for sites that did not respond to the survey (whose stock values are assigned by default)	double	%

The experimental plan proposed is a global sensitivity analysis. It aims to find the level of influence of both input parameters (Table 28) on output parameters (Table 19).

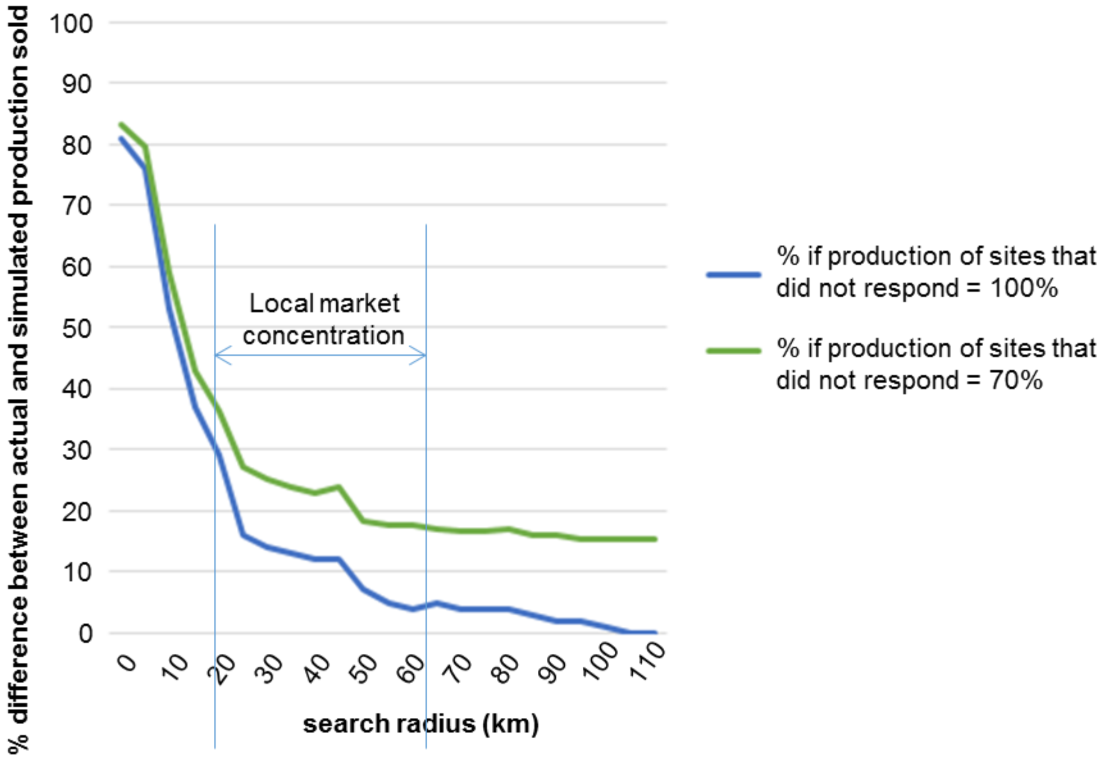
The plan covers the following experimentations:

- vary the search radius between 0 and 170 km in 5 km steps. In France, materials will not generally be transported by a distance of more than 170 km (Rodriguez-Chavez, 2010).
- for the production rate at sites that did not respond, enter 100% then 70%. 70% does not correspond to any field need. It is purely hypothetical and used to test the model's validity if we add a lack in production.

II.2 Effects of inputs on the difference between actual/simulated production

The effects of the inputs on actual/simulated production difference are shown in Figure 8. This result also corresponds to model validation. To simplify feedbacks to readers, the maximum value of the search radius in the figure stops at 110 km (instead of 170 km) because in the result, and for 100% of production, the margin is above this value at 0.

Figure 8: Sensitivity analysis and validation: Effect of variation (a) in the search radius and (b) production rate of sites that did not respond to the 2015 survey, on the difference between actual global production (2015) and simulated production of materials



Regardless of the production rate, the difference for 0 km of search always starts around 80% and not 100% (Figure 8). Indeed, some municipalities record production used internally (See Equation 10 as well). The difference then falls quickly to around 30% at 20 km. Then, still for a production rate at 100% of sites that did not respond to the survey, the curve falls gently to 0 (very low difference between actual sold and simulated) when the search radius approaches 105 km. For a production rate at 70%, the difference stagnates at around 15%. It is normal that it never reaches 0 given this rate reduction.

In terms of interpretation, the curves falling then stagnating shows local market concentration between about 20 km and 60 km of radius, which corresponds to the reality on the ground (Rodriguez Chavez et al., 2010). In fact, 105 (km) corresponds to where alignment between actual and simulated emerged from mathematical calculation and not a reality on the ground. The existence of such a value (105) does however show a scientific advance in solving relations between parties in a complex market. Further, actual transport up to such a distance is not excluded (our initial test was up to 170 km) even if it difficult to know the exact proportion at this stage.

II.3 Effects of inputs on the geographical distribution of renovation rate

The effects of inputs on the geographical distribution of renovation rate per municipality and per Department respectively, are shown by maps. Nevertheless, to simplify returns, the only effects shown here are for a sample of input values from the experimental plan (Table 28), a sample chosen after the results in Figure 8. Specifically:

- for input `mm.µBR`, radii of 20 km, 60 km and 105 km
- for input `mm.ρM0`, production rate of 100%

The mapping representation can display values. However, when the number of results is high (e.g. PACA contains 968 municipalities), the representation can also be made simply by colors (both are possible in the model's implementation platform, Is@Tem). The conversion values → color is described by Table 29.

Table 29: Conversion rules for a renovation rate, a value to a color

Display parameters	Description
`Min value (%)`	The minimum threshold of the value displayed
`Max value (%)`	The maximum threshold of the displayed value
`Min color value (%)`	The minimum value corresponding to `Min color` (See below)
`Max color value (%)`	The maximum value corresponding to `Max color` (See below)
`Min color`	Color assigned to `Min color value`
`Max color`	Color assigned to `Max color value`
`Below min color`	Unique color assigned to any value below `Min value`
`Beyond max color`	Unique color assigned to any value beyond `Max value`

Regarding Table 29, we add:

- for any value oscillating between `min color value` and `max color value`, the color associated is the result of a gradual and linear change of the value on R, G, B color components (varying commonly between 0 and 255) between `min color` and `max color` (i.e. : `min color value` ↔ 0 and `max color value` ↔ 255).
- The values are assigned by default in the table as a function of the statistical data distribution to be displayed (grouped, dispersed). This is done by trial and error, according to the visual representation that the user wishes.

Figure 9 gives the distribution hypotheses for renovation rate by municipality for the search radius scenario of 60 km and according to the conversion rules in Table 29. The figure is provided only as a visual illustration and not for interpretation (the values are difficult to read there). The model is interpreted from Figure 10 instead, and from colors only (too many values).

Figure 9: For visual illustration, estimation of the renovation rate distribution in each municipality when the supplier search radius is 60 km

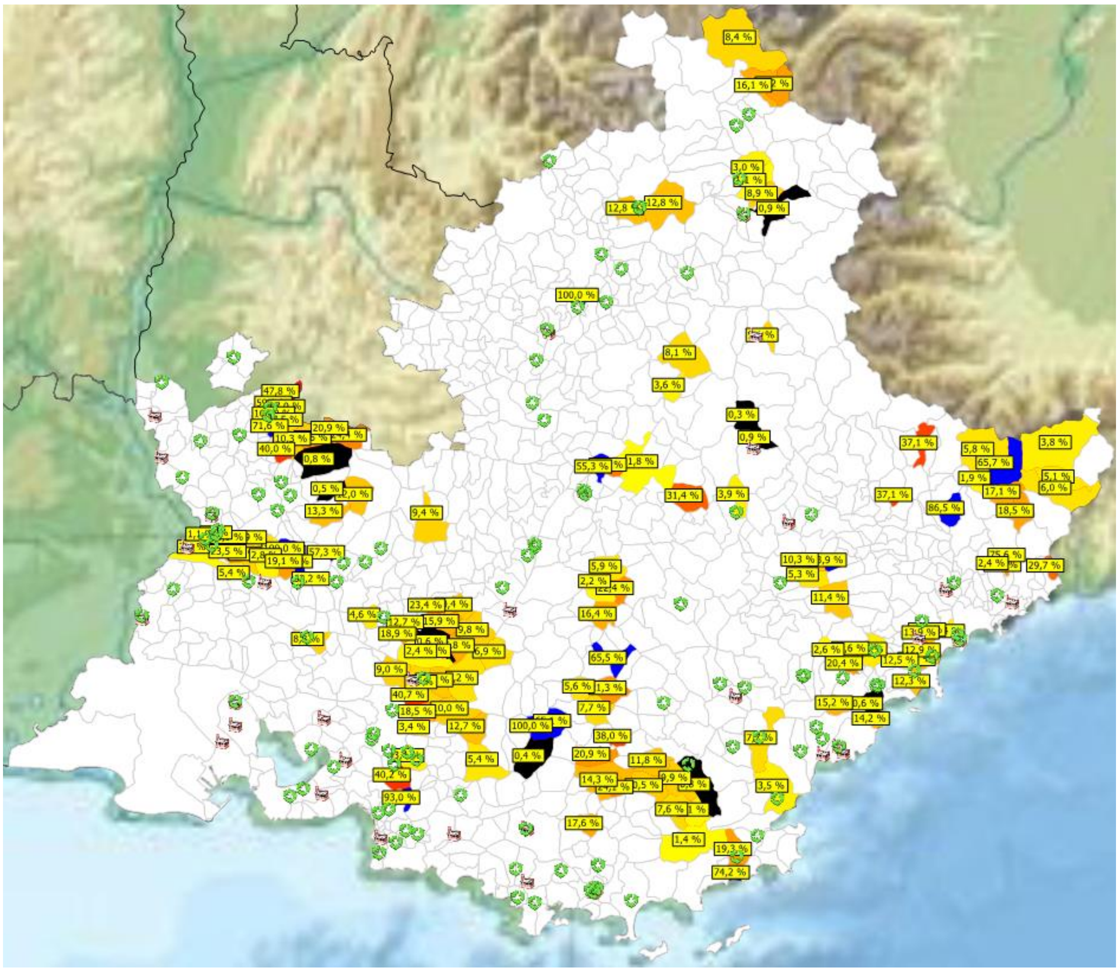
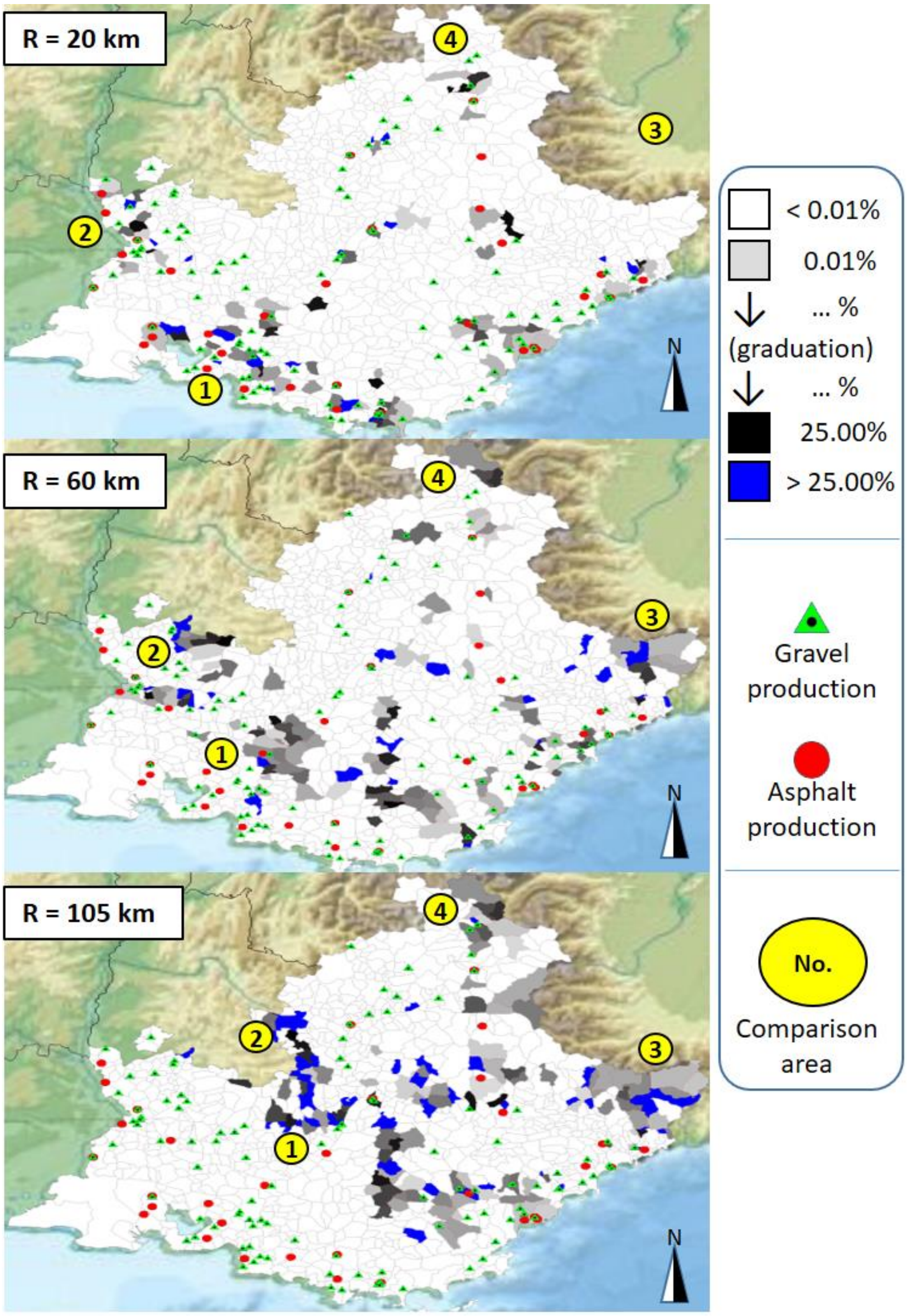


Figure 10 gives the distribution hypotheses for renovation rate by municipality for the respective search radius scenarios of 20, 60 and 105 km.

Figure 10: Distribution hypotheses for the renovation rate of each municipality as a function of the simultaneous search radius for gravel and asphalt suppliers.

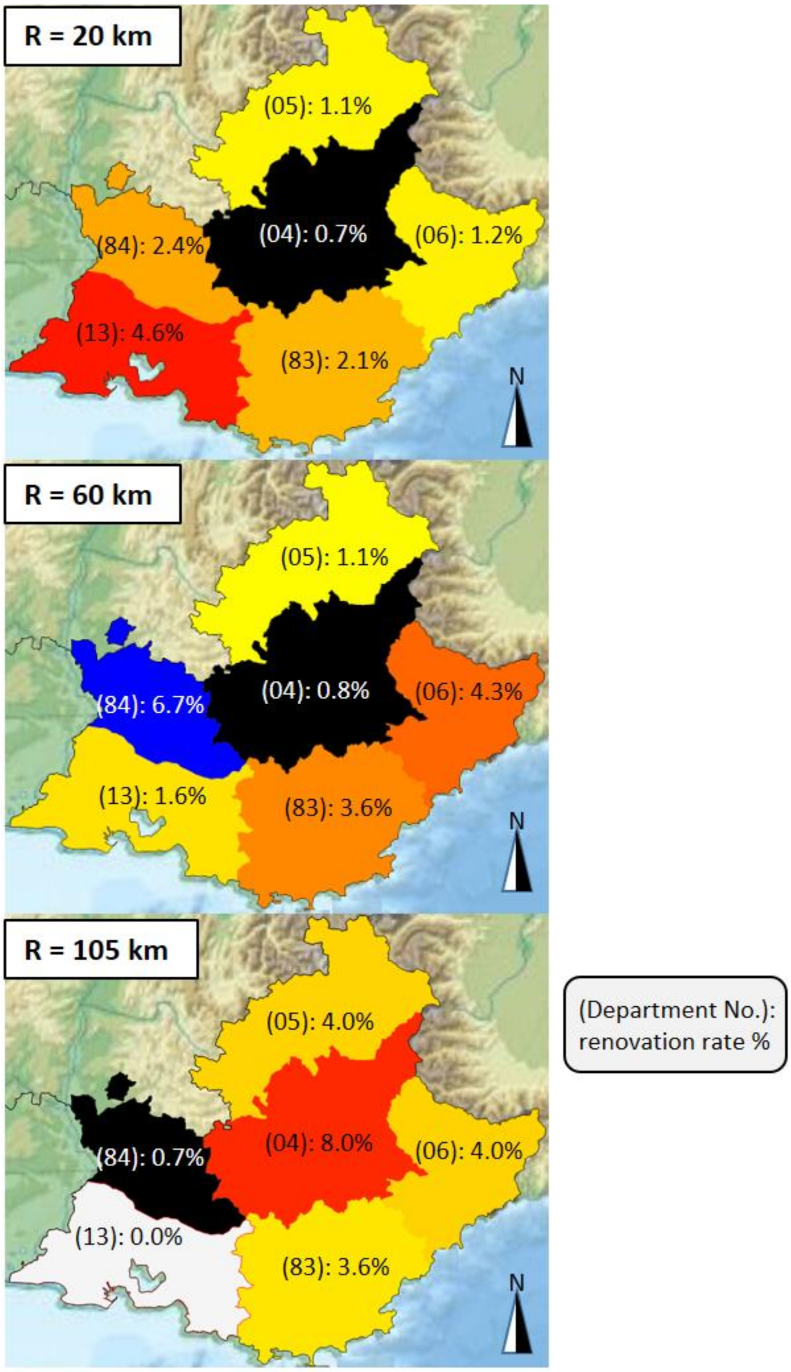


In Figure 10, we see two situations: as we increase the search radius, we see that the renovation work in the North-east area intensifies to the detriment of the South-west area. The explanation for this is purely scientific. Our algorithm privileges municipalities that ordered first (Equation 5). Next, when a municipality has not found suppliers because the stock at the site selected has been exhausted by prior orders, the algorithm allows them to directly continue that search for sites in a broader area (See Table 15 and Equation 11). This occurs to the detriment of orders that have not yet been processed and that therefore may find their nearby site out of stock from the first orders. So the IGN data supplier (IGN Carto Admin, n.d.) stored the data for the PACA municipalities from North-east (first) to South-west, hence the results in Figure 10. This situation can be seen as a current limit of the proposed algorithm. The effects of this limit are low for a low search radius. For example, in the case of the 20 km radius, and even if, globally, not all is used (See Figure 8), we see use around production sites (See Figure 10 – upper section), which corresponds more to reality in Bouches-du-Rhône, a high-population density Department (See 13 in Figure 2).

The first goal of this work step was though to know whether there is a mathematical search radius from which all stocks produced would be sold. This was achieved (See Figure 8), and future work would improve above-mentioned limit. A first idea would be to start by suspending searches for non-exhausted sites in a broader area to allow other orders to be processed as well, under the same conditions. In the end, we return to the first orders for a second round, etc. This would produce a more and more uneven search radius more suitable for different areas.

Figure 11 gives distribution hypotheses for renovation rates at the Department scale after averaging the results of municipalities (Equation 1) and does so using the same scenarios and explanations as in Figure 10.

Figure 11: Distribution hypotheses for the renovation rate of each Department as a function of the simultaneous search radius for gravel and asphalt suppliers.



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