

Mathematical algorithm to transform digital biomass distribution maps into linear programming networks in order to optimize bio-energy delivery chains

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Abstract

Many linear programming models have been developed to model the logistics of bio-energy chains. These models help to determine the best set-up of bio-energy chains. Most of them use network structures built up from nodes with one or more depots, and arcs connecting these depots. Each depot is source of a certain biomass type. Nodes can also be a storage point for a certain biomass type or a production facility (e.g. power plant) where the biomass is used. Arcs represent transport between depots. To be able to combine GIS spatial studies with linear programming models it is necessary to build a network from a digital map. In this work a mathematical calculation method is developed to select the actual points on the map where to collect biomass that will then be considered as biomass sources in a network model. The base data for this *model* are spatial surveys of forest and agricultural biomass given in GIS maps (shape files). The limits of the studied area should be defined in advance for example a country (like Holland or Spain) a province or a region. In the different layers of the GIS maps the different types of biomass are defined. These energy-biomass production maps are overlapped with a grid 1 km x 1 km in the studied area. The result is a grid where the total available biomass of all the different types in every quadrant is known. Also the harvesting or collecting costs are defined. The connections between all $n \times m$ quadrants of the studied area are defined by the available road network. Every quadrant is associated to one point of the road network. Criteria selection for sources of biomass (sub areas) will be the following: firstly a minimum productivity of a type of available biomass is required; and secondly the cost to harvest and collection should be minimal. The results of the *algorithm* are the locations of points where the biomass of an associated area can be concentrated.

These obtained points of biomass collection are then taken as source nodes in the network during the implementation of the logistics models. In the next step the network is analyzed by linear programming techniques to supply the optimal position of energy plants or factories given the available biomass sources.

1. Introduction

Modelling the logistics of bio-energy chains helps to determine the best set-up of bio-energy systems. By means of computer models developed for bio-energy chains either one specific objective can be optimized by linear programming or several heterogeneous objectives can be combined by applying goal programming: maximize profits, minimize costs, minimize greenhouse gas emissions, maximize energy returns, minimize energy use, and maximize energy profit. A mathematical model developed by Wageningen University & Research Centre is called ***Bioloco (Biomass Logistics Computer Optimization)*** (Annevelink & de Mol, 2007; Diekema, et al., 2005). This is an optimization model, which uses integer linear programming. Input for *Bioloco* is a network structure with all relevant parameters (Figure 1). These parameters are costs figures (e.g. transport costs per km, pre-treatment costs, energy conversion costs, etc.), but also capacity constraints or parameters describing the storage losses or seasonality's in supply or demand. A file with all input data needed for the optimization is generated from a dedicated database. *Bioloco* is a system to analyze biomass network models. The network model is built up from nodes with one or more depots, and arcs connecting depots. Each depot is source of a biomass type, a storage point for a certain biomass type or production facility (e.g. power plant) where the biomass is used. Arcs represent transport between depots, combined with pre-treatment for loading and/or for unloading, taking into account: seasonal fluctuations in supply and demand; moisture losses due to drying; dry-matter losses due to biological processes (heating). The flows in the network are regulated by the demand of the production facilities and the supply of the sources.

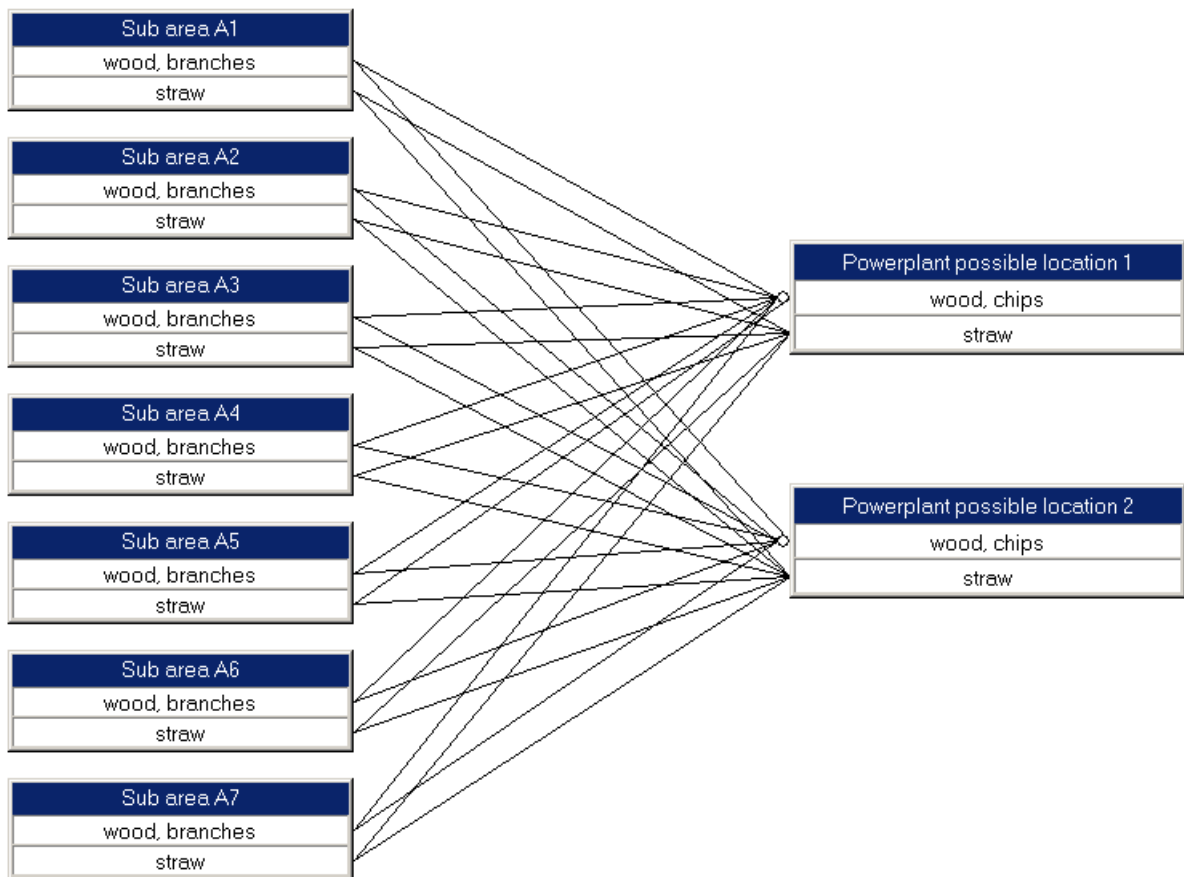


Figure 1. Example of a network model in Bioloco

To be able to combine GIS spatial studies with linear programming models like Bioloco it is necessary to build a network from a map. An approach to achieve the combination of GIS maps with network models like *Bioloco* is given by the ***Borvemar model***. The objective of the *Borvemar model* is to find possible locations where biomass can be collected. The selected points to collect biomass can be considered as biomass sources in the network model of *Bioloco*.

2. The *Borvemar*, mathematical model to select biomass collection points

The Bioloco model can only handle a limited number of source locations during the optimization procedure. Otherwise the problem would become too big to solve. Therefore the high number of detailed areas within a GIS map have to be combined into larger subareas that each contain several quadrants of the GIS map. So the objective of the *Borvemar model* is to combine quadrants of the GIS map in order to locate biomass source points (subareas) for the implementation within the *Bioloco model*. The base data for this *Borvemar model* are spatial surveys of forest and agricultural biomass given in GIS maps (shape files). They give

information about the specie and plants per hectare of food-biomass that also supply streams of residual biomass. Thus energy-biomass production maps are obtained. Previous to this calculation several studies have quantified the potential of available biomass coming from different agricultural and forest systems. Different coefficients of productivity of residual biomass coming from pruning of fruit trees, renewals of fruit trees and straw from cereals have been calculated according to specie, variety and system of cultivation. The limits of the studied area should be defined in advance for example a country (like Holland or Spain), a province or a region. Other cartographic data (shape files) to implement the model are a net of transportation, orography, hydrology, urban areas and administrative limits.

Biologo defines the different types of biomass $b \in \{a, b, \dots, z\}$. These energy-biomass production maps are overlapped with a grid 1 km x 1 km in the studied area (Figure 2). The quadrants are named $a_{ij} / i \in \{1, \dots, n\}; j \in \{1, \dots, m\}$. They form a $n \times m$ matrix. The result is a grid where the total available biomass in every quadrant is known (m_{ij}). The ratios of every type of biomass in every quadrant are also known. Every a_{ij} has an associated vector of ratios

$$\vec{r}_{ij} = (r_{ija}, r_{ijb}, \dots, r_{ijz}) / \sum_{h=1}^z r_{ijh} = 1$$

The parameter r_{ija} is the ratio of biomass type a inside quadrant a_{ij} ; the parameter r_{ijb} is the ratio of biomass type b inside quadrant a_{ij} , etc. Also a harvesting or collecting cost vector $\vec{H} = (H_a, H_b, \dots, H_z)$ is defined. The parameter H_a is the cost to harvest the biomass type a ; the parameter H_b is the cost to harvest the biomass type b etc. The product $\vec{H} \cdot \vec{r}_{ij}$ is the harvesting cost for all biomass of the quadrant a_{ij} . ($\vec{H} \cdot \vec{r}_{ij} = H_a \cdot r_{ija} + H_b \cdot r_{ijb} + \dots + H_z \cdot r_{ijz}$)

Figure 2 is a digital map obtained for the quantification of biomass of “La Hoya de Buñol” county of C. Valenciana, Spain (IEE, 2006).

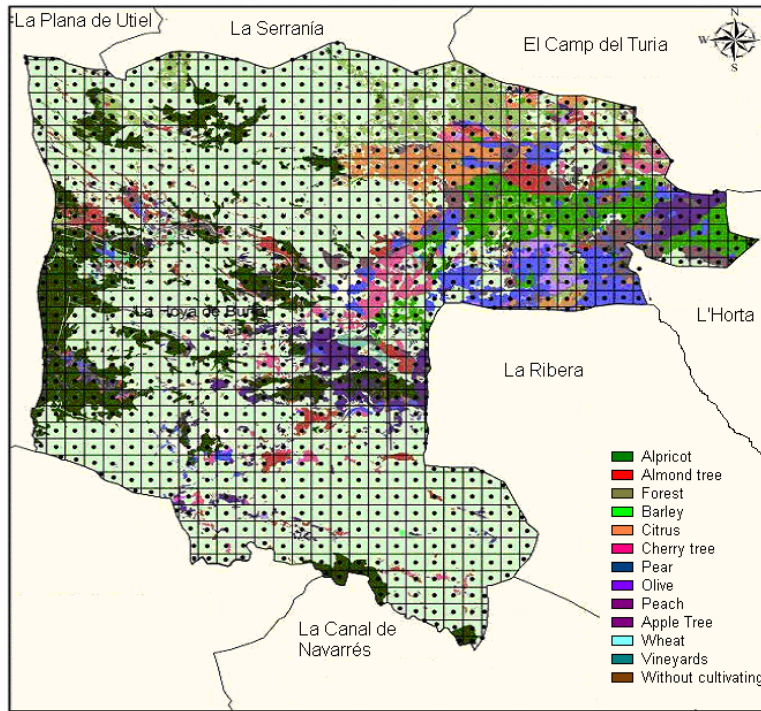


Figure 2. Grids with quantified biomass of “Hoya de Buñol” county (C. Valenciana, Spain).

The grids should be connected by the network communications. The connection among all $n \times m$ quadrants of the studied area is defined by the road network. Every quadrant is associated to one point of the road network. This connection is carried out by means of the tool Network Analyst. A distance parameter $D(a_{ij}, a_{nm})$ can be defined that is the distance between the quadrant a_{ij} and a_{nm} by the road that connects them. All distances $D(a_{ij}, a_{nm})$ define a matrix $n \times n$.

Another simplified method to connect the grids is to calculate the *Euclidean distances* between every quadrant centre, and multiply this value for a parameter called *CR* “curvature of the road” that can vary between 1,1 and 1,8 (IEE, 2006).

$$D(a_{ij}, a_{nm}) = CR \cdot \sqrt{(X_{ij} - X_{nm})^2 + (Y_{ij} - Y_{nm})^2} \quad (1)$$

While all the quadrants are possible origin of biomass, only some of them can be the location of a production facility (e.g. a power plant) for the transformation of biomass. Urban areas, lakes, rivers, slope areas, roads, electric lines, airports and others should not be considered. Therefore the quadrants that are located in these areas are deleted.

Now the main problem when connecting the GIS Map to the optimization model is to concentrate the biomass of the area in few points of collection, which will then be analyzed by the *Biolooco model*. Every collection point is associated a sub-area that contains one or more quadrants a_{ij} . Criteria for the selection of biomass sources (sub areas) will be the following:

- a minimum productivity of the type of available biomass is required (parameter Q_t);
- the cost to harvest and collection should be minimal.

To select the different sub-areas $\{A_1, A_2, \dots, A_n\}$ within the $n \times m$ matrix it is necessary to follow n iterations. First the description of the steps within an iteration are described in this section. Then an example is given in section 3.

Iteration 1:

Step 1. Every quadrant a_{ij} is checked to find those that have a specific type of available biomass greater that Q_t located inside a radius R (e.g. $R = 60$ km).

$$D(a_{ij}, a_{nm}) < R$$

$$\sum_{i,j}^{n,m} m(a_{ij}, a_{nm}) > Q_t \quad \text{t of biomass (selected types)}$$

Where $m(a_{ij}, a_{nm})$ is biomass of the selected type to transport from every quadrant a_{nm} to a_{ij} / $D(a_{ij}, a_{nm}) < R$

Step 2. The quadrants, that have the previous conditions, are selected.

Step 3. For every quadrant a_{ij} selected, the cost to harvest and collect all available biomass from all other a_{nm} to a_{ij} is calculated / $D(a_{ij}, a_{nm}) < R$. The cost is obtained by the equation (2).

$$C_{ij} = \frac{\sum_{ij}^{nm} [m(a_{ij}, a_{nm}) \cdot \bar{H} \cdot \bar{r}_{nm}] + \sum_{ij}^{nm} \frac{m(a_{ij}, a_{nm})}{CT} \cdot CF_i + \sum_{ij}^{nm} \frac{D(a_{ij}, a_{nm}) \cdot m(a_{ij}, a_{nm})}{CT} \cdot CV}{\sum_{ij}^{nm} m(a_{ij}, a_{nm})} \quad (2)$$

Where CF_i are the fixed costs of transportation (€/travel). This includes the operator costs during the loading time (3 - 4 hour); CV are the variable costs of transportation (€/km). It includes fuel consumption and operator costs; CT is the transport capacity (e.g. 5 t/travel)

Step 4. All the quadrants a_{ij} are ordered according to their costs. The quadrant a_{ij} with the lowest costs is selected. Thus the **first sub-area A1** is formed with all $a_{nm} / D(a_{ij}, a_{nm}) < R$ and C_{ij} minimum.

Iteration 2

Step 1. All remaining quadrants a_{ij} are checked to find those that have available biomass greater than Q_b around a radius $R / a_{ij} \notin A_1$

Step 2. The quadrants, that have the previous conditions, are selected.

Step 3. For every a_{ij} selected, the cost to harvest and collect all available biomass from a_{nm} to a_{ij} is calculated $/ D(a_{ij}, a_{nm}) < R$. The cost is obtained by the equation (2).

Step 4. All the quadrants a_{ij} are ordered according to their costs. The quadrant a_{ij} with the lowest costs is selected. Thus the **second sub-area A2** is formed with all $a_{nm} / D(a_{ij}, a_{nm}) < R$ and C_{ij} minimum.

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Iteration n

Step 1. Every quadrant a_{ij} is checked to find those that have available biomass greater than Q , around a radius $R / a_{ij} \notin A_1 \cup A_2 \cup \dots \cup A_{n-1}$

Follow step 2-4.

3. Example of calculation

Figure 2 shows a hypothetical grid (10 x 10) of an area where the available biomass in every quadrant is known. Every quadrant represents an area of 1 x 1 km. The number inside every quadrant represents the amount of tonnes of biomass that can be collected from it.

9.46	2.69	7.70	3.09	4.49	7.21	6.89	2.85	9.81	6.19
5.90	8.13	6.66	9.88	3.05	9.29	3.47	0.21	2.92	8.14
1.75	8.90	6.32	6.15	9.78	1.62	1.96	4.70	4.42	7.94
2.31	0.61	1.32	1.74	3.71	1.40	1.55	4.50	2.68	6.77
2.72	8.55	3.59	1.10	2.04	8.66	3.19	0.46	1.29	9.93
0.10	0.18	4.65	1.58	3.31	2.92	9.34	6.75	1.47	5.54
5.99	0.25	1.62	3.18	7.15	8.38	9.74	7.46	3.42	5.48
0.83	9.56	6.95	4.13	8.38	7.83	8.47	0.51	1.12	3.05
3.92	0.68	1.83	5.42	4.36	1.89	1.07	7.32	9.98	7.01
4.52	5.16	5.23	5.67	6.45	4.99	1.39	0.04	1.31	3.87

Figure 3. Available biomass of type b in each quadrant 1 km x 1 km of a studied area in tonnes.

To select sub-areas a minimum productivity of 50 t/year of biomass type b is defined, that should be available to perform feasible collecting operations. A maximum distance to do collecting operations is fixed to 2 km ($R = 2$ km). According to iteration 1, step 1 of the Borvemar calculation model, every quadrant a_{ij} is checked to find those that have more than 50 tonnes of biomass type b available around it with a radius less than 2 km. The distances are normally defined by a matrix generated according to the road transportation net, but in this example we have used the Euclidean distances. For every quadrant the area to check is defined by Figure 4.

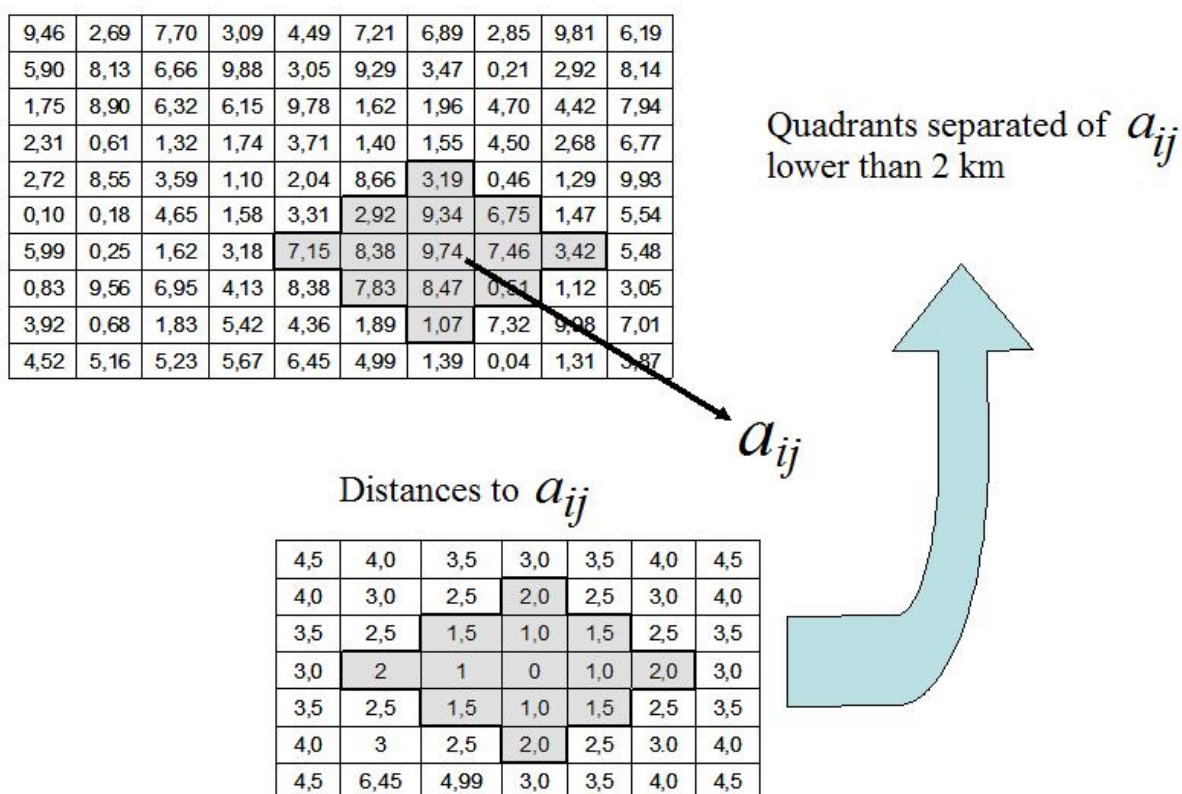


Figure 4. Area closer to a_{ij} than 2 km.

In Table 1 the tonnes of available biomass for every possible sub-area are shown.

Table 1. Amount biomass that is available within 2 km radius around every a_{ij} in tonnes

35.62	52.53	58.43	50.92	61.38	41.96	46.19	44.25	41.43	37.86
45.80	68.01	69.79	76.28	68.40	59.26	45.73	59.17	53.33	46.40
46.10	59.30	72.55	63.33	61.44	62.56	52.98	39.29	55.34	53.70
32.17	46.14	55.64	49.23	45.44	52.37	47.25	39.88	48.64	51.21
25.81	34.31	36.04	49.59	50.17	47.69	53.80	61.98	50.42	41.56
25.59	39.41	36.40	37.21	64.41	72.29	71.70	56.58	54.94	43.70
25.17	42.55	50.68	56.12	64.62	86.71	76.21	69.91	55.80	44.48
32.80	41.11	52.73	67.67	75.91	69.81	72.88	66.75	56.59	39.97
32.49	44.35	54.53	54.18	59.18	65.94	57.58	47.56	38.69	39.13
20.33	36.56	41.91	43.25	43.79	33.69	32.92	30.48	32.04	25.26

The considered logistical cost have been the following:

- harvesting-collection costs, $H= 2 \text{ €/t}$;
- fixed costs of the transportation, $CF= 0.5 \text{ €/travel}$;
- variable costs of the transportation, $CV= 1.5 \text{ €/km}$;

- transport capacity, $CT = 5$ t/travel.

The cost per ton of biomass to transport to every subarea centre can be seen in Table 2

Table 2. Collecting cost per ton of biomass in every possible sub-area.

2.434	2.489	2.511	2.505	2.544	2.426	2.492	2.525	2.441	2.448
2.458	2.466	2.460	2.492	2.487	2.470	2.480	2.569	2.479	2.438
2.537	2.484	2.510	2.476	2.479	2.549	2.570	2.503	2.500	2.488
2.528	2.508	2.553	2.538	2.494	2.546	2.561	2.521	2.491	2.484
2.505	2.452	2.493	2.593	2.552	2.475	2.509	2.583	2.528	2.443
2.542	2.541	2.512	2.518	2.556	2.507	2.475	2.482	2.527	2.492
2.485	2.530	2.546	2.526	2.487	2.495	2.455	2.505	2.537	2.536
2.503	2.448	2.496	2.524	2.504	2.468	2.500	2.532	2.526	2.502
2.504	2.493	2.512	2.477	2.486	2.544	2.555	2.496	2.386	2.454
2.428	2.506	2.513	2.481	2.484	2.500	2.577	2.546	2.478	2.450

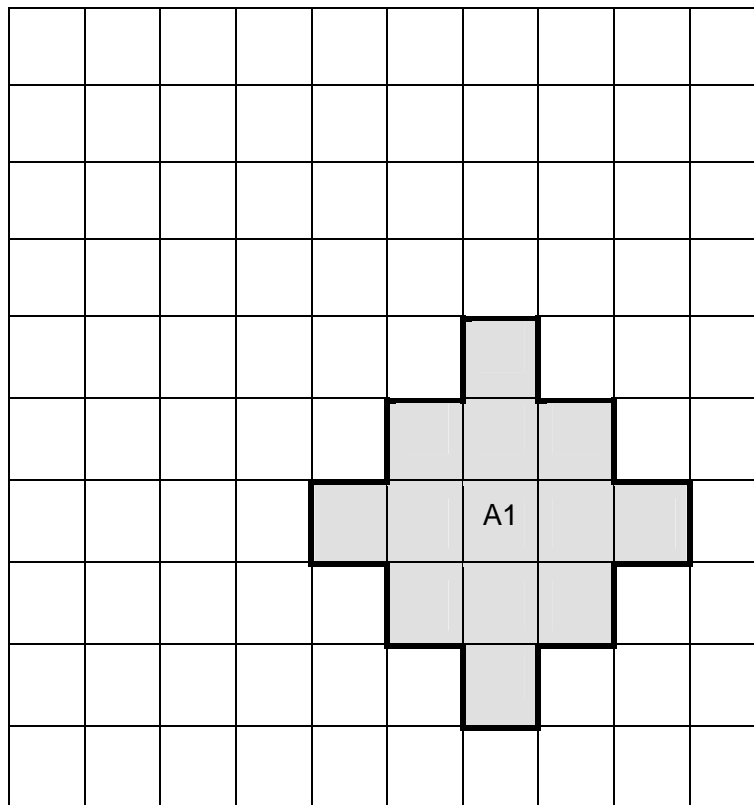


Figure 5. Sub-area A1 coming from iteration 1

The subarea with a quantity of available biomass higher than 50 t/year with the lowest cost is defined by the quadrant a_{77} , which is shown in Figure 5. Please note that although there are

quadrants with lower costs than a_{77} these have less than 50 t/year available. The quantity of available biomass of type b in the subarea A1 is 76.21 t/year, and the collecting costs are 2.455 €/t.

In order to carry out iteration 2 the quadrants of subarea A1 are deleted from the grid of Figure 3, which leads to Figure 6.

9.46	2.69	7.70	3.09	4.49	7.21	6.89	2.85	9.81	6.19
5.90	8.13	6.66	9.88	3.05	9.29	3.47	0.21	2.92	8.14
1.75	8.90	6.32	6.15	9.78	1.62	1.96	4.70	4.42	7.94
2.31	0.61	1.32	1.74	3.71	1.40	1.55	4.50	2.68	6.77
2.72	8.55	3.59	1.10	2.04	8.66	-	0.46	1.29	9.93
0.10	0.18	4.65	1.58	3.31	-	-	-	1.47	5.54
5.99	0.25	1.62	3.18	-	-	-	-	-	5.48
0.83	9.56	6.95	4.13	8.38	-	-	-	1.12	3.05
3.92	0.68	1.83	5.42	4.36	1.89	-	7.32	9.98	7.01
4.52	5.16	5.23	5.67	6.45	4.99	1.39	0.04	1.31	3.87

Figure 6. Available biomass in each quadrant 1 km x 1 km for doing the iteration 2

In Table 3, the tonnes of available biomass for every possible sub-area in iteration 2 are recalculated.

Table 3. Biomass that is available inside of 2 km radius around every a_{ij} in the iteration 2

35.62	52.53	58.43	50.92	61.38	41.96	46.19	44.25	41.43	37.86
45.80	68.01	69.79	76.28	68.40	59.26	45.73	59.17	53.33	46.40
46.10	59.30	72.55	63.33	61.44	62.56	49.80	39.29	55.34	53.70
32.17	46.14	55.64	49.23	45.44	46.27	34.73	29.94	48.64	51.21
25.81	34.31	36.04	49.59	36.92	23.87	21.87	35.25	37.06	41.56
25.59	39.41	36.40	27.14	36.62	17.00	15.47	13.26	27.97	33.53
25.17	42.55	43.53	40.59	28.61	25.43	0.00	15.85	27.92	33.60
32.80	41.11	52.73	52.68	44.08	23.76	20.10	21.51	36.73	36.04
32.49	44.35	54.53	54.18	43.13	40.21	29.97	30.06	33.70	39.13
20.33	36.56	41.91	43.25	43.79	24.79	23.39	28.91	32.04	25.26

Following the iterations 1, 2, 3 and 4 defined by the Borvemar method leads to the four subareas (collection points A1, A2, A3 and A4) that are shown in Figure 7.

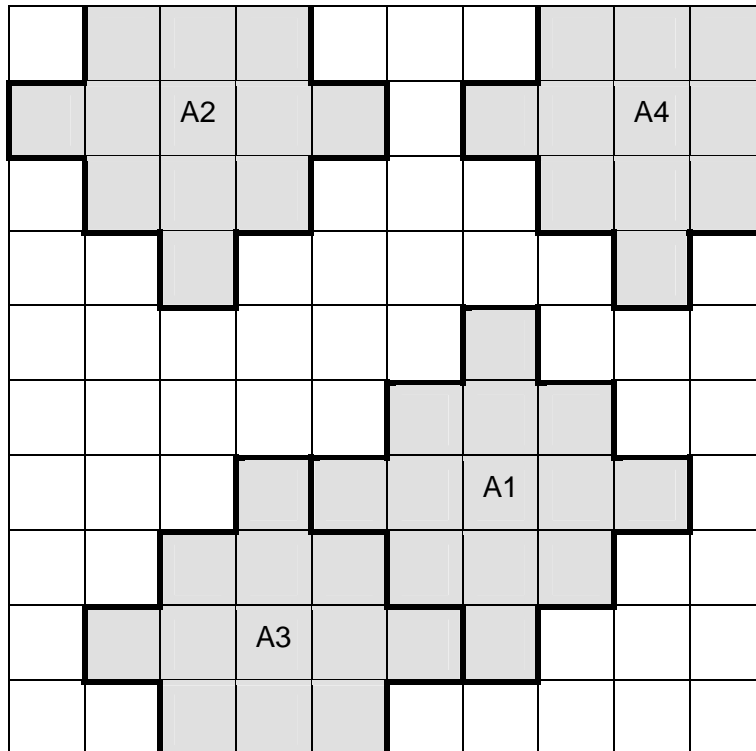


Figure 7. Sub-areas A1, A2, A3 and A4 coming from iteration 1-4 of the Borvemar model.

In order to carry out the iteration 5 the sub-areas A1, A2, A3 and A4 are deleted in the grid of Figure 3.

9.46	-	-	-	4.49	7.21	6.89	-	-	-
-	-	-	-	-	9.29	-	-	-	-
1.75	-	-	-	9.78	1.62	1.96	-	-	-
2.31	0.61	-	1.74	3.71	1.40	1.55	4.50	-	6.77
2.72	8.55	3.59	1.10	2.04	8.66	-	0.46	1.29	9.93
0.10	0.18	4.65	1.58	3.31	-	-	-	1.47	5.54
5.99	0.25	1.62	-	-	-	-	-	-	5.48
0.83	9.56	-	-	-	-	-	-	1.12	3.05
3.92	-	-	-	-	-	-	7.32	9.98	7.01
4.52	5.16	-	-	-	4.99	1.39	0.04	1.31	3.87

Figure 8. Available biomass in each quadrant 1 km x 1 km for doing the iteration 5

In Table 4, the tonnes of available biomass for every possible sub-area in iteration 5 are shown.

Table 4. Biomass that is available inside of 2 km radius around every a_{ij} in the iteration 5

11.21	9.46	13.95	11.70	37.66	29.51	29.85	14.10	6.89	0.00
13.52	11.82	0.00	25.30	36.10	42.65	28.53	22.64	0.00	6.77
16.85	13.23	17.47	17.95	36.04	45.19	37.00	10.10	14.52	16.71
16.04	21.46	26.27	25.56	34.93	46.27	23.88	17.94	25.98	28.03
25.81	24.08	28.39	38.94	36.92	23.87	21.87	27.87	29.97	30.94
25.59	39.41	24.94	19.82	25.06	17.00	15.47	13.26	25.29	33.53
25.17	31.74	27.43	12.52	8.55	11.98	0.00	15.85	27.92	33.60
25.16	27.52	16.91	12.75	3.31	4.99	9.83	21.51	36.73	36.04
29.97	24.23	20.26	0.00	4.99	13.70	23.73	28.17	33.70	39.13
14.42	23.15	9.68	10.16	6.38	6.43	15.05	28.91	32.04	25.26

Table 4 shows that no possible sub-area has a quantity of available biomass higher than 50 tonnes/year. Therefore, within the specified constraints, only four collecting sub-areas are

selected and their centres are used as a source node by the *Bioloco model* to optimize logistics operations. Each sub-area has the following values:

- Sub-area A1 has 76.21 t/year of available biomass with collecting costs 2.455 €/t.
- Sub-area A2 has 69.79 t/year of available biomass with collecting costs 2.460 €/t.
- Sub-area A3 has 54.18 t/year of available biomass with collecting costs 2.477 €/t.
- Sub-area A4 has 53.33 t/year of available biomass with collecting costs 2.479 €/t.

The total amount of biomass selected according to the specified restrictions by the *Borvemar* algorithm is 253.51 t/year, and the average costs are 2.466 €/t.

4. Extensions to the method

The main disadvantage of the *Borvemar model* is that it might exclude a lot of quadrants, so that they will not be selected by the algorithm to collect biomass from. In the example the available biomass of 52% of the quadrants is not mobilized. To overcome this problem several options are available:

Option 1: Repeat the calculation process several times with different values for the minimum amount of biomass and the maximum distances to do the collecting operations. For example $Q_b = 40$ t/year and $R = 3$ km. The results of the calculations with these parameters is shown in Figure 9a. It can be noted that the percentage of quadrants with non-mobilized biomass has significantly decreased until 7%. So a modification of the algorithm could be to find a procedure that selects the optimum value for Q and R in order to maximize the number of quadrants mobilized. However this still has to be developed.

Option 2: After the last iteration with a certain value for Q and R it is possible to do further calculations for the quadrants that are not allocated with a lower value for the minimum amount of biomass and the maximum distance to do new collecting operations. In this case, some smaller sub-areas appear together with the large sub-areas selected filling in the gaps that were left by the first calculation process. For example after the first calculation process, sub-areas with $Q_b = 20$ t/year and $R=1$ km were checked. The results (extra subareas A5-A8) are shown in Figure 9b.

Option 3: A extension buffer with a selected thickness can be applied to add more quadrants around the already selected sub-areas. The quadrants that can be added to the sub-areas

are allocated according to the lowest transportation cost related to the respective concentration points (Figure 9c and 9d).

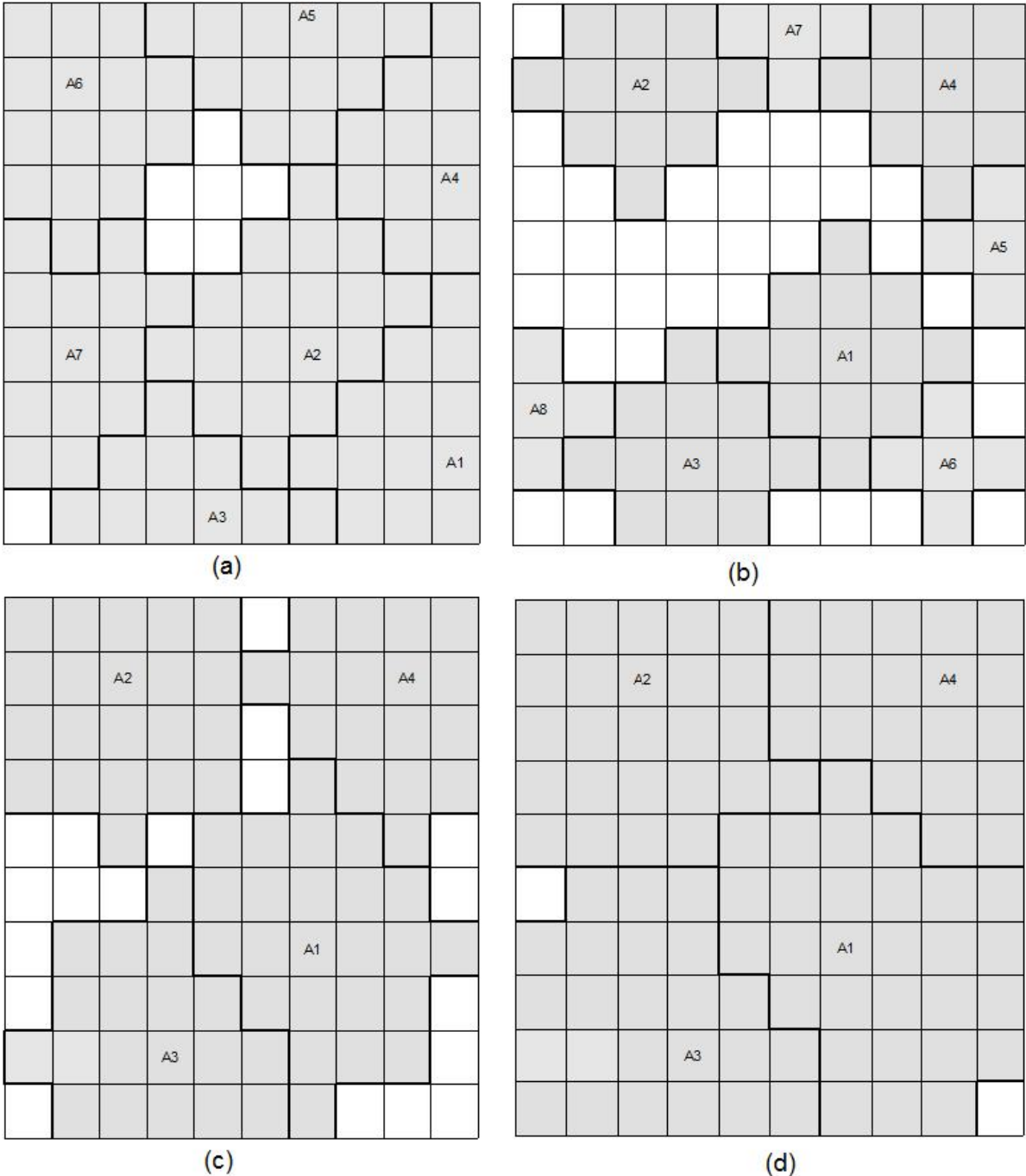


Figure 9. (a) Obtained sub-areas when $Q= 40$ t/year and $R=3$ km; (b) Obtained sub-areas in a first calculation with $Q= 40$ t/year and $R=2$ km, and obtained sub-areas in a second calculation with $Q= 20$ t/year and $R=1$ km; (c) Buffer of 1 km carried out to the sub-areas A1, A2, A3 and A4 obtained with $Q= 50$ t/year and $R=2$ km; (d) Buffer of 2 km carried out to the sub-areas A1, A2, A3 and A4 with $Q= 50$ t/year and $R=2$ km

5. Conclusion

To be able to combine GIS spatial studies with linear programming models it is necessary to build a network from a digital map. In this work a mathematical calculation method, the Borvemar model, has been described to select the actual points on the map where to collect biomass that will then be considered as biomass sources in a network model. At the moment the Borvemar method is a theoretical approach that still has to be tested in practice. Therefore it is recommended that regional case studies should be performed in the near future to further verify the Borvemar model for the development of actual biomass chains.

6. References

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