# **Optimal Transportation Networks as Free Dirichlet Regions for the Monge-Kantorovich Problem**

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**Abstract.** In the paper the problem of constructing an optimal urban transportation network in a city with given densities of population and of workplaces is studied. The network is modeled by a closed connected set of assigned length, while the optimality condition consists in minimizing the Monge-Kantorovich functional representing the total transportation cost. The cost of trasporting a unit mass between two points is assumed to be proportional to the distance between them when the transportation is carried out outside of the network, and negligible when it is carried out along the network. The same problem can be also viewed as finding an optimal Dirichlet zone minimizing the Monge-Kantorovich cost of transporting the given two measures. The paper basically studies qualitative topological and geometrical properties of optimal networks. A mild regularity result for optimal networks is also provided.

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## 1. – Introduction

Let an open bounded set  $\Omega \subset \mathbb{R}^n$  stand for the city where the density of population is given by a finite Borel measure  $\varphi^+$ . The aim of an urban transportation network (i.e. the set of metro and street traffic routes) is to provide the easiest access of the people to their workplaces, the density of which is supposed to be a given finite Borel measure  $\varphi^-$ . Such a transportation network will be modeled by a closed connected set  $\Sigma \subset \overline{\Omega}$ . It is reasonable to suppose that getting to a workplace without using urban traffic in general would cost a single citizen an effort (estimated in time required and, at the end, also in terms of respective financial loss) proportional to the actual walking distance while the cost of using the urban traffic (the price of the ticket) is independent of the actual length of the traffic route used, and, moreover, for simplicity can

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be considered negligible with respect the cost of transportaion without using urban traffic. Under this assumption the total cost of everyday movement of the city population to their workplaces can be modeled by the functional  $I_{\Sigma}$  defined on the set of finite Borel measures over  $\bar{\Omega} \times \bar{\Omega}$  by the relationship

$$I_{\Sigma}(\gamma) := \int_{\bar{\Omega} \times \bar{\Omega}} d_{\Sigma}(x, y) \, d\gamma(x, y),$$

where the distance function  $d_{\Sigma}$  in  $\overline{\Omega}$  is defined by the formula

$$d_{\Sigma}(x, y) := d(x, y) \wedge (\operatorname{dist}(x, \Sigma) + \operatorname{dist}(y, \Sigma)),$$

*d* standing for the geodesic distance on  $\overline{\Omega}$  (which is equal to the standard Euclidean one when  $\Omega$  is convex) and dist $(x, \Sigma)$  standing for the distance between x and  $\Sigma$ , i.e.

$$\operatorname{dist}(x, \Sigma) := \inf_{z \in \Sigma} d(x, z).$$

In other words, each resident x to reach a destination y will choose the most convenient route between avoiding the urban transportation network (i.e. "not taking any urban traffic line and going by feet"), in which case he has to walk the distance d(x, y), or using the latter, in which case he has to walk the distance dist $(x, \Sigma)$  + dist $(y, \Sigma)$ .

The measure  $\gamma$  can be viewed here as the "plan of trasportation" (i.e. in a very intuitive way one can think that  $\gamma(x, y)$  stands for the amount of people which moves from point x to point y) and has to satisfy the restriction

(1) 
$$\pi_{\#}^{+}\gamma - \pi_{\#}^{-}\gamma = \varphi^{+} - \varphi^{-} \text{ over } \bar{\Omega} \setminus \Sigma,$$

where  $\pi^{\pm}$ :  $\bar{\Omega} \times \bar{\Omega} \to \bar{\Omega}$  stand for the projections on the first and the second factor respectively, namely,  $\pi^{\pm}(x^+, x^-) := x^{\pm}$ . The generalized Monge-Kantorovich optimal transport problem consists in fact in finding a Borel measure  $\gamma_{opt}$  over  $\bar{\Omega} \times \bar{\Omega}$  (called *optimal transport plan*) minimizing  $I_{\Sigma}$  over all Borel measures  $\gamma$  in  $\bar{\Omega} \times \bar{\Omega}$  satisfying (1) (called *admissible* measures). It is quite easy to show that such a problem always admits a solution. More realistic models where different pricing policies for using the transportation network are considered can be found in [6].

We will further refer to the set  $\Sigma$  as a Dirichlet constraint for the Monge-Kantorovich problem. The reason for this name stems from the fact that, as shown in [4], the above mass transportation problem is equivalent to the system of PDEs

(2) 
$$\begin{cases} -\operatorname{div}(\mu\nabla_{\mu}u) = \varphi^{+} - \varphi^{-} & \text{in } \bar{\Omega} \setminus \Sigma, \\ |\nabla_{\mu}u| = 1 & \mu - \text{a.e. in } \bar{\Omega}, \\ \mu(\Sigma) = 0 \end{cases}$$

with respect to the unknown 1-Lipschitz function u called the *Kantorovich* potential and the unknown positive Radon measure  $\mu$  called the *transport density*,

where  $\nabla_{\mu}$  is the tangential gradient operator with respect to  $\mu$  defined in [4]. From the point of view of the model chosen,  $\Sigma$  stands for the zone where the cost of transporting the measure  $\varphi^+$  to  $\varphi^-$  vanishes. In the sequel we will denote by  $MK(\varphi^+, \varphi^-, \Sigma)$  both the above Monge-Kantorovich problem with the Dirichlet constraint  $\Sigma$  and the respective minumum value of the functional  $I_{\Sigma}$ . We will also omit the reference to  $\Sigma$  and write simply  $MK(\varphi^+, \varphi^-)$ , if  $\Sigma = \emptyset$ .

This paper is devoted to the problem of finding the optimal Dirichlet constraint  $\Sigma$  (or, in terms of the above model, the optimal urban transportation network) for the Monge-Kantorovich problem of transporting  $\varphi^+$  to  $\varphi^-$  under the given constraint on the total length of  $\Sigma$ , i.e. to the problem of finding

(3) 
$$\min\left\{MK(\varphi^+,\varphi^-,\Sigma): \Sigma \subset \overline{\Omega} \text{ closed and connected, } \mathcal{H}^1(\Sigma) \le \alpha\right\},\$$

where  $\alpha > 0$  is given. The length constraint corresponds to the restriction on the cost of building the urban transportation network which, of course, depends on the length of the latter.

It is worth remarking that the above model does not necessarily require  $\varphi^+(\bar{\Omega}) = \varphi^-(\bar{\Omega})$ . In fact, it even remains reasonable when  $\varphi^- = 0$  while  $\varphi^+ \neq 0$ . In the latter case one simply has that

$$MK(\varphi^+,\varphi^-,\Sigma) = \int_{\bar{\Omega}} \operatorname{dist}(x,\Sigma) d\varphi^+(x)$$

is just the average distance functional, and hence the problem (3) can be interpreted as that of finding the urban transportation network  $\Sigma_{opt}$  which is in average most easily reachable by the city population and satisfies the given length constraint. This model situation has been considered in [5] where the reader can find also several numerical computations.

#### 2. – Preliminaries on connected spaces

We recall that a topological space  $\Sigma$  is called

- connected, if it contains no subset except  $\Sigma$  and  $\emptyset$  which is both closed an open,
- continuum, if it is connected and compact,
- *metric continuum*, if it a metric space and a continuum in the topology induced by the metric,
- locally connected, if every open set contains a connected open subset.

An *path* (resp. *arc*) in  $\Sigma$  is defined as a continuous (resp. homeomorphic) image of an interval. Namely, we call a path (resp. arc)  $[a, b] \subset \Sigma$  connecting the couple of points  $\{a, b\} \subset \Sigma$  an image Im $\gamma$  of some continuous (resp.

continuous injective) map  $\gamma: [0, L] \subset \mathbb{R} \to \Sigma$  satisfying  $\gamma(0) = a$  and  $\gamma(L) = b$  for some  $L \in \mathbb{R}$ . We also say in this case that the path (resp. arc)  $[a, b] \subset \Sigma$  starts at a and ends at b. The map  $\gamma$  is called a parametrization of [a, b]. For the sake of brevity we will frequently abuse the notation identifying the path (resp. arc) with its parametrization, i.e. writing  $\gamma = [a, b]$  instead of Im  $\gamma = [a, b]$ . A path (resp. arc) is called *Lipschitz*, if it admits Lipschitz-continuous parametrization. If  $\gamma_1$  and  $\gamma_2$  are two paths satisfying  $\gamma_1(1) = \gamma_2(0)$ , then we set  $\gamma_1 \circ \gamma_2$  to be a path defined by

$$\gamma_1 \circ \gamma_2(t) := \begin{cases} \gamma_1(2t), & t \in [0, 1/2), \\ \gamma_2(2t-1), & t \in [1/2, 1]. \end{cases}$$

At last, we let (a, b) stand for the path (resp. arc) without endpoints connecting a and b, i.e.  $(a, b) := [a, b] \setminus \{a, b\}$ .

Further, a topological space  $\Sigma$  is called

- arcwise connected, if every couple of points {a, b} ⊂ Σ, a ≠ b, is connected by some arc [a, b] ⊂ Σ.
- *locally arcwise connected*, if every open set contains an arcwise connected open subset.

Note that according to these definition formally every topological space consisting of a single point is always considered to be arcwise connected and locally arcwise connected.

It is well-known that

- (i) every arcwise connected (resp. locally arcwise connected) space is connected (resp. locally connected);
- (ii) the reverse implication to the above is, generally speaking, false;
- (iii) nevertheless, a complete locally connected space is locally arcwise connected (Mazurkiewicz-Moore-Menger Theorem II.1 from [10, Section 50]);
- (iv) a connected locally arcwise connected space is arcwise connected (Theorem I.2 from [10, Section 50]);
- (v) a continuum is locally connected (hence also locally arcwise connected and arcwise connected by (iii) and (iv)), if an only if it is a path, i.e. a continuous image of an interval (Hahn-Mazurkiewicz-Sierpiński Theorem II.2 from [10, Section 50]);
- (vi) in view of (v), every path connecting a to b,  $a \neq b$ , contains an arc connecting those points. In particular, a topological space  $\Sigma$  is arcwise connected (resp. locally arcwise connected), if and only if every couple of points in  $\Sigma$  is connected by some path  $[a, b] \subset \Sigma$  (resp. if every open set  $U \subset \Sigma$  contains an open subset  $V \subset U$  such that every couple of points of the latter can be connected by a path contained in V).

We now introduce the following notions.

DEFINITION 2.1. Let  $\Sigma$  be a connected space. Then  $x \in \Sigma$  is called noncut point of  $\Sigma$ , if  $\Sigma \setminus \{x\}$  is connected. Otherwise, x is called cut point of  $\Sigma$ .

The following general assertion (Moore Theorem IV.5 from [10, Section 47]) holds.

PROPOSITION 2.1. Every continuum has at least two noncut points.

Another relevant notion is that of an order of a point and of branching points and endpoints.

DEFINITION 2.2. Let  $\Sigma$  be a topological space. We will say that the order of the point  $x \in \Sigma$  does not exceed n, writing

$$\operatorname{ord}_{x}\Sigma \leq \mathfrak{n},$$

where n is a cardinal, if for every  $\varepsilon > 0$  there is an open subset  $U \subset \Sigma$  such that  $x \in U$ , diam $(U) < \varepsilon$  and  $\# \partial U \leq n$ , # standing for cardinality of a set.

The order of the point  $x \in \Sigma$  is said to be equal n, written

$$\operatorname{ord}_{x}\Sigma = \mathfrak{n},$$

if  $\mathfrak{n}$  is the least cardinal for which  $\operatorname{ord}_{x} \Sigma \leq \mathfrak{n}$ .

If  $\operatorname{ord}_x \Sigma = \mathfrak{n}$ , with  $\mathfrak{n} \ge 3$ , then x will be called branching point of  $\Sigma$ , while if  $\operatorname{ord}_x \Sigma = 1$ , then x will be called endpoint of  $\Sigma$ .

We recall that according to the theorem V.1 from [10, Section 51], if  $\operatorname{ord}_x \Sigma \leq 1$ , then x is a noncut point of  $\Sigma$ . In particular, every endpoint of  $\Sigma$  is a noncut point.

Further, the point  $x \in \Sigma := \bigcup_{i=1}^{k} [x, a_i]$  belonging to the union  $\Sigma$  of k arcs  $[x, a_1], \ldots, [x, a_k]$  which does not intersect elsewhere but in x, i.e.  $[x, a_i] \cap [x, a_j] = \{x\}$  for all  $i, j = 1, \ldots, k$ , has order k in  $\Sigma$ . Vice versa, the following proposition (Claim 8 in [10, Section 51.II]) is valid.

**PROPOSITION 2.2.** Let  $x \in \Sigma$ , where  $\Sigma$  is a locally connected continuum. Then

$$ord_x \Sigma \ge k, \qquad k \in \mathbb{N},$$

implies the existence of at least k arcs  $\{\gamma_i\}_{i=1}^k$ ,  $\gamma_i \subset \Sigma$ , i = 1, ..., k starting at x which are pairwise nonintersecting except in the point x, i.e.  $\gamma_i \cap \gamma_j = \{x\}$  for all i, j = 1, ..., k.

We remark that in view of the above Proposition 2.2, whenever  $\Sigma$  is a locally connected continuum which does not contain any simple closed curve (a homeomorphic image of  $S^1$ ), then every noncut point of  $\Sigma$  is its endpoint. In fact, if  $x \in \Sigma$  is a noncut point and  $\operatorname{ord}_x \Sigma \ge 2$ , then there exist at least two arcs  $[x, a_1] \subset \Sigma$  and  $[x, a_2] \subset \Sigma$  such that  $[x, a_1] \cap [x, a_2] = \{x\}$ . But since  $\Sigma \setminus \{x\}$  is still arcwise connected and hence there is an arc  $\gamma \subset \Sigma \setminus \{x\}$  connecting  $a_1$  and  $a_2$ . But then  $[x, a_1] \cup \gamma \cup [a_2, x]$  forms a simple closed curve.

#### 3. - Existence of optimal sets

THEOREM 3.1. Problem (3) admits a solution  $\Sigma_{opt}$ .

PROOF. Let

$$m := \inf \left\{ MK(\varphi^+, \varphi^-, \Sigma) : \Sigma \subset \Omega \text{ closed and connected, } \mathcal{H}^1(\Sigma) \le \alpha \right\}$$

and consider a sequence  $\{\Sigma_{\nu}\}_{\nu=1}^{\infty}$  of closed connected subsets of  $\overline{\Omega}$ , satisfying  $\mathcal{H}^{1}(\Sigma_{\nu}) \leq \alpha$  for all  $\nu \in \mathbb{N}$  and such that

$$MK(\varphi^+, \varphi^-, \Sigma_{\nu}) \searrow m,$$

that is, a minimizing sequence for the functional  $MK(\varphi^+, \varphi^-, \cdot)$ . The space of closed subsets of  $\overline{\Omega}$  endowed by the Hausdorff metric is a compact metric space according to the Blaschke theorem (Theorem 4.4.6 of [2]), and therefore up to a subsequence (not relabeled) we may assume that  $\Sigma_{\nu} \to \Sigma$  in the sense of Hausdorff convergence, while  $\Sigma \subset \overline{\Omega}$  is still closed and connected. The Golab semicontinuity theorem (Theorem 4.4.7 of [2]) implies then  $\mathcal{H}^1(\Sigma) \leq \alpha$ . Observe now that the Hausdorff convergence implies  $d(x, \Sigma_{\nu}) \to d(x, \Sigma)$  for all  $x \in \overline{\Omega}$ , and hence

$$d_{\Sigma_{\mathcal{V}}}(x, y) \to d_{\Sigma}(x, y)$$

for all  $(x, y) \in \overline{\Omega} \times \overline{\Omega}$ . Moreover, since all the functions  $d_{\Sigma_{\nu}}$  are Lipschitz continuous with the same Lipschitz constant, then  $d_{\Sigma_{\nu}} \to d_{\Sigma}$  uniformly in  $\overline{\Omega}$ .

We modify the measures  $\varphi^{\pm}$  over each  $\Sigma_{\nu}$  in order to obtain new Borel measures  $\varphi_{\nu}^{\pm}$  over  $\bar{\Omega}$  satisfying

$$\varphi_{\nu}^{\pm} \ \ \Box \bar{\Omega} \setminus \Sigma_{\nu} = \varphi^{\pm} \ \ \Box \bar{\Omega} \setminus \Sigma_{\nu}, \varphi_{\nu}^{\pm}(\bar{\Omega}) \le \varphi^{+}(\bar{\Omega}) \lor \varphi^{-}(\bar{\Omega}) \text{ and} \\ \varphi_{\nu}^{+}(\bar{\Omega}) = \varphi_{\nu}^{-}(\bar{\Omega}).$$

By Lemma 3.1 below there exists an optimal transport plan  $\gamma_{\nu}$  of the problem  $MK(\varphi_{\nu}^+, \varphi_{\nu}^-, \Sigma_{\nu})$ , and hence of  $MK(\varphi^+, \varphi^-, \Sigma_{\nu})$ , satisfying  $\pi_{\#}^{\pm}\gamma_{\nu} = \varphi_{\nu}^{\pm}$ , and hence by construction the sequence  $\{\gamma_{\nu}(\bar{\Omega} \times \bar{\Omega})\}_{\nu=1}^{\infty}$  is bounded. Therefore, up to a subsequence (again not relabeled)  $\gamma_{\nu} \rightharpoonup \gamma$  \*-weakly in the sense of measures, where  $\gamma$  is some positive Borel measure over  $\bar{\Omega}$ . Clearly then

$$\pi_{\#}^{+}\gamma - \pi_{\#}^{-}\gamma = \varphi^{+} - \varphi^{-} \text{ on } \overline{\Omega} \setminus \Sigma,$$

or, in other words,  $\gamma$  is an admissible measure for the problem  $MK(\varphi^+, \varphi^-, \Sigma)$ . In fact, since  $\Sigma_{\nu} \to \Sigma$  in the sense of Hausdorff, then every function with compact support in  $\overline{\Omega} \setminus \Sigma$  has also compact support in  $\overline{\Omega} \setminus \Sigma_{\nu}$  for sufficiently large  $\nu \in \mathbb{N}$ , and therefore, for every  $\psi \in C_0(\overline{\Omega} \setminus \Sigma)$  one has

$$\int_{\bar{\Omega}} \psi \, d(\pi_{\#}^+ \gamma - \pi_{\#}^- \gamma) = \lim_{\nu} \int_{\bar{\Omega}} \psi \, d(\pi_{\#}^+ \gamma_{\nu} - \pi_{\#}^- \gamma_{\nu}) = \int_{\bar{\Omega}} \psi \, d(\varphi^+ - \varphi^-).$$

At last it remains to observe that

$$MK(\varphi^+,\varphi^-,\Sigma) \leq \int_{\bar{\Omega}\times\bar{\Omega}} d_{\Sigma}(x,y) \, d\gamma(x,y) = \lim_{\nu} \int_{\bar{\Omega}\times\bar{\Omega}} d_{\Sigma_{\nu}}(x,y) \, d\gamma_{\nu}(x,y) = m,$$

which means that  $\Sigma$  is a minimizer.

LEMMA 3.1. Let  $\varphi^+(\overline{\Omega}) = \varphi^-(\overline{\Omega})$ . Then there exists an optimal transport plan  $\gamma$  of the problem  $MK(\varphi^+, \varphi^-, \Sigma)$  such that

$$\pi^{\pm}_{\#}\gamma=arphi^{\pm}\ on\ ar{\Omega}$$
 .

PROOF. Let  $\gamma'$  be an arbitrary optimal transport plan for  $MK(\varphi^+, \varphi^-, \Sigma)$ . Define the measure  $\gamma$  over  $\overline{\Omega} \times \overline{\Omega}$  by

$$\gamma(e) := \gamma'(e) - \delta^+(\pi^+(e \cap \Delta) \cap (\bar{\Omega} \setminus \Sigma)) - (\delta^+ \otimes \delta^-)(e \cap (\Sigma \times \Sigma))/|\delta^-|(\Sigma),$$

where

$$\delta^{\pm} := \pi^{\pm}_{\#} \gamma' - \varphi^{\pm}$$

 $\Delta := \{(x, x) : x \in \overline{\Omega}\}$ . Since  $\gamma'$  is an admissible transport plan, then  $\delta^+ = \delta^-$  over  $\overline{\Omega} \setminus \Sigma$ , and therefore  $|\delta^-|(\Sigma) = |\delta^+|(\Sigma)$ . Now, a simple calculation for a Borel set  $e \subset \overline{\Omega}$  shows

$$\gamma(e \times \overline{\Omega}) = (\pi_{\#}^{+} \gamma')(e) - (\pi_{\#}^{+} \gamma')(e \setminus \Sigma) + \varphi^{+}(e \setminus \Sigma) - \delta^{+}(e \cap \Sigma)$$
$$= \varphi^{+}(e),$$

and symmetrically,  $\gamma(\bar{\Omega} \times e) = \varphi^{-}(e)$ . Hence  $\gamma$  is still admissible for the problem  $MK(\varphi^{+}, \varphi^{-}, \Sigma)$ , while

$$\pi^{\pm}_{\#}\gamma = \varphi^{\pm}$$
 on  $\bar{\Omega}$ .

It is enough now to observe that since the function  $d_{\Sigma}$  vanishes over the diagonal  $\Delta$  and over  $\Sigma \times \Sigma$ , then  $I_{\Sigma}(\gamma) = I_{\Sigma}(\gamma')$ , that is,  $\gamma$  is still an optimal transport plan for  $MK(\varphi^+, \varphi^-, \Sigma)$ .

### 4. - Auxiliary constructions

Consider the Monge-Kantorovich problem  $MK(\varphi^+, \varphi^-, \Sigma)$  with the Dirichlet condition (i.e. with  $\Sigma \neq \emptyset$ ). From now on we will be silently assuming that  $\Omega$  is a convex set. Of course, without loss of generality we may consider  $\varphi^{\pm}(\Sigma) = 0$ . Denote

$$\mathcal{R} := \{ (x, y) \in \Omega \times \Omega : \operatorname{dist}(x, \Sigma) + \operatorname{dist}(y, \Sigma) > d(x, y) \}$$

and observe that  $d_{\Sigma}(x, y) = d(x, y)$  over  $\mathcal{R}$ . Set now

$$\varphi_r^{\pm} := \pi_{\#}^{\pm}(\gamma \ \ \Box \mathcal{R}), \qquad \varphi_s^{\pm} := \pi_{\#}^{\pm}(\gamma \ \ \Box(\bar{\Omega} \times \bar{\Omega}) \setminus \mathcal{R}) \ \ \Box(\bar{\Omega} \setminus \Sigma),$$

where  $\gamma$  is an optimal plan for the Monge-Kantorovich problem  $MK(\varphi^+, \varphi^-, \Sigma)$ . It is worth noting that, since according to our assumption  $\varphi^{\pm}$  do not charge  $\Sigma$ , one has  $\varphi^{\pm} = \varphi_r^{\pm} + \varphi_s^{\pm}$ . We denote  $\varphi_s := \varphi_s^{\pm} + \varphi_s^{-}$ . Define  $K: \overline{\Omega} \to \Sigma$  to be the set-valued projection to  $\Sigma$  according to the formula

$$K(x) := \{ y \in \Sigma : d(x, y) = \operatorname{dist}(x, \Sigma) \}$$

The map K admits a Borel measurable selection k:  $\overline{\Omega} \rightarrow \Sigma$ . Let then

$$\gamma^+(e) := \varphi_s^+(\{x : (x, k(x)) \in e\}), \text{ and } \gamma^-(e) := \varphi_s^-(\{y : (k(y), y) \in e\})$$

for all Borel sets  $e \subset \overline{\Omega} \times \overline{\Omega}$ . At last, set  $\psi^{\mp} := \pi_{\#}^{\mp} \gamma^{\pm}$  and  $\psi := \psi^{+} + \psi^{-}$ .

We also will use the dual setting for the problem  $MK(\varphi^+, \varphi^-, \Sigma)$ . The latter consists in finding a  $u \in \operatorname{Lip}_{1,\Sigma}(\Omega, \Sigma)$  (called *Kantorovich transport potential*) which maximizes the functional

$$MK'(v) := \int_{\bar{\Omega}} v \, d(\varphi^+ - \varphi^-).$$

over all  $v \in \operatorname{Lip}_{1,\Sigma}(\Omega)$ , where  $\operatorname{Lip}_{1,\Sigma}(\Omega)$  stands for the set of Lipschitz continuous functions on  $\overline{\Omega}$  vanishing on  $\Sigma$  and having Lipschitz constant one. In particular, if  $\Sigma = \emptyset$ , then  $\operatorname{Lip}_{1,\Sigma}(\Omega) = \operatorname{Lip}_1(\Omega)$  is just the set of 1-Lipschitz continuous functions on  $\overline{\Omega}$ .

The following result holds.

LEMMA 4.1. Assume that there exist Borel measures  $\tilde{\varphi}_r^{\pm}$  and  $\tilde{\varphi}_s^{\pm}$  over  $\bar{\Omega}$  such that  $\tilde{\varphi}_r^+(\bar{\Omega}) = \tilde{\varphi}_r^-(\bar{\Omega})$  and  $\varphi^{\pm} = \tilde{\varphi}_r^{\pm} + \tilde{\varphi}_s^{\pm}$ . Then

$$MK(\varphi^+,\varphi^-,\Sigma) \le MK(\tilde{\varphi}_r^+,\tilde{\varphi}_r^-) + \int_{\bar{\Omega}} \operatorname{dist}(z,\Sigma) d\tilde{\varphi}_s^+(z) + \int_{\bar{\Omega}} \operatorname{dist}(z,\Sigma) d\tilde{\varphi}_s^-(z).$$

If  $\tilde{\varphi}_r^{\pm} = \varphi_r^{\pm}$  and  $\tilde{\varphi}_s^{\pm} = \varphi_s^{\pm}$ , then the above estimate becomes an equality.

PROOF. Let  $\gamma$  stand for an optimal transport plan of  $MK(\varphi^+, \varphi^-, \Sigma)$ . Denote by  $\tilde{\gamma}_r$  an optimal transport plan for the problem  $MK(\tilde{\varphi}_r^+, \tilde{\varphi}_r^-)$ , and set

$$\tilde{\gamma}^+(e) := \tilde{\varphi}_s^+(\{x : (x, k(x)) \in e\}), \qquad \tilde{\gamma}^-(e) := \tilde{\varphi}_s^-(\{y : (k(y), y) \in e\})$$

for all Borel sets  $e \subset \overline{\Omega} \times \overline{\Omega}$ . Clearly, in this case  $\tilde{\gamma}^{\pm}$  are optimal transport plans for problems  $MK(\tilde{\varphi}_s^{\pm}, \tilde{\psi}^{\mp})$ , where  $\tilde{\psi}^{\mp} := \pi_{\#}^{\mp} \tilde{\gamma}^{\pm}$ . Due to the optimality of  $\gamma$  and to the fact that the measure  $\tilde{\gamma}_r + \tilde{\gamma}^+ + \tilde{\gamma}^-$  satisfies the admissibility condition (1), one has

$$\begin{split} MK(\varphi^+,\varphi^-,\Sigma) &= \int_{\bar{\Omega}\times\bar{\Omega}} d_{\Sigma}(x,y) \, d\gamma(x,y) \\ &\leq \int_{\bar{\Omega}\times\bar{\Omega}} d_{\Sigma}(x,y) \, d(\tilde{\gamma}_r + \tilde{\gamma}^+ + \tilde{\gamma}^-)(x,y) \\ &= \int_{\bar{\Omega}\times\bar{\Omega}} d_{\Sigma}(x,y) \, d\tilde{\gamma}_r(x,y) + \int_{\bar{\Omega}\times\bar{\Omega}} d_{\Sigma}(x,y) \, d\tilde{\gamma}^+(x,y) \\ &+ \int_{\bar{\Omega}\times\bar{\Omega}} d_{\Sigma}(x,y) \, d\tilde{\gamma}^-(x,y). \end{split}$$

But

$$\int_{\bar{\Omega}\times\bar{\Omega}} d_{\Sigma}(x, y) \, d\tilde{\gamma}_r(x, y) \leq \int_{\bar{\Omega}\times\bar{\Omega}} d(x, y) \, d\tilde{\gamma}_r(x, y) = MK(\tilde{\varphi}_r^+, \tilde{\varphi}_r^-),$$

while

$$\int_{\bar{\Omega}\times\bar{\Omega}} d_{\Sigma}(x, y) \, d\tilde{\gamma}^{\pm}(x, y) = \int_{\bar{\Omega}} \operatorname{dist}(z, \Sigma) \, d\tilde{\varphi}_{s}^{\pm}(z),$$

thus showing the first part of the statement.

To prove the second part, we note that

$$MK(\varphi^+, \varphi^-, \Sigma) = I_{\Sigma}^0(\gamma) + I_{\Sigma}'(\gamma), \text{ where}$$
$$I_{\Sigma}^0(\gamma) := \int_{\mathcal{R}} d_{\Sigma}(x, y) \, d\gamma(x, y),$$
$$I_{\Sigma}'(\gamma) := \int_{(\bar{\Omega} \times \bar{\Omega}) \setminus \mathcal{R}} d_{\Sigma}(x, y) \, d\gamma(x, y)$$

Since  $d_{\Sigma} = d$  over  $\mathcal{R}$ , one has

$$I_{\Sigma}^{0}(\gamma) = MK(\varphi_{r}^{+}, \varphi_{r}^{-}).$$

It remains to observe that

$$\begin{split} I'_{\Sigma}(\gamma) &= \int_{\bar{\Omega}\times\bar{\Omega}} d(x,K(x)) \, d\gamma_{\mathcal{R}^c}(x,y) + \int_{\bar{\Omega}\times\bar{\Omega}} d(y,K(y)) \, d\gamma_{\mathcal{R}^c}(x,y) \\ &= \int_{\bar{\Omega}} d(x,K(x)) \, d(\varphi_s^+ + \tilde{\psi}^+)(x) + \int_{\bar{\Omega}} d(y,K(y)) \, d(\varphi_s^- + \tilde{\psi}^-)(y) \\ &= \int_{\bar{\Omega}\setminus\Sigma} \operatorname{dist}(x,\Sigma) \, d\varphi_s^+(x) + \int_{\bar{\Omega}\setminus\Sigma} \operatorname{dist}(y,\Sigma) \, d\varphi_s^-(y), \end{split}$$

where  $\gamma_{\mathcal{R}^c} := \gamma \ \lfloor (\bar{\Omega} \times \bar{\Omega} \setminus \mathcal{R}) \text{ and } \tilde{\psi}^{\pm}$  are some measures concentrated on  $\Sigma$ .  $\Box$ 

We will also use the following constructions from [8]. Let *u* stand for a Kantorovich potential of  $MK(\varphi^+, \varphi^-)$ . We call a *transport ray* the maximum segment  $R = (l^+, l^-)$  not including endpoints  $l^+$ ,  $l^-$  such that

$$u(l^+) - u(l^-) = d(l^+, l^-).$$

For every  $p \in \mathbb{R}$  the set

$$\{x \in \Omega : u(x) = p \text{ and } \exists \nabla u(x) \neq 0\}$$

admits a Borel covering  $\{S_{pi}\}_{i=1}^{\infty}$  such that there exist Lipschitz coordinates U:  $\mathbb{R}^n \to \mathbb{R}^{n-1}$  and V:  $\mathbb{R}^{n-1} \to \mathbb{R}^n$  satisfying V(U(x)) = x for all  $x \in S_{pi}$ . For each triple  $(p, i, j) \in \mathbb{Q} \times \mathbb{N}^2$  one can define now the "ray clusters"  $T_{pij}$  as the union of transport rays R piercing  $S_{pi}$  in some point which is distant at least 1/j from both endpoints of R. Note that without loss of generality these clusters can be considered disjoint, while it is easy to prove that every transport ray R of  $MK(\varphi^+, \varphi^-)$  belongs to some of these clusters. Each cluster  $T_{pij}$  then admits coordinates  $G := G_{pij}$ :  $T_{pij} \to \mathbb{R}^{n-1} \times \mathbb{R}$ , which are Lipschitz over

$$T_{pij}^{\sigma} := \left\{ x \in T_{pij} : \min\{d(z, l^+), d(z, l^-)\} \ge \sigma > 0 \right\},\$$

where  $l^+$  and  $l^-$  stand for the ends of the unique transport ray  $R_x$  passing through x, and admit the Lipchitz inverse  $F = F_{pij}$ :  $G(T_{pij}) \to \mathbb{R}^n$  given by the formula

$$F(X, x_n) := V(X) + x_n \nu(V(X)),$$

where  $\nu(x)$  stands for the unit vector pointing in the direction of  $R_x$ . Moreover, one has

$$G(x) = (U(z), u(x) - u(z)), \text{ where } \{z\} := R_x \cap S_{pi}.$$

In particular, all the clusters  $T_{pij}$  are Borel measurable. Moreover, the set  $\mathcal{E}$  of endpoints of all transport rays is also Borel measurable and  $\mathcal{L}^n(\mathcal{E}) = 0$ . Hence, if  $\varphi^{\pm} \ll \mathcal{L}^n$ , we may consider without loss of generality the latter measures to be concentrated over the union of all the ray clusters. Further, in this case one has the mass balance relationship

$$\varphi^+(T_{pij}) = \varphi^-(T_{pij}),$$

for each ray cluster  $T_{pij}$ , as well as the relationship

(4) 
$$MK(\varphi^+,\varphi^-) = \sum_{(p,i,j)\in\mathbb{Q}\times\mathbb{N}^2} MK(\varphi^+ \ \ \Box T_{pij},\varphi^- \ \ \Box T_{pij}).$$

With the use of this construction we may prove the following statement.

LEMMA 4.2. Let  $\varphi^{\pm} \ll \mathcal{L}^n$ ,  $\varphi^+ \neq \varphi^-$  and  $\Sigma = \Sigma_{opt}$ . Then

$$\varphi_s(\Omega) > 0.$$

PROOF. Assume the contrary, namely, that both  $\varphi_s^+(\bar{\Omega}) = 0$  and  $\varphi_s^-(\bar{\Omega}) = 0$ , i.e.  $\varphi^{\pm} = \varphi_r^{\pm}$ . Note that this can only happen when  $\varphi^+(\bar{\Omega}) = \varphi^-(\bar{\Omega})$ , since by definition  $\varphi_r^+(\bar{\Omega}) = \varphi_r^-(\bar{\Omega})$ .

Our assumption means that  $MK(\varphi^+, \varphi^-, \Sigma_{opt}) = MK(\varphi^+, \varphi^-)$ . To arrive at a contradiction, it is enough therefore to find a closed connected  $\Sigma$  with very small length such that  $MK(\varphi^+, \varphi^-, \Sigma) < MK(\varphi^+, \varphi^-)$ . In order to do so, in view of (4), it is enough to show the existence of a sequence of  $\varepsilon_k \to 0^+$ (further on the index k will be omitted for brevity) and of closed connected sets  $\Sigma_{\varepsilon}$  with  $\mathcal{H}^1(\Sigma_{\varepsilon}) \leq C\varepsilon$  for some C > 0 such that

(5) 
$$MK(\varphi^+ \sqcup T_{pij}, \varphi^- \sqcup T_{pij}, \Sigma_{\varepsilon}) < MK(\varphi^+ \sqcup T_{pij}, \varphi^- \sqcup T_{pij})$$

just for some particular ray cluster  $T_{pij}$  of  $MK(\varphi^+, \varphi^-)$ , where the ray clusters are chosen in such a way that

diam 
$$S_{pi} \leq \varepsilon$$

for all  $(p, i) \in \mathbb{Q} \times \mathbb{N}$ . In fact, one obviously has

$$MK(\varphi^+ \ \ \Box T_{pij}, \varphi^- \ \ \Box T_{pij}, \Sigma_{\varepsilon}) \le MK(\varphi^+ \ \ \Box T_{pij}, \varphi^- \ \ \Box T_{pij})$$

for all  $(p, i, j) \in \mathbb{Q} \times \mathbb{N}^2$ , and

$$MK(\varphi^+,\varphi^-,\Sigma_{\varepsilon}) \leq \sum_{(p,i,j)\in\mathbb{Q}\times\mathbb{N}^2} MK(\varphi^+ \ \ \Box T_{pij},\varphi^- \ \ \Box T_{pij},\Sigma_{\varepsilon}).$$

Consider for this purpose a ray cluster  $T_{pij}$  for which

(such a cluster exists since otherwise one would have  $\varphi^+ = \varphi^-$  contrary to the assumption).

From now on we will concentrate on the problem  $MK(\phi^+, \phi^-)$ . For  $c \in \mathbb{R}$ and  $\varepsilon > 0$  set

$$\Gamma_{c,\varepsilon} := \{ (x, y) \in \Omega \times \Omega : u(x) \ge c + \varepsilon/2 \text{ and } u(y) \le c - \varepsilon/2 \}.$$

Let us show now that there exists a  $c \in \mathbb{R}$  and an  $\varepsilon_0 > 0$  such that

(6) 
$$\gamma(\Gamma_{c,\varepsilon}) > 0$$

for each  $\varepsilon < \varepsilon_0$ , where  $\gamma$  stands for the optimal transport plan of the problem  $MK(\phi^+, \phi^-)$ . For this purpose, supposing the contrary, we have the existence for every  $c \in \mathbb{R}$  of a sequence  $\varepsilon_k \to 0^+$  as  $k \to \infty$  such that  $\gamma(\Gamma_{c,\varepsilon_k}) = 0$  for each sufficiently large  $k \in \mathbb{N}$ . Let now

$$\Gamma_c := \{(x, y) \in \overline{\Omega} \times \overline{\Omega} : u(x) > c\} \text{ and } \Gamma'_c := \{(x, y) \in \Gamma_c : u(y) < c\}.$$

One has then  $\gamma(\Gamma'_c) = 0$  for all  $c \in \mathbb{R}$ . In fact, for all  $(x, y) \in \Gamma'_c$  one has  $u(x) \ge c + \varepsilon/2$  and  $u(y) \le c - \varepsilon/2$  for each sufficiently small  $\varepsilon > 0$ , and hence  $\Gamma'_c \subset \Gamma_{c,\varepsilon_k}$  whenever  $k \in \mathbb{N}$  is sufficiently large, while the latter sets are  $\gamma$ -negligible. Consider now the set

$$\Gamma := \{ (x, y) \in \Omega \times \Omega : u(x) \neq u(y) \}.$$

For every  $(x, y) \in \Gamma$  there is a  $c \in \mathbb{Q}$  such that u(x) > c and u(y) < c, that is,  $(x, y) \in \Gamma'_c$ . Hence,

$$\Gamma = \bigcup_{c \in \mathbb{Q}} \Gamma'_c,$$

which implies  $\gamma(\Gamma) = 0$ . Therefore, for  $\gamma$ -a.e.  $(x, y) \in \overline{\Omega} \times \overline{\Omega}$  one has u(x) = u(y), and hence  $MK(\phi^+, \phi^-) = 0$  which implies  $\phi^+ = \phi^-$  contradicting the original assumption and proving the claim.

Choose now  $c \in \mathbb{R}$  such that (6) is satisfied for all sufficiently small  $\varepsilon > 0$ . Let  $\overline{Q}_{\varepsilon} \subset \mathbb{R}^{n-1} \times \mathbb{R}^1$  stand for for the closed parallelepiped with the base of side  $\lambda_U \varepsilon$  and height  $\varepsilon$ , centered at  $(0, \ldots, 0, c)$ , where  $\lambda_U$  stands for the Lipschitz constant of U. Note that in this way the projection of  $U(S_{pi})$  to the plane  $\{x_n = 0\}$  is contained in  $\overline{Q}_{\varepsilon}$ . Denote by  $\Sigma'_{\varepsilon} \subset \overline{Q}_{\varepsilon}$  the union of two uniform grids in the upper and lower faces of  $\overline{Q}_{\varepsilon}$  dividing each of those faces into equal smaller n - 1-dimensional cubes with side  $\varepsilon/2(n - 1)^{1/2}\lambda_F$ , and a vertical segment of length  $\varepsilon$  connecting them, where  $\lambda_F$  stands for the Lipschitz constant of F (see figure 1).

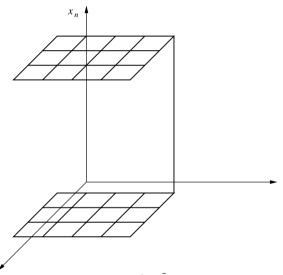


Fig. 1. The set  $\Sigma'_{\varepsilon} \subset \overline{Q}_{\varepsilon}$  (thick lines).

Finally, let  $\Sigma_{\varepsilon} := F(\Sigma'_{\varepsilon})$ . Clearly,  $\mathcal{H}^1(\Sigma_{\varepsilon}) \leq C\varepsilon$  for a C > 0 which depends only on n,  $\lambda_U$  and  $\lambda_F$  (note that the latter two constants can be considered independent of  $\varepsilon$ ).

Then for  $\gamma$ -a.e.  $(x, y) \in \Gamma_{c,\varepsilon}$  one has

$$d_{\Sigma_{\varepsilon}}(x, y) \le d(x, y) - \varepsilon + \varepsilon/2 < d(x, y),$$

and hence,

$$MK(\phi^+, \phi^-, \Sigma_{\varepsilon}) < MK(\phi^+, \phi^-)$$

which shows (5) and thus concludes the proof.

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#### 5. - Basic properties of optimal sets

We first prove that when the measures  $\varphi^{\pm}$  are absolutely continuous with respect to the Lebesgue measure, then the optimal Dirichlet region  $\Sigma_{opt}$  must have maximum length. Clearly, here as well as everywhere in the sequel, the trivial case  $\varphi^+ = \varphi^-$  (which allows  $\Sigma_{opt} = \emptyset$ ) has to be excluded. We remind that here and everywhere in the sequel we are assuming that  $\Omega$  is a convex set.

THEOREM 5.1. Let 
$$n > 1$$
,  $\varphi^{\pm} \ll \mathcal{L}^n$ ,  $\varphi^+ \neq \varphi^-$ . Then  $\mathcal{H}^1(\Sigma_{opt}) = \alpha$ .

PROOF. Suppose  $\mathcal{H}^1(\Sigma_{opt}) < \alpha$ . Lemma 4.2 implies that  $\varphi_s \neq 0$ . Then according to Lemma 5.1 below one can find a closed connected  $\Sigma' \subset \overline{\Omega}$  with  $\Sigma_{opt} \subset \Sigma'$  and  $\mathcal{H}^1(\Sigma') \leq \alpha$  such that

$$\int_{\bar{\Omega}} \operatorname{dist}(x,\,\Sigma')\,d\varphi_s(x) < \int_{\bar{\Omega}} \operatorname{dist}(x,\,\Sigma_{opt})\,d\varphi_s(x).$$

Using Lemma 4.1 one arrives then at inequalities

$$\begin{split} MK(\varphi^+, \varphi^-, \Sigma') &\leq MK(\varphi_r^+, \varphi_r^-) + \int_{\bar{\Omega}} \operatorname{dist}(z, \Sigma') \, d\varphi_s(z) \\ &< MK(\varphi_r^+, \varphi_r^-) + \int_{\bar{\Omega}} \operatorname{dist}(z, \Sigma_{opt}) \, d\varphi_s(z) \\ &= MK(\varphi^+, \varphi^-, \Sigma_{opt}), \end{split}$$

contradicting the optimality of  $\Sigma_{opt}$ .

LEMMA 5.1. Let  $\varphi$  be a nonzero finite Borel measure over  $\overline{\Omega}$ ,  $\varphi \ll \mathcal{L}^n$ , while  $\Sigma \subset \overline{\Omega}$  be a closed set satisfying  $\mathcal{L}^n(\Sigma) = 0$ . Then for every  $\varepsilon > 0$  there is a closed segment  $I_{\varepsilon} \subset \overline{\Omega}$  with  $\mathcal{H}^1(I_{\varepsilon}) = \varepsilon$  such that  $\Sigma \cap I_{\varepsilon} \neq \emptyset$  and

$$\int_{\bar{\Omega}} \operatorname{dist}(x,\,\Sigma_{\varepsilon})\,d\varphi(x) < \int_{\bar{\Omega}} \operatorname{dist}(x,\,\Sigma)\,d\varphi(x) - L(\varepsilon),$$

where  $\Sigma_{\varepsilon} := \Sigma \cup I_{\varepsilon}$  and  $L(\varepsilon) > 0$ , while for all  $\varepsilon > 0$  small enough one has

$$L(\varepsilon) > C\varepsilon^{(n+1)/2}$$

for some constant C > 0 independent of  $\varepsilon$ .

PROOF. It is enough to apply Lemma 5.2 below with  $\Sigma_{\nu} := \Sigma$  and  $B := \overline{\Omega}$ (note that then  $T' = \overline{\Omega} \setminus \Sigma$ , and thus the validity of the condition  $\varphi(T') > 0$  is provided in this case by the assumptions  $\mathcal{L}^n(\Sigma) = 0$  and  $\varphi \ll \mathcal{L}^n$ ,  $\varphi(\overline{\Omega}) > 0$ ).

The lemma below is just a slightly refined version of Lemma 5.1 which we will use in the sequel.

LEMMA 5.2. Let  $\varphi$  be a nonzero finite Borel measure over  $\overline{\Omega}$ ,  $\varphi \ll \mathcal{L}^n$ , while  $\Sigma_{\nu} \subset \overline{\Omega}$  be a sequence of closed sets. Assume that there exists a Borel set  $B \subset \overline{\Omega}$  such that  $\Sigma := \Sigma_{\nu} \cap B$  is independent of  $\nu$ . Denote

 $T' := \left\{ x \in \overline{\Omega} : \exists v_0 = v_0(x) \text{ with } 0 < \operatorname{dist}(x, \Sigma) < \operatorname{dist}(x, \Sigma_v \setminus \Sigma) \text{ for all } v \ge v_0 \right\}$ 

and assume that  $\varphi(T') > 0$ . Then for every  $\varepsilon > 0$  there is such a closed segment  $I_{\varepsilon} \subset \overline{\Omega}$  with  $\mathcal{H}^{1}(I_{\varepsilon}) = \varepsilon$  such that  $\Sigma \cap I_{\varepsilon} \neq \emptyset$  and

$$\int_{\bar{\Omega}} \operatorname{dist}(x,\,\Sigma_{\nu,\varepsilon})\,d\varphi(x) < \int_{\bar{\Omega}} \operatorname{dist}(x,\,\Sigma_{\nu})\,d\varphi(x) - L(\varepsilon),$$

where  $\Sigma_{v,\varepsilon} := \Sigma_v \cup I_{\varepsilon}$  and  $L(\varepsilon) > 0$ , while there is an  $\varepsilon_0 > 0$  independent of v such that

$$L(\varepsilon) > C\varepsilon^{(n+1)/2}$$

for some constant C > 0 independent of both v and  $\varepsilon$  and for all  $\varepsilon < \varepsilon_0$ .

PROOF. Let  $\Omega'_{\nu} \subset \overline{\Omega}$  stand for the set of points admitting a unique projection to  $\Sigma_{\nu}$ . The respective projection map will be denoted  $k^{\nu}$ :  $\Omega'_{\nu} \to \Sigma_{\nu}$ . Clearly since  $\Omega'_{\nu}$  is the set of differentiability points of the distance function  $u(\cdot) :=$ dist $(\cdot, \Sigma_{\nu})$ , then  $\mathcal{L}^n(\Omega'_{\nu}) = \mathcal{L}^n(\overline{\Omega})$ . Our assumption  $\varphi \ll \mathcal{L}^n$  allows hence to consider without loss of generality  $\varphi$  to be restricted to  $\Omega' := \cap_{\nu} \Omega'_{\nu}$ .

Consider an arbitrary  $x \in T' \cap \Omega'$  and the transport ray  $R_x^{\nu}$  of  $MK(\varphi, k_{\#}^{\nu}\varphi)$ of positive length  $l_{\nu}$  passing through x. According to the conditions of the lemma being proven, this ray ends on  $\Sigma$  once  $\nu$  is sufficiently large, and, moreover,  $R_x^{\nu} \subset R_x^{\nu'}$  once  $\nu' \ge \nu \ge \nu_0$ . Then  $R_x^{\nu} \uparrow R_x$  in the set-theoretic sense, where  $R_x$  is some ray of positive length l ending on  $\Sigma$ . Clearly,  $l_{\nu} \uparrow l$ . Let  $O_{\nu} \notin \Sigma$  stand for the upper end of  $R_x^{\nu}$ . Then

$$\Sigma_{\nu} \cap B_{l_{\nu}}(O_{\nu}) = \emptyset.$$

We assume without loss of generality the origin of the coordinate system to coincide with  $O_{\nu}$ , and, moreover, the coordinate axis  $x_n$  to be directed along  $R_x$  upwards, so that the lower endpoint A of  $R_x$  has coordinates  $A = (0, \ldots, 0, -l_{\nu})$ . Let  $A_{\varepsilon} := (0, \ldots, 0, -l_{\nu} + \varepsilon l_{\nu}), I_{\varepsilon} := [A, A_{\varepsilon}]$  stand for the closed segment with endpoints A and  $A_{\varepsilon}$  and  $\Sigma_{\nu,\varepsilon} := \Sigma_{\nu} \cup I_{\varepsilon}$ . For each  $\nu \in \mathbb{N}$  and  $\varepsilon < l_{\nu}$  consider the set

$$\Lambda_{\nu,\varepsilon} := \left\{ z = (Y, x_n) \in B_{l_{\nu}}(0) : x_n \le 0, d(z, A_{\varepsilon}) - \text{dist} \left( z, \partial B_{l_{\nu}}(0) \right) \le -\varepsilon l_{\nu}/4 \right\}$$

If we are able to prove that, up to a correct choice of x, one has

(7) 
$$\varphi\left(\Lambda_{\nu,\varepsilon}\right) \ge C\varepsilon^{(n-1)/2}$$

for all sufficiently small (independently of  $\nu$ )  $\varepsilon > 0$  and for some constant C > 0 (independent both of  $\nu$  and  $\varepsilon$ ), then the proof will be finished. Indeed, let  $\nu_1 = \nu_1(x) \ge \nu_0 \in \mathbb{N}$  be such that

$$l_{\nu} \geq l/2$$
 for all  $\nu \geq \nu_1$ .

Then for  $z \in \Lambda_{\nu,\varepsilon}$  one has

$$\operatorname{dist}(z, \Sigma_{\nu, \varepsilon}) \leq d(z, A_{\varepsilon}) \leq \operatorname{dist}(z, \partial B_{l_{\nu}}(0)) - \varepsilon l_{\nu}/4 \leq \operatorname{dist}(z, \Sigma) - \varepsilon l/8$$

for all  $\nu \geq \nu_1$ , and hence

$$\int_{\bar{\Omega}} \operatorname{dist} \left( z, \, \Sigma_{\nu, \varepsilon} \right) \, d\varphi(z) - \int_{\bar{\Omega}} \operatorname{dist} \left( z, \, \Sigma \right) \, d\varphi(z) \le -\varepsilon l \varphi \left( \Lambda_{\nu, \varepsilon} \right) / 8$$
$$< -C \varepsilon^{(n+1)/2}.$$

It remains therefore to obtain the estimate (7). For this purpose let 0 < m < 1/2 and set (see Figure 2)

$$\Pi_{m,\nu,\varepsilon} := \left\{ z = (Y, x_n) \in B_{l_{\nu}}(0) : |x_n + l_{\nu}/2| \le l_{\nu}(1 - 4m^2)^{1/2}/2, |Y| \le m l_{\nu} \varepsilon^{1/2} \right\}.$$

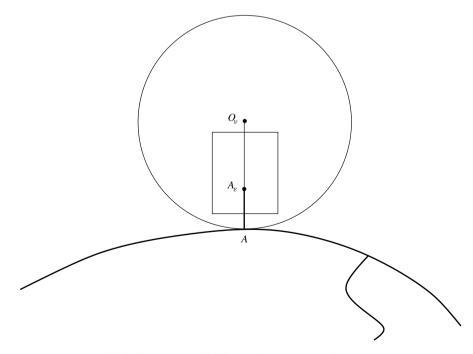


Fig. 2. The sets  $\Sigma_{\nu,\varepsilon}$  (thick lines) and  $\Pi_{m,\nu,\varepsilon}$  (rectangle).

For every  $z = (Y, x_n) \in \prod_{m,\nu,\varepsilon}$  we have

$$d(z, A_{\varepsilon}) - \operatorname{dist} (z, \partial B_{l_{\nu}}(0)) \leq (|Y|^{2} + (x_{n} + l_{\nu} - \varepsilon l_{\nu})^{2})^{1/2} - l_{\nu} + (x_{n}^{2} + |Y|^{2})^{1/2} \leq (m^{2}l_{\nu}^{2}\varepsilon + (x_{n} + l_{\nu} - \varepsilon l_{\nu})^{2})^{1/2} - l_{\nu} + (m^{2}l_{\nu}^{2}\varepsilon + x_{n}^{2})^{1/2} \leq -l_{\nu} + |x_{n}| + m^{2}l_{\nu}^{2}\varepsilon/2|x_{n}| + (x_{n} + l_{\nu}) + \varepsilon (m^{2}l_{\nu}^{2} - 2l(x_{n} + l_{\nu})) / 2(x_{n} + l_{\nu}) + \alpha\varepsilon^{2} = \varepsilon (m^{2}l_{\nu}^{2}/(x_{n} + l_{\nu}) - 2l_{\nu} + m^{2}l_{\nu}^{2}/|x_{n}|) / 2 + \alpha\varepsilon^{2},$$

where  $\alpha = \alpha(m, l) > 0$  is some constant independent of  $\nu$  (we minded that  $l_{\nu} \uparrow l$  when making the latter estimate). It is easy to verify that

$$m^{2}l_{\nu}^{2}/(x_{n}+l_{\nu})-2l_{\nu}+m^{2}l_{\nu}^{2}/|x_{n}|\leq -l_{\nu},$$

whenever  $z \in \Pi_{m,\nu,\varepsilon}$ , and hence, assuming  $\nu \geq \nu_1$ , one has

$$d(z, A_{\varepsilon}) - \text{dist}(z, \partial B_{l_{v}}(0)) \leq -\varepsilon l_{v}/4$$

whenever  $\varepsilon < l/8\alpha$  (in fact, in this case  $\varepsilon < l_{\nu}/4\alpha$  since  $\nu \ge \nu_1$ ). This means  $\prod_{m,\nu,\varepsilon} \subset \Lambda_{\nu,\varepsilon}$  for such  $\varepsilon$ .

Assume now that x is chosen in such a way that  $\mathcal{H}^1$ -a.e.  $z \in R_x^{\nu}$  is a Lebesgue point of  $\frac{d\varphi}{d\mathcal{L}^n}$  (in view of Lemma 5.4 from [7], this holds for  $\varphi$ -a.e.  $x \in \overline{\Omega}$ , hence for  $\varphi$ -a.e.  $x \in T' \cap \Omega'$ ). Then, fixed an arbitrary  $\nu \geq \nu_1$ , the relationship

(8) 
$$\liminf_{\varepsilon \to 0^+} \frac{\varphi(\Pi_{m,\nu,\varepsilon})}{\varepsilon^{(n-1)/2}} \ge C_m(R_x^{\nu}) := C \int_{l_{\nu,m}^-}^{l_{\nu,m}^+} \frac{d\varphi}{d\mathcal{L}^n}(Y,x_n) \, d\mathcal{H}^1(x_n)$$

holds, where  $l_{\nu,m}^{\pm} := l_{\nu}/2 \pm l_{\nu}(1 - 4m^2)^{1/2}/2$ , and C > 0 is some constant independent of  $\nu$ . In fact, one has

$$\begin{split} \varphi(\Pi_{m,\nu,\varepsilon}) &= \int_{l_{\nu,m}}^{l_{\nu,m}^+} d\mathcal{H}^1(x_n) \int_{|Y| < ml_\nu \sqrt{\varepsilon}} \frac{d\varphi}{d\mathcal{L}^n}(Y,x_n) \, d\mathcal{H}^{n-1}(Y) \\ &= \frac{1}{2\sqrt{\varepsilon}} \int_{-\sqrt{\varepsilon}}^{\sqrt{\varepsilon}} dh \int_0^l d\mathcal{H}^1(x_n) \int_{|Y| < ml_\nu \sqrt{\varepsilon}} f_\nu(Y,x_n+h) \, d\mathcal{H}^{n-1}(Y) \\ &= \int_0^l f_{\nu,\varepsilon}(x_n) \, d\mathcal{H}^1(x_n), \end{split}$$

where

$$f_{\nu}(Y, x_n) := \frac{d\varphi}{d\mathcal{L}^n}(Y, x_n) \cdot \mathbf{1}_{[l_{\nu,m}^+, l_{\nu,m}^-]}(x_n),$$
  
$$f_{\nu,\varepsilon}(x_n) := \frac{1}{2\sqrt{\varepsilon}} \int_{x_n - \sqrt{\varepsilon}}^{x_n + \sqrt{\varepsilon}} \int_{|Y| < ml_{\nu}\sqrt{\varepsilon}} f_{\nu}(Y, s) \, d\mathcal{H}^{n-1}(Y) d\mathcal{H}^1(s).$$

But in view of our assumption on  $R_x$ , we have  $\mathcal{H}^1$ -a.e. on  $R_x$  the convergence

$$\frac{f_{\varepsilon}(x_n)}{\varepsilon^{(n-1)/2}} \to C_n (ml_{\nu})^{n-1} f(0, x_n),$$

where  $C_n > 0$  is a constant depending only on the space dimension *n*. This, together with Fatou lemma and the estimate  $l_{\nu} \ge l/2$  shows (8).

Observe now that  $C_m(R_x^{\nu}) > 0$  for some  $x \in T' \cap \Omega'$  and some *m* since otherwise  $\varphi \perp T'$  would be concentrated on the set of upper and lower ray ends of  $MK(\varphi, k_{\#}^{\nu}\varphi)$ , contrary to our original assumption. Choose a  $\bar{\nu} \geq \nu_1$  and an  $\bar{m} = \bar{m}(\bar{\nu}) \in (0, 1/2)$  such that  $C_{\bar{m}}(R_x^{\bar{\nu}}) > 0$ . Then (8) implies

(9) 
$$\varphi\left(\Pi_{\bar{m},\bar{\nu},\varepsilon}\right) \ge C_{\bar{m}}(R_x^{\bar{\nu}})\varepsilon^{(n-1)/2}$$

for all  $\varepsilon < \varepsilon_0$ , where  $\varepsilon_0 = \varepsilon_0(\bar{\nu}) > 0$ .

We claim now that for every  $\nu \ge \overline{\nu}$  there is an  $m = m(\nu)$  such that

(10) 
$$\Pi_{\bar{m},\bar{\nu},\varepsilon} \subset \Pi_{m,\nu,\varepsilon}.$$

In fact, in view of the inequality  $l_{\nu} \ge l_{\bar{\nu}}$  the desired inclusion (10) is valid whenever

(11) 
$$l_{\nu,m}^+ \ge l_{\bar{\nu},\bar{m}}^+, \quad l_{\nu,m}^- \le l_{\bar{\nu},\bar{m}}^- \text{ and } \bar{m}l_{\bar{\nu}} \le ml_{\nu}.$$

Denoting

$$\delta_{\nu} := l_{\bar{\nu}}/l_{\nu},$$

one immediately observes that (11) are equivalent to the system of inequalities

$$\begin{split} 4\bar{m}^2 \delta_{\nu}^2 &\leq 4m^2 \leq 1 - (\delta_{\nu} \sqrt{1 - 4\bar{m}^2} + 1 - \delta_{\nu})^2 \\ &= \delta_{\nu} (1 - \sqrt{1 - 4\bar{m}^2}) (2 + \delta_{\nu} \sqrt{1 - 4\bar{m}^2} - \delta_{\nu}). \end{split}$$

For this system of inequalities to be solvable with respect to m it is necessary and sufficient that

$$4\bar{m}^2\delta_{\nu} \le (1 - \sqrt{1 - 4\bar{m}^2})(2 + \delta_{\nu}\sqrt{1 - 4\bar{m}^2} - \delta_{\nu}).$$

Multiplying both sides of the latter inequality by  $(1 + \sqrt{1 - 4\bar{m}^2})/4\bar{m}^2$ , one obtains the equivalent one

$$\delta_{\nu}(1+\sqrt{1-4\bar{m}^2}) \leq 2+\delta_{\nu}\sqrt{1-4\bar{m}^2}-\delta_{\nu},$$

which is clearly equivalent to  $\delta_{\nu} \leq 1$ , and hence is always valid, since  $l_{\nu}$  is a nondecreasing sequence. Therefore, one can also find an  $m = m(\nu)$  satisfying (11) and hence also (10).

It remains to observe that (10) applied to (9) yields

(12) 
$$\varphi\left(\Pi_{m,\nu,\varepsilon}\right) \ge \varphi\left(\Pi_{\bar{m},\bar{\nu},\varepsilon}\right) \ge C\varepsilon^{(n-1)/2}$$

for a  $C = C(\bar{\nu}) > 0$  independent on  $\nu$  and  $\varepsilon$  and for all  $\varepsilon \le \varepsilon_0$ . At last, since  $\prod_{m,\nu,\varepsilon} \subset \Lambda_{\nu,\varepsilon}$  we get from (12) the estimate

$$\varphi(\Lambda_{\nu,\varepsilon}) \ge \varphi(\Pi_{m,\nu,\varepsilon}) \ge C\varepsilon^{(n-1)/2}$$

for the same C > 0 and  $\varepsilon$  as in (12), which is exactly (7), and hence the proof is concluded.

We emphasize that both the condition  $\varphi^{\pm} \ll \mathcal{L}^n$  and n > 1 are essential for the result of Theorem 5.1 to hold, as the following examples show.

EXAMPLE 5.1. Let  $\varphi^+ := \delta_0$ , where *O* stands for the origin of the coordinate system,  $\varphi^- := 0$ ,  $\alpha := 1$  and  $\Omega := B_1(0)$ . Then clearly  $\Sigma := \{O\}$  is optimal, but  $\mathcal{H}^1(\Sigma) = 0 < \alpha$ .

EXAMPLE 5.2. Let n = 1,  $\Omega = (0, 1)$  and  $\alpha > 1$ . Then, whatever are the measures  $\varphi^{\pm}$  concentrated on  $\overline{\Omega}$ , one has that  $\Sigma := [0, 1]$  is optimal, while  $\mathcal{H}^1(\Sigma) = 1 < \alpha$ .

Another relatively simple result regards the location of the optimal set  $\Sigma_{opt}$ . PROPOSITION 5.1. Let n > 1,  $\varphi^{\pm} \ll \mathcal{L}^n$ ,  $\varphi^+ \neq \varphi^-$ . Then

 $\Sigma_{opt} \subset \overline{co} (\operatorname{supp} \varphi^+ \cup \operatorname{supp} \varphi^-).$ 

PROOF. Denote

$$D := \overline{\operatorname{co}} \left( \operatorname{supp} \varphi^+ \cup \operatorname{supp} \varphi^- \right)$$

and suppose  $\Sigma_{opt} \setminus D \neq \emptyset$ . Let then  $\Sigma'$  stand for the projection of  $\Sigma_{opt}$  on D. Clearly,  $\Sigma'$  is still closed and connected, while  $\mathcal{H}^1(\Sigma') < \alpha$ . We claim that for all  $x \in D$  one has

(13) 
$$\operatorname{dist}(x, \Sigma') \leq \operatorname{dist}(x, \Sigma_{opt}).$$

This claim in fact leads immedately to the conclusion since it implies  $d_{\Sigma'}(x, y) \le d_{\Sigma_{ont}}(x, y)$  for all  $(x, y) \in \operatorname{supp} \varphi^+ \times \operatorname{supp} \varphi^-$ , and hence

$$MK(\varphi^+, \varphi^-, \Sigma') \leq MK(\varphi^+, \varphi^-, \Sigma_{opt}).$$

The latter means that  $\Sigma'$  is also an optimal set for the same problem, while then  $\mathcal{H}^1(\Sigma') < \alpha$  contradicts Theorem 5.1.

To prove (13), suppose the contrary, namely that

(14) 
$$\operatorname{dist}(x, \Sigma') > \operatorname{dist}(x, \Sigma_{opt}).$$

for some  $x \in D$ . Let  $x_0 \in \Sigma_{opt}$  be a point of minimum distance to  $x_0$  in  $\Sigma_{opt}$ . Clearly, (14) can only hold when  $x_0 \in \Sigma_{opt} \setminus D$ . Let  $x'_0$  stand for the projection of  $x_0$  on D. Since  $x'_0 \in \Sigma'$ , then

$$\operatorname{dist}(x, \Sigma') \leq \operatorname{dist}(x, x_0').$$

But

$$dist(x, x'_0) < d(x_0, x).$$

The latter inequality follows immediately from the fact that both  $x'_0$  and x belong to the same half-space formed by a hyperplane  $\pi$  which is parallel to the supporting hyperplane of D at  $x'_0$  and passes through the medium point of the segment  $[x_0, x'_0]$ : in fact,  $\pi = \{z : d(x_0, z) = d(x'_0, z)\}$  (see Figure 3).

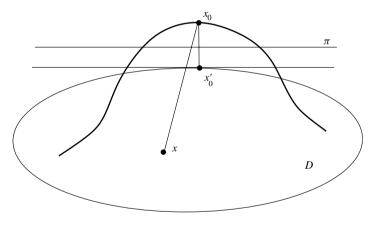


Fig. 3. The original set  $\Sigma_{opt}$  (thick line) and the hyperplane  $\pi$ .

We conclude now

$$\operatorname{dist}(x, \Sigma') \leq \operatorname{dist}(x, x'_0) < d(x_0, x) = \operatorname{dist}(x, \Sigma_{opt}),$$

contradicting (14).

The condition  $\varphi^{\pm} \ll \mathcal{L}^n$  is clearly essential also in the statement of Proposition 5.1. In fact, in Example 5.1 every closed connected  $\Sigma$  containing the origin and satisfying the length constraint is optimal, while for all such  $\Sigma$  except  $\Sigma = \{O\}$  Proposition 5.1 does not hold.

#### 6. - Absense of loops

The following result is valid.

THEOREM 6.1. Let n = 2,  $\varphi^{\pm} \ll \mathcal{L}^2$ ,  $\varphi^+ \neq \varphi^-$ . Then  $\Sigma_{opt}$  contains no simple closed curve (a homeomorphic image of  $S^1$ ). In particular,  $\mathbb{R}^2 \setminus \Sigma_{opt}$  is connected.

To prove the above theorem, we need several auxiliary constructions. We start with the following lemma.

LEMMA 6.1. Let  $\Sigma$  be a locally connected metric continuum consisting of more than one point and  $x \in \Sigma$  be a noncut point of  $\Sigma$ . Then there is a sequence of open sets  $D_{\nu} \subset \Sigma$  satisfying

- (i)  $x \in D_{\nu}$  for all sufficiently large  $\nu$ ;
- (*ii*)  $\Sigma \setminus D_{v}$  are connected for all v;

(iii) diam  $D_{\nu} \searrow 0$  as  $\nu \rightarrow \infty$ ;

(iv)  $D_v$  are connected for all v.

PROOF. Let  $z \in \Sigma$ ,  $z \neq x$ . For every couple of points  $\{y_1, y_2\} \subset \Sigma$  we will say that  $y_1$  is connected to  $y_2$  through a closed connected set  $\Gamma \subset \Sigma$ , if  $\{y_1, y_2\} \subset \Gamma$ . Define now

 $X_{\nu} := \{ y \in \Sigma : y \text{ connected to } z \text{ through a } \Gamma \subset \Sigma \setminus B_{1/\nu}(x) \},\$  $O_{\nu} := \Sigma \setminus X_{\nu}.$ 

We show first that  $O_{\nu}$  are open for all  $\nu$ , while

- (i')  $x \in O_{\nu}$  for all sufficiently large  $\nu$ ;
- (ii')  $\Sigma \setminus D_{\nu}$  are connected for all  $\nu$ ;

(iii') diam  $O_{\nu} \searrow 0$  as  $\nu \to \infty$ .

We first observe, that all  $X_{\nu}$  are closed, hence  $O_{\nu}$  are open. In fact, if  $y_k \in X_{\nu}, y_k \to y$  as  $k \to \infty$ , then each  $y_k$  is connected to z through a set  $\Gamma_k$  satisfyng  $\Gamma_k \subset \Sigma \setminus B_{1/\nu}(x)$ . Then, up to a subsequence (not relabeled)  $\Gamma_k \to \Gamma$  in the sense of Hausdorff convergence, while  $\Gamma$  is a closed connected set which connects y to z, and  $\Gamma \subset \Sigma \setminus B_{1/\nu}(x)$ . In other words,  $y \in X_{\nu}$ .

Now, clearly, (i') holds since otherwise one would have z = x. Moreover, (ii') is also immediate from the definition of  $X_{\nu}$ . To prove (iii'), suppose the contrary, namely, that there is an r > 0 such that for all  $\nu$  outside of  $B_r(x)$ there are points  $y_{\nu} \in O_{\nu} \setminus B_r(x)$ . It follows that for every set  $\Gamma_{\nu}$  connecting  $y_{\nu}$ with z one has

(15) 
$$\Gamma_{\nu} \cap B_{1/\nu}(x) \neq \emptyset.$$

Consider an arbitrary accumulation point y of a sequence  $\{y_{\nu}\}$ . The local connectedness of  $\Sigma$  implies (see Theorem I.2 from [10, Section 49]) that for each sufficiently large  $\nu$  there is a closed connected set  $C_{\nu} \subset \Sigma$  satisfying  $C_{\nu} \cap B_{r/2}(x) = \emptyset$  which connects y and  $y_{\nu}$ . Therefore, for every set  $\Gamma \subset \Sigma$  connecting y to z one has  $x \in \Gamma$ . In fact, otherwise minding the compactness

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of  $\Gamma$  we would have  $(\Gamma \cup C_{\nu}) \cap B_{\varepsilon}(x) = \emptyset$  for some  $\varepsilon > 0$  independent of  $\nu$ , although  $\Gamma \cup C_{\nu}$  connects  $y_{\nu}$  to z, in contradiction with (15).

Mind now that  $y \notin B_r(x)$  and hence  $y \in \Sigma \setminus \{x\}$ . But the latter space is locally connected (as an open subset of a locally connected space  $\Sigma$ ) and, being completely metrizable (again, as an open subset of  $\Sigma$ ), is therefore also locally arcwise connected. Since it is supposed to be connected (because x is a noncut point of  $\Sigma$ ), then it is arcwise connected. In particular, this means that there is an arc  $\gamma \subset \Sigma \setminus \{x\}$  connecting y to z. But according to what has just been proven, every arc in  $\Sigma$  connecting y to z must pass through x. This contradiction thus proves (iii').

Let now  $D_{\nu}$  stand for the connected component of  $O_{\nu}$  which contains x. Then  $D_{\nu}$  is relatively (with respect to  $O_{\nu}$ ) open in view of local connectedness of  $\Sigma$  and hence is open in  $\Sigma$ . One immediately observes that (i) and (ii) hold in view of (i') and (ii') respectively. Since (iv) automatically follows from the construction, it remains to verify (iii). The latter, in view of (iii') will be shown one we prove that for every  $y \in O_{\nu} \setminus D_{\nu}$  there is a set  $\Gamma$  connecting y to zsuch that  $\Gamma \cap D_{\nu} = \emptyset$ .

To prove the latter claim, suppose the contrary, i.e. that for some  $y \in O_{\nu} \setminus D_{\nu}$ and for every  $\Gamma$  connecting y to z one has  $\Gamma \cap D_{\nu} \neq \emptyset$ . Let  $\gamma$  be an arbitrary arc connecting y to z (so that  $\gamma(0) = y$  and  $\gamma(1) = z$ ), and set

$$\bar{t} := \sup\{t \in [0, 1] : \gamma(s) \notin D_{\nu} \text{ for all } s \in [0, t)\}, \qquad \tilde{x} := \gamma(t).$$

Consider now the arc  $[y, \tilde{x}] \subset \gamma$  which connects y to  $\tilde{x}$ , and let  $[y, \tilde{x}) := [y, \tilde{x}] \setminus {\tilde{x}}$ . We claim

(16) 
$$[y,\tilde{x}) \subset O_{\nu}.$$

In fact, if  $v \in [y, \tilde{x})$ , then for every set  $\Gamma'$  connecting v with z there is an  $x' \in \Gamma' \cap D_v$ , since otherwise, minding that for  $[y, v] \subset \gamma$  one has  $[y, v] \cap D_v = \emptyset$  and hence, contrary to our assumption,  $([y, v] \cup \Gamma') \cap D_v = \emptyset$  despite the fact that  $[y, v] \cup \Gamma'$  connects y to z. Since  $x' \in O_v$  then necessarily  $\Gamma' \cap \overline{B}_{1/v}(x) \neq \emptyset$ . Since the latter holds for an arbitrary closed connected  $\Gamma'$  connecting v to z, then by construction  $v \in O_v$  which implies (16) in view of arbitrarity of v.

We prove now  $\tilde{x} \in O_{\nu}$ . In fact, if this is not the case, then there is a set  $\tilde{\Gamma}$  connecting  $\tilde{x}$  to z such that  $\tilde{\Gamma} \subset X \setminus B_{1/\nu}(x)$ , hence,  $\tilde{\Gamma} \cap O_{\nu} = \emptyset$  and in particular  $\tilde{\Gamma} \cap D_{\nu} = \emptyset$ . But then  $([y, \tilde{x}] \cup \tilde{\Gamma}) \cap D_{\nu} = \emptyset$  contrary to our assumption since  $[y, \tilde{x}] \cup \tilde{\Gamma}$  connects y to z.

Combining the latter observation with (16), we get

$$[y, \tilde{x}] \subset O_{\nu},$$

which implies that that  $y \in D_{\nu}$  (since  $D_{\nu}$  is a connected component of  $O_{\nu}$ ). This however contradicts the choice of y and thus proves the claim.

We may now claim the following assertion.

PROPOSITION 6.1. Let n = 2,  $\varphi^{\pm} \ll \mathcal{L}^2$ ,  $\varphi^+ \neq \varphi^-$ . Then  $\mathcal{H}^1$ -a.e.  $x \in \Sigma_{opt}$  is a cut point of  $\Sigma_{opt}$ .

PROOF. Suppose the contrary, namely that the set A of noncut points of  $\Sigma_{opt}$  has positive length, i.e.  $\mathcal{H}^1(A) > 0$ . We observe that since  $\mathcal{H}^1(\Sigma_{opt}) < +\infty$ , then  $\Sigma_{opt}$  is a continuous (in fact, even Lipschitz continuous) image of the unit interval, and hence is locally connected in view of the Hahn-Mazurkiewicz-Sierpiński Theorem II.2 from [10, Section 50]. Hence for each  $x \in A$  we may consider the sequence of sets  $\{D_{\nu}\}$  with the properties announced in Lemma 6.1. We denote  $\varepsilon_{\nu} := \operatorname{diam} D_{\nu}$ . Note that  $\mathcal{H}^1(D_{\nu}) \geq \varepsilon_{\nu}$ . For the sake of brevity of the notation, further on we omit the reference to the index  $\nu$  writing always  $\varepsilon$  instead of  $\varepsilon_{\nu}$ . The contradiction will be achieved in two steps.

STEP 1. For every  $x \in A$  and  $\varepsilon > 0$  let  $T(x, \varepsilon)$  stand for the union of transport rays of the Monge-Kantorovich problem  $MK(\varphi_s, \psi)$  which end at  $\Sigma_{opt} \cap B_{\varepsilon}(x)$ . Choose an arbitrary  $x \in A$  and set  $\Sigma_{\varepsilon}(x) := \Sigma_{opt} \setminus D_{v}$ . Clearly, according to our assumption,  $\Sigma_{\varepsilon}(x)$  is still closed and connected, and, of course, satisfies the length constraint since  $\mathcal{H}^{1}(\Sigma_{\varepsilon}(x)) \leq \mathcal{H}^{1}(\Sigma_{opt})$ . Since  $D_{v} \subset B_{\varepsilon}(x)$ , the following estimate is valid

$$\begin{split} \int_{\bar{\Omega}} \operatorname{dist}(z, \Sigma_{\varepsilon}(x)) \, d\varphi_{s}(z) \\ &= \int_{\bar{\Omega} \setminus T(x,\varepsilon)} \operatorname{dist}(z, \Sigma_{\varepsilon}(x)) \, d\varphi_{s}(z) + \int_{T(x,\varepsilon)} \operatorname{dist}(z, \Sigma_{\varepsilon}(x)) \, d\varphi_{s}(z) \\ &\leq \int_{\bar{\Omega} \setminus T(x,\varepsilon)} \operatorname{dist}(z, \Sigma_{opt}) \, d\varphi_{s}(z) + \int_{T(x,\varepsilon)} (\operatorname{dist}(z, \Sigma_{opt}) + \varepsilon) \, d\varphi_{s}(z) \\ &= \int_{\bar{\Omega}} \operatorname{dist}(z, \Sigma_{opt}) \, d\varphi_{s}(z) + \varepsilon \varphi_{s}(T(x,\varepsilon)). \end{split}$$

By definition of  $\psi$  one has

$$\varphi_s(T(x,\varepsilon)) = \psi(B_\varepsilon(x)).$$

But

$$\limsup_{\varepsilon \to 0^+} \frac{\psi(B_\varepsilon(x))}{\varepsilon} < +\infty$$

for  $\mathcal{H}^1$ -a.e.  $x \in A$ , which implies

$$\psi(D_{\nu}) \leq \psi(B_{\varepsilon}(x)) \leq C\varepsilon + o(\varepsilon)$$

for some C = C(x) > 0 depending on x,  $\mathcal{H}^1$ -a.e. in A. Summing up, for  $\mathcal{H}^1$ -a.e.  $x \in A$  one has

(17) 
$$\int_{\bar{\Omega}} \operatorname{dist}(z, \Sigma_{\varepsilon}(x)) \, d\varphi_s(z) \leq \int_{\bar{\Omega}} \operatorname{dist}(z, \Sigma_{opt}) \, d\varphi_s(z) + C\varepsilon^2 + o(\varepsilon^2).$$

Note that the constant C depends on x. Since  $\mathcal{H}^1(A) > 0$  in view of our original assumption, we can choose an  $x \in A$  such that the above estimate holds with some constant C > 0.

Step 2. Let

$$l(\varepsilon) := \mathcal{H}^{1}(\Sigma_{opt}) - \mathcal{H}^{1}(\Sigma_{\varepsilon}(x)).$$

One clearly has  $l(\varepsilon) \geq \varepsilon$ . In view of Lemma 4.2 we may apply now Lemma 5.2 with  $\varphi := \varphi_s$ ,  $\Sigma_{\nu} := \Sigma_{\varepsilon}(x)$  and  $B := \overline{\Omega} \setminus B_{\varepsilon}(x)$  to find a closed connected  $\Sigma' \subset \overline{\Omega}$  satisfying  $\mathcal{H}^1(\Sigma') = \mathcal{H}^1(\Sigma_{\varepsilon}) + \varepsilon$  and (using the fact that n = 2)

$$\int_{\bar{\Omega}} \operatorname{dist}(x,\,\Sigma')\,d\varphi(x) < \int_{\bar{\Omega}} \operatorname{dist}(x,\,\Sigma_{\varepsilon}(x))\,d\varphi(x) - C\varepsilon^{3/2}$$

for some C > 0 as  $\varepsilon > 0$  is small enough. But

$$MK(\varphi^+, \varphi^-, \Sigma') \le MK(\varphi_r^+, \varphi_r^-) + \int_{\bar{\Omega}} \operatorname{dist}(z, \Sigma') d\varphi_s(z)$$

in view of Lemma 4.1, and hence one has

$$MK(\varphi^+, \varphi^-, \Sigma') \leq MK(\varphi_r^+, \varphi_r^-) + \int_{\bar{\Omega}} \operatorname{dist}(z, \Sigma_{\varepsilon}(x)) d\varphi_s(z) - C\varepsilon^{3/2}.$$

Using (17), one arrives at the estimate

$$MK(\varphi^+, \varphi^-, \Sigma') \le MK(\varphi_r^+, \varphi_r^-) + \int_{\bar{\Omega}} \operatorname{dist}(z, \Sigma_{opt}) d\varphi_s(z) - C\varepsilon^{3/2}$$
$$= MK(\varphi^+, \varphi^-, \Sigma_{opt}) - C\varepsilon^{3/2}$$

as  $\varepsilon > 0$  is small enough. Hence for such  $\varepsilon$  one has

$$MK(\varphi^+, \varphi^-, \Sigma') < MK(\varphi^+, \varphi^-, \Sigma_{opt})$$

contradicting the optimality of  $\Sigma_{opt}$ .

PROOF OF THEOREM 6.1: Suppose there is a simple closed loop  $S \subset \Sigma_{opt}$ . If  $x \in S$  is a cut point for  $\Sigma_{opt}$  then there is a continuum  $L_x$  such that  $L_x \cap S = \{x\}$  and  $L_x \setminus \{x\} \neq \emptyset$ . One has then  $L_x \cap L_y = \emptyset$  whenever  $x \neq y$ . But then  $\mathcal{H}^1(L_x) > 0$  for only at most countable number of x, otherwise one would have  $\mathcal{H}^1(\Sigma_{opt}) = +\infty$ . All the other  $x \in S$  are noncut for  $\Sigma_{opt}$  contradicting Proposition 6.1.

To prove the connectedness of  $\mathbb{R}^2 \setminus \Sigma_{opt}$ , note that it follows from Theorem II.5 of [10, Section 61], that if  $D \subset \mathbb{R}^2$  is a bounded connected set with locally connected boundary, then there is a simple closed curve  $S \subset \partial D$ . Then, if  $\mathbb{R}^2 \setminus \Sigma_{opt}$  were disconnected, there would exist a bounded connected component D of  $\mathbb{R}^2 \setminus \Sigma_{opt}$  such that  $\partial D \subset \Sigma_{opt}$ , and hence  $\Sigma_{opt}$  would contain a simple closed curve contrary to what has been just proven.

#### 7. – Noncut points

The following fundamental result regarding noncut points of the optimal set is valid.

THEOREM 7.1. Let n = 2,  $\varphi^{\pm} \in L^{p}(\Omega)$ , where p > 4/3, and  $\varphi^{+} \neq \varphi^{-}$ . Then there is a constant C > 0 such that for every noncut point  $x \in \Sigma_{opt}$  one has  $\psi(\{x\}) > C$ . In particular, the number of noncut points in  $\Sigma_{opt}$  is finite.

The proof of the above theorem is just a combination of the following two statements.

PROPOSITION 7.1. Let n = 2,  $\varphi^{\pm} \ll \mathcal{L}^n$ ,  $\varphi^+ \neq \varphi^-$ . Assume that there is an  $y \in \Sigma_{opt}$  such that  $\psi(\{y\}) > 0$ . Then there is a constant C > 0 such that for every noncut point  $x \in \Sigma_{opt}$  one has  $\psi(\{x\}) \ge C$ . In particular, in this case the number of noncut points in  $\Sigma_{opt}$  is finite.

PROOF. According to Lemma 4.2 one has  $\varphi_s \neq 0$ , hence  $\psi \neq 0$ . We divide the proof in two steps.

STEP 1. Let  $x \in \Sigma_{opt}$  be a noncut point. We prove first

(18) 
$$\psi(\lbrace x \rbrace) \ge \sup_{y \in \Sigma_{opt}} \psi(\lbrace y \rbrace)/2\pi.$$

For this purpose consider an arbitrary  $y \in \Sigma_{opt}$  and let  $\{D_{\nu}\}_{\nu \in \mathbb{N}}$  stand for the decreasing sequence of subsets of  $\Sigma_{opt}$  indicated by Lemma 6.1, with  $x \in D_{\nu}$ . We also suppose the diameters of  $D_{\nu}$  to be small enough so that  $y \notin D_{\nu}$  for all  $\nu \in \mathbb{N}$ . We set  $\varepsilon_{\nu} := \text{diam } D_{\nu}$ . Note that  $\mathcal{H}^1(D_{\nu}) \ge \varepsilon_{\nu}$ . For the sake of brevity, further on we omit the reference to the index  $\nu$  writing always  $\varepsilon$  instead of  $\varepsilon_{\nu}$ .

According to Proposition 5.1 we may assume without loss of generality that

$$\overline{\operatorname{co}}\,(\operatorname{supp}\varphi^+\cup\operatorname{supp}\varphi^-)\subset\subset\Omega.$$

Setting  $\Sigma_{\varepsilon}^{1} := \Sigma_{opt} \setminus D_{\nu}$ , while  $\Sigma_{\varepsilon}^{2} := \Sigma_{\varepsilon}^{1} \cup \partial B_{\varepsilon/2\pi}(y)$ , one has that  $\Sigma_{\varepsilon}^{2} \subset \Omega$  and is still closed, connected and satisfies the length constraint. Then

$$\int_{\bar{\Omega}} \operatorname{dist}(z, \Sigma_{\varepsilon}^{1}) \, d\varphi_{s}(z) \leq \int_{\bar{\Omega}} \operatorname{dist}(z, \Sigma_{opt}) \, d\varphi_{s}(z) + \varepsilon \psi(D_{\nu}),$$

but

$$\begin{split} \int_{\bar{\Omega}} \operatorname{dist}(z, \Sigma_{\varepsilon}^{2}) \, d\varphi_{s}(z) \\ &\leq \int_{\bar{\Omega}} \operatorname{dist}(z, \Sigma_{\varepsilon}^{1}) \, d\varphi_{s}(z) - \frac{\varepsilon}{2\pi} \left( \psi(\{y\}) - \varphi_{s}(B_{\varepsilon/2\pi}(y)) \right) \end{split}$$

Therefore,

$$\int_{\bar{\Omega}} \operatorname{dist}(z, \Sigma_{\varepsilon}^{1}) d\varphi_{s}(z) \leq \int_{\bar{\Omega}} \operatorname{dist}(z, \Sigma_{opt}) d\varphi_{s}(z) + \varepsilon \psi(D_{\nu}) \\ - \frac{\varepsilon}{2\pi} \left( \psi(\{y\}) - \varphi_{s}(B_{\varepsilon/2\pi}(y)) \right).$$

Taking into account  $\varepsilon \to 0$ ,  $\psi(D_{\nu}) \to \psi(\{x\})$  and  $\varphi_s(B_{\varepsilon/2\pi}(y)) \to 0$  as  $\nu \to \infty$ , one has that the latter inequality would contradict the optimality of  $\Sigma_{opt}$  unless  $\psi(\{x\}) \ge \psi(\{y\})/2\pi$ , which shows (18).

STEP 2. Consider now two arbitrary noncut points  $x_i \in \Sigma_{opt}$ , i = 1, 2. As an immediate corollary of (18) one has

$$\psi(\{x_2\}) \le 2\pi \,\psi(\{x_1\}).$$

Exchanging  $x_1$  with  $x_2$ , one arrives then at the estimate

(19) 
$$\psi(\{x_2\}) \le 2\pi \psi(\{x_1\}) \le 4\pi^2 \psi(\{x_2\}).$$

Under the conditions of the proposition being proven, the estimate (18) implies  $\psi(\{x\}) > 0$  for every noncut point  $x \in \Sigma_{opt}$ , and hence, combined with (19) proves the existence of a C > 0 such that  $\psi(\{x\}) > C$  for every noncut point  $x \in \Sigma_{opt}$ , which proves the first claim. It is now immediate to conclude that the number of noncut points is finite since  $\psi(\bar{\Omega}) < +\infty$ .

Another key ingredient of the proof of Theorem 7.1 is the following auxiliary weak assertion.

LEMMA 7.1. Let n = 2,  $\varphi^{\pm} \in L^{p}(\Omega)$  where p > 4/3. Then there is an  $x \in \Sigma_{opt}$  such that  $\psi({x}) > 0$ .

To prove the above lemma, we need some auxiliary constructions. Let  $\Sigma$  be a locally connected metric continuum consisting of more than one point. Take  $x \in \Sigma$ ,  $z \in \Sigma$  with  $z \neq x$  and define

 $D(x, z) := \{y \in \Sigma; y \text{ is connected to } x \text{ through a path } \gamma, \text{ such that } z \notin \gamma\}.$ 

Figure 4 illustrates how D(x, z) may look like when z is a nonbranching point (upper figure) and when z is a branching point (lower figure) of  $\Sigma$ .

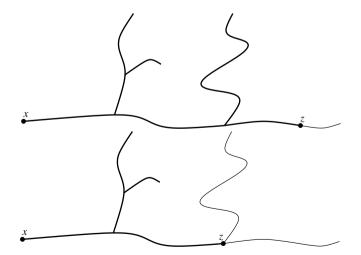


Fig. 4. The set D(x, z) (thick line).

We make an important observation: if  $\Sigma$  contains no simple closed curve (a homeomorphic image of  $S^1$ ), then every couple of points in  $\Sigma$  is connected by a unique arc (Corollary VI.2 in [10, Section 51]). In this case, if  $\gamma$  is an arc of  $\Sigma$  starting at x and  $\{z_1, z_2\} \subset \gamma$ , we will write

$$z_1 \leq_{\gamma,x} z_2,$$

if  $[x, z_1] \subset [x, z_2]$ . The above relationship obviously defines a total order on  $\gamma$ . We also will write  $z_1 <_{\gamma,x} z_2$ , if  $z_1 \leq_{\gamma,x} z_2$  and  $z_1 \neq z_2$ . For a sequence  $\{z_\nu\}_{\nu=1}^{\infty} \subset \gamma$  we will say that  $z_\nu \searrow_{\gamma} x$  as  $\nu \to \infty$ , if for every  $z \in \gamma$  there is a  $\bar{\nu} \in \mathbb{N}$  such that  $z_\nu \leq_{\gamma,x} z$  for all  $\nu \geq \bar{\nu}$ . In particular, minding that  $[x, z_\nu]$  is a unique arc connecting x to  $z_\nu$ , one has that  $z_\nu \searrow_{\gamma} x$  holds if and only if  $d^{\Sigma}(z_\nu, x) \searrow 0$  as  $\nu \to \infty$ , where  $d^{\Sigma}$  stands for the geodesic distance over  $\Sigma$ , namely,

 $d^{\Sigma}(u, v) := \inf\{\mathcal{H}^{1}(\gamma) : \gamma \text{ is an arc in } \Sigma \text{ connecting } u \text{ and } v\}.$ 

The following statement regarding D(x, z) is valid.

PROPOSITION 7.2. Let  $\Sigma$  be a locally connected metric continuum consisting of more than one point and  $x \in \Sigma$ . Then for all  $z \in \Sigma$ ,  $z \neq x$  one has

- (i) D(x, z) is connected and  $x \in D(x, z)$ ;
- (ii)  $\Sigma \setminus D(x, z)$  is connected and closed.

Moreover, suppose that  $\Sigma$  satisfies  $\mathcal{H}^1(\Sigma) < +\infty$  and contains no simple closed curve (a homeomorphic image of  $S^1$ ). Then for every arc  $\gamma$  in  $\Sigma$  starting at x one has

- (iii)  $D(x, z_1) \subset D(x, z_2)$  and  $\mathcal{H}^1(D(x, z_1)) < \mathcal{H}^1(D(x, z_2))$  whenever  $z_1 \leq_{\gamma, x} z_2$ , while
- (iv)  $\cap_{\nu} D(x, z_{\nu}) = \{x\}$  whenever  $z_{\nu} \searrow_{\gamma} x$  as  $\nu \to \infty$  and x is an endpoint of  $\Sigma$ (*i.e.*  $ord_x \Sigma = 1$ ).

PROOF. The statement (i) is immediate from the definition of D(x, z). To show (ii), note first that  $z \notin D(x, z)$ . If  $\gamma' \subset \Sigma$  is an arc connecting  $y \in$  $\Sigma \setminus D(x, z)$  to z, then  $\gamma' \subset \Sigma \setminus D(x, z)$ . In fact, otherwise for some  $v \in \gamma'$ we would have  $v \in D(x, z)$ , which would mean the existence of some path  $\tilde{\gamma}$ connecting v to x such that  $z \notin \tilde{\gamma}$ . Let  $[y, v] \subset \gamma'$  stand for the path connecting y and v. Then  $[y, v] \circ \tilde{\gamma}$  would connect y to x without containing z, which contradicts the choice of y. Therefore,  $\Sigma \setminus D(x, z)$  is connected.

To complete the proof of (ii), we need to show that the latter set is closed. For this purpose consider an arbitrary sequence  $\{y_{\nu}\}_{\nu=1}^{\infty} \subset \Sigma \setminus D(x, z)$  such that  $y_{\nu} \to y \in \Sigma$  as  $\nu \to \infty$ . To prove  $y \notin D(x, z)$  suppose the contrary, namely that y is connected to x through some path  $\gamma \subset \Sigma$  satisfying  $z \notin \gamma$ . We may suppose  $y \neq z$  (otherwise there is nothing to prove since  $z \notin D(x, z)$ ). Let  $\varepsilon > 0$  be such that  $z \notin B_{\varepsilon}(y)$ . Since for all sufficiently large  $\nu \in \mathbb{N}$  one has  $y_{\nu} \in B_{\varepsilon}(y)$ , then by the local arcwise connectedness of  $\Sigma$  for each sufficiently large  $\nu$  there is an arc  $\gamma_{\nu}$  connecting  $y_{\nu}$  with y such that  $\gamma_{\nu} \subset \Sigma \cap B_{\varepsilon}(y)$ , hence  $z \notin \gamma_{\nu}$ . Since  $\gamma$  is also supposed not to touch z, then we conclude that  $y_{\nu}$  for all suffciently large  $\nu \in \mathbb{N}$  are connected to *x* through a path  $\gamma_{\nu} \circ \gamma \subset \Sigma$  which does not touch *z*, hence contradicting the assumption  $y_{\nu} \notin D(x, z)$  and concluding the proof of (ii).

To prove (iii), let  $\gamma$  be an arc in  $\Sigma$  passing through x and  $z_1 \leq_{\gamma,x} z_2$ . To show  $D(x, z_1) \subset D(x, z_2)$  consider an arbitrary  $y \in D(x, z_1)$ . We exploit extensively the fact that every two points in  $\Sigma$  are connected by a unique arc. Consider the arc  $\gamma'$  connecting x to y. The set  $\gamma \cap \gamma'$  is such that whenever  $v \in \gamma \cap \gamma'$  then also for all u satisfying either  $u <_{\gamma,x} v$  or  $u <_{\gamma',x} v$  one has  $u \in \gamma \cap \gamma'$  (otherwise there would be a couple of points which can be connected by different arcs). Hence,  $\gamma \cap \gamma'$  is either the point x or an arc  $[x, y'] \subset \gamma$ . Obviously,  $y' <_{\gamma,x} z_1$  for some  $z \in \gamma$ , since otherwise we would have  $y \notin D(x, z_1)$  contrary to our assumption. Hence  $y' <_{\gamma,x} z_2$ , and therefore  $z_2 \notin \gamma'$ , which means  $y \in D(x, z_2)$ . In view of arbitrarity of y we have shown therefore that  $D(x, z_1) \subset D(x, z_2)$ .

Let now  $\Delta := [z_1, z_2]$ . Clearly,  $\Delta \subset \gamma$  since every two points are connected by a unique arc, i.e.  $\Delta$  is a piece of  $\gamma$  between  $z_1$  and  $z_2$ . We show that  $\Delta \subset D(x, z_2) \setminus D(x, z_1)$ , which will imply (iii) since  $\mathcal{H}^1(\Delta) > 0$ . To this aim consider an arbitrary  $z \in \Delta$ . Clearly,  $z \in D(x, z_2)$ . To show  $z \notin D(x, z_1)$ , suppose the opposite, namely that z is connected to x through an arc  $\gamma_1$  in  $\Sigma$ such that  $z_1 \notin \gamma_1$ . This comes in contradiction with the fact that z cannot be connected to x by two different arcs.

At last, to show (iv), assume that  $x \in \Sigma$  is an endpoint and  $z_{\nu} \searrow_{\gamma} x$  as  $\nu \to \infty$ . Suppose the contrary, namely that there is an  $y \in \bigcap_{\nu} D(x, z_{\nu}), y \neq x$ . Let  $\gamma' := [x, y]$  (mind that such an arc is uniquely defined). But  $\gamma \cap \gamma' \neq \{x\}$ , since in this case  $\operatorname{ord}_x \Sigma \ge 2$ . Hence the latter intersection is an arc, namely,  $\gamma \cap \gamma' = [x, y']$  for some  $y' \in \gamma$ . But this implies  $y \notin D(x, z_{\nu})$  for all  $\nu \in \mathbb{N}$  such that  $z_{\nu} \le_{\gamma, x} y'$ , contradicting the assumption.

It might be curious to note that Proposition 7.2 provides an alternative construction to that suggested by Lemma 6.1. In fact, suppose that  $\Sigma$  contains no simple closed curve,  $x \in \Sigma$  be an endpoint and  $\gamma$  be an arc in  $\Sigma$  starting at x. One might set then  $D_{\nu} := D(x, z_{\nu})$  for an arbitrarily chosen sequence  $\{z_{\nu}\}_{\nu=1}^{\omega} \subset \gamma$  satisfying  $z_{\nu} \searrow_{\gamma} x$  as  $\nu \to \infty$ . The sets  $D_{\nu}$  will then according to Proposition 7.2 satisfy all the conditions of Lemma 6.1. However, it is important to emphasize that the assertions (iii) and (iv) of Proposition 7.2 are only true when  $\Sigma$  contains no simple closed curve (in fact, this has been used essentially in the proof). If  $\Sigma$  contained loops then both assertions could be false: e.g. (iii) does not hold for  $\Sigma = S^1$ , since in this case  $D(x, z) = \Sigma \setminus \{z\}$  for all  $z \in \Sigma \setminus \{x\}$ .

We need now the following lemmata regarding the optimal set  $\Sigma_{opt}$ .

LEMMA 7.2. Let  $\{x_{\nu}\}_{\nu=1}^{\infty} \subset \Sigma_{opt}$  be any sequence of noncut points, and  $\{z_{\nu}\}_{\nu=1}^{\infty} \subset \Sigma_{opt}$  be such that

$$\varepsilon_{\nu} := \operatorname{diam} D(x_{\nu}, z_{\nu}) \to 0$$

as  $v \to \infty$ . Then for every  $\sigma > (n-1)/2$  one has

$$\lim_{\nu\to\infty}\frac{\psi(D(x_{\nu},z_{\nu}))}{\varepsilon_{\nu}^{\sigma}}=+\infty.$$

PROOF. Up to passing to a subsequence (not relabeled), we assume that  $x_{\nu} \to x \in \Sigma_{opt}$ . We abbreviate  $D_{\nu} := D(x_{\nu}, z_{\nu})$ , while  $\varepsilon_{\nu}$  will, as usual, be further denoted by  $\varepsilon$  omitting the index  $\nu$  for brevity. Set  $\Sigma_{\varepsilon} := \Sigma_{opt} \setminus D_{\nu}$  and note that the  $\Sigma_{\varepsilon}$  is still closed and connected in view of Proposition 7.2. Moreover, one has

(20) 
$$\int_{\bar{\Omega}} \operatorname{dist}(z, \Sigma_{\varepsilon}) \, d\varphi_s(z) \leq \int_{\bar{\Omega}} \operatorname{dist}(z, \Sigma_{opt}) \, d\varphi_s(z) + \varepsilon \psi(D_{\nu}).$$

Observe now that there is a r > 0 such that

$$\psi(\Omega) > \psi(B_r(x)).$$

In fact, otherwise one would have  $\psi(\bar{\Omega}) = \psi(B_r(x))$  for all r > 0, and hence, taking a limit in the latter relationship as  $r \to 0$ ,  $\psi(\bar{\Omega}) = \psi(\{x\})$ , which means that the one-point set  $\{x\}$  would be optimal, contradicting Theorem 5.1. Lemma 5.2 is then applicable with  $B := \bar{\Omega} \setminus B_r(x)$ ,  $\Sigma_{\nu} := \Sigma_{\varepsilon}$  and  $\varphi := \varphi_s$ . In fact,  $\Sigma_{\varepsilon} \cap B = \Sigma_{opt} \cap B$  for all sufficiently large  $\nu$ , while  $k^{-1}(\Sigma_{opt} \cap B) \subset T'$ and hence

$$\varphi_s(T') = \psi(B) = \psi(\Omega) - \psi(B_r(x)) > 0.$$

Hence, Lemma 5.2 asserts the existence of a new  $\Sigma'_{\varepsilon}$  such that

$$\mathcal{H}^{1}(\Sigma_{\varepsilon}') = \mathcal{H}^{1}(\Sigma_{\varepsilon}) + \mathcal{H}^{1}(D_{\nu}) = \mathcal{H}^{1}(\Sigma_{opt})$$

and

$$\int_{\bar{\Omega}} \operatorname{dist}(z, \Sigma_{\varepsilon}') \, d\varphi_s(z) \leq \int_{\bar{\Omega}} \operatorname{dist}(z, \Sigma_{\varepsilon}) \, d\varphi_s(z) - C \varepsilon^{(n+1)/2},$$

for some C > 0 independent of  $\nu$  as  $\varepsilon > 0$  is small enough (also independently of  $\nu$ ). We now argue by contradiction. Supposing the contrary, we get

$$\varepsilon\psi(D_{\nu}) = o(\varepsilon^{(n+1)/2})$$

for some subsequence of  $\nu$  (not relabeled). Together with (20) and Lemma 4.1 this gives

$$MK(\varphi^+, \varphi^-, \Sigma_{\varepsilon}') < MK(\varphi^+, \varphi^-, \Sigma_{opt})$$

for sufficiently small  $\varepsilon$  contradicting the optimality of  $\Sigma_{opt}$ .

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LEMMA 7.3. Let  $\varphi^{\pm} \in L^{p}(\Omega)$ , p > 2n/(n + 1), and  $x \in \Sigma_{opt}$  be an endpoint, while  $\gamma$  be an injective arc in  $\Sigma$  starting at x. Then there is a  $\sigma > 1$  such that  $(n - 1)p'\sigma/2n < 1$  and for all  $z \in \gamma$  the set of  $y \in D(x, z)$  for which there is a  $z' \in \gamma$  such that  $y \in D(x, z')$  and

$$l_{y} \ge \left(\mathcal{H}^{1}(D(x, z'))\right)^{(n-1)p'\sigma/2n},$$

where  $l_y$  stands for the maximum length of transport rays of  $MK(\varphi_s, \psi)$  which end in y, has positive measure  $\psi$ .

PROOF. Due to our assumption on p one has p' < 2n/(n-1) and hence, there is a  $\sigma > 1$  such that  $(n-1)p'\sigma/2n < 1$ . Suppose that the statement of the lemma is not valid with this  $\sigma$ , namely, that there is a  $z \in \gamma$  such that  $\psi(B_z) = \psi(D(x, z))$ , where

$$B_{z} := \{ y \in D(x, z) : l_{y} < (\mathcal{H}^{1}(D(x, z')))^{(n-1)p'\sigma/2n} \text{ for all } z' \in \gamma, y \in D(x, z') \}.$$

Let  $z' \in \gamma$  be an arbitrary point with  $z' \in D(x, z)$  and let  $y \in B_z$  and be an arbitrary point satisfying  $y \in D(x, z')$  (which exists due to our assumption). For the sake of brevity we denote  $\varepsilon := \mathcal{H}^1(D(x, z'))$ . Note that due to the arbitrarity of the choice of z' we can make  $\varepsilon$  as small as necessary. Consider an arbitrary v such that k(v) = y (in other words, v belongs to a closure of some transport ray of  $MK(\varphi_s, \psi)$  which ends in y). Then

$$|v - z'| \le |v - y| + |y - z'| \le l_y + \varepsilon < \varepsilon^{(n-1)p'\sigma/2n} + \varepsilon.$$

Observe that one has  $(n-1)p'\sigma/2n < 1$  and hence, if  $\varepsilon$  is sufficiently small, the above estimate implies  $|v - z'| < 2\varepsilon^{(n-1)p'\sigma/2n}$ . Therefore

$$\psi(D(x, z')) = \psi(D(x, z') \cap B_z)$$
  
=  $\varphi_s(\{v : k(v) \in D(x, z') \cap B_z\})$   
 $\leq \varphi_s(B_{2\varepsilon^{(n-1)p'\sigma/2n}}(z'))$ 

and applying to the latter expression the Hölder inequality one gets

$$\psi(D(x, z')) \leq C ||\varphi_s||_p \varepsilon^{(n-1)\sigma/2}$$

for some C > 0, which contradicts Lemma 7.2, hence concluding the proof.  $\Box$ 

At last, we provide also the following construction which is specific to a two-dimensional case, i.e. n = 2. Let  $T_s \subset \overline{\Omega}$  stand for the transport set (i.e. the union of transport rays without ray ends) of the Monge-Kantorovich problem  $MK(\varphi_s, \psi)$  and set

$$T_s^+ := \{ x \in T_s : \pi_1(x) > \pi_1(k(x)) \text{ or } \pi_1(x) = \pi_1(k(x)), \ \pi_2(x) > \pi_2(k(x)) \}, \\ T_s^- := T_s \setminus T_s^+,$$

where  $\pi_i: \mathbb{R}^2 \to \mathbb{R}$ , i = 1, 2, stand for projections on the first and second coordinate axis respectively, i.e.  $\pi_i(x_1, x_2) := x_i$ , i = 1, 2, while k(x) stands for the projection of x onto  $\Sigma_{opt}$  (note that for  $x \in T_s$  such a projection is uniquely defined). Define then new Borel measures  $\psi_{\pm}$  by setting  $\psi_{\pm}(e) := k_{\#}\varphi_s \sqcup T_s^{\pm}$ , i.e.

$$\psi_{\pm}(e) = \varphi_s(k^{-1}(e) \cap T_s^{\pm})$$

for all Borel sets  $e \subset \overline{\Omega}$ . Let  $y \in \Sigma_{opt}$  be such a lower endpoint of some transport ray of  $MK(\varphi_s, \psi)$  that all the transport rays ending at y belong to the same line l. Let then  $\theta(x) \in [0, \pi/2]$  stand for the angle between l and  $e_2$ , where  $e_2$  stands for the second unit coordinate vector.

LEMMA 7.4. Assume n = 2. Let  $x \in \Sigma_{opt}$  be a noncut point and  $D \subset \overline{\Omega}$  be such an open set that  $\theta(y)$  is well defined for  $\psi$ -a.e.  $y \in \Sigma_{opt} \cap D$ , while  $x \notin D$ and  $\psi^+(D) \ge \psi^-(D)$ . Then for every  $f \in C_0^1(D)$  one has

$$\int_D f \sin \theta \, d(\psi^+ - \psi^-) \le \psi(\{x\}).$$

PROOF. As in the proof of Proposition 7.1, let  $\{D_{\nu}\}_{\nu\in\mathbb{N}}$  stand for the decreasing sequence of subsets of  $\Sigma_{opt}$  indicated by Lemma 6.1, with  $x \in D_{\nu}$ . We also suppose  $\varepsilon_{\nu} := \operatorname{diam} D_{\nu}$  (denoted further  $\varepsilon$  omitting the index  $\nu$  for brevity) to be small enough so that  $D_{\nu} \cap D = \emptyset$  for all  $\nu \in \mathbb{N}$ . Let  $\Sigma_{\varepsilon} := \Sigma_{opt} \setminus D_{\nu}$ . Then

$$\int_{\bar{\Omega}} \operatorname{dist}(z, \Sigma_{\varepsilon}) \, d\varphi_s(z) \leq \int_{\bar{\Omega}} \operatorname{dist}(z, \Sigma_{opt}) \, d\varphi_s(z) + \varepsilon \psi(D_{\nu}).$$

We further assume without loss of generality, referring to Proposition 5.1, that  $\Omega$  is large enough so as to satisfy

$$\overline{\operatorname{co}}\,(\operatorname{supp}\varphi^+\cup\operatorname{supp}\varphi^-)\subset\subset\Omega.$$

Now consider an arbitrary positive smooth function  $f \in C_0^1(D)$  and define a diffeomorphism  $\Phi_{\delta}: \overline{\Omega} \to \overline{\Omega}$  by the formula

$$\Phi_{\delta}(x_1, x_2) := (x_1 - \delta f(x_1, x_2), x_2),$$

for all sufficiently small  $\delta > 0$ . Then

$$\mathcal{H}^1(\Phi_{\delta}(\Sigma_{\varepsilon})) \leq \mathcal{H}^1(\Sigma_{\varepsilon}) + C_f \delta$$

for some constant  $C_f > 0$  depending on f. We choose  $\delta := \varepsilon/C_f$ . With this choice one has for  $\Sigma'_{\varepsilon} := \Phi_{\delta}(\Sigma_{\varepsilon})$  the estimate

$$\mathcal{H}^{1}(\Sigma_{\varepsilon}') \leq \mathcal{H}^{1}(\Sigma_{\varepsilon}) + C_{f}\delta \leq \mathcal{H}^{1}(\Sigma_{opt}) - \varepsilon + C_{f}\delta = \mathcal{H}^{1}(\Sigma_{opt}),$$

because  $\mathcal{H}^1(D_\nu) \geq \varepsilon$ . It follows that  $\Sigma'_{\varepsilon}$  satisfies the length constraint and is closed and connected, while

$$\begin{split} \int_{\bar{\Omega}} \operatorname{dist}(z,\,\Sigma_{\varepsilon}')\,d\varphi_{s}(z) &\leq \int_{\bar{\Omega}} \operatorname{dist}(z,\,\Sigma_{\varepsilon}')\,d\varphi_{s}(z) - C\varepsilon + o(\varepsilon) \\ &\leq \int_{\bar{\Omega}} \operatorname{dist}(z,\,\Sigma_{opt})\,d\varphi_{s}(z) - C\varepsilon + o(\varepsilon) + \varepsilon\psi(D_{\nu}), \end{split}$$

where

$$C := \int_D f \sin \theta \, d(\psi_- - \psi_+).$$

Using Lemma 4.1, we obtain thus

$$MK(\varphi^+, \varphi^-, \Sigma_{\varepsilon}') \leq MK(\varphi^+, \varphi^-, \Sigma_{opt}) + C\varepsilon + o(\varepsilon) + \varepsilon \psi(D_{\nu}).$$

In order not ho have a contradiction with the optimality of  $\Sigma_{opt}$  for sufficiently small  $\varepsilon$ , the relationship  $C \leq \psi(D_{\nu})$  has to be satisfied. Taking a limit in the latter when  $\nu \to \infty$ , we obtain the desired conlusion.

We are now finally in a position to prove Lemma 7.1.

PROOF OF LEMMA 7.1: Suppose the opposite, namely,  $\psi({x}) = 0$  for all  $x \in \Sigma_{opt}$ . We will then achieve a contradiction in several steps.

STEP 1. PREPARATORY CONSTRUCTIONS. Observe that the assumption on  $\psi$  implies that  $\theta$  is defined  $\psi$ -a.e. In fact, the set *E* where  $\theta$  is undefined can be decomposed as follows:

$$E := E_0 \cup E_1,$$

where  $E_0$  stands for the set of points of  $\Sigma_{opt}$  which are not endpoints of transport rays of nonzero length, while  $E_1$  stands for the set of those points of  $\Sigma_{opt}$  which are endpoints of several noncollinear transport rays of positive length. Clearly, then

$$\psi(E_0) = \varphi_s(E_0) \le \varphi_s(\Sigma_{opt}) = 0,$$

while the set  $E_1$  is at most countable, and hence the assumption  $\psi(\{y\}) = 0$  for all  $y \in \Sigma_{opt}$  implies also  $\psi(E_1) = 0$ .

We claim now

$$\psi_+ = \psi_-$$

In fact, Lemma 7.4 together with the assumption on  $\psi$  implies  $\psi_{\theta,+}(e) = \psi_{\theta,-}(e)$  for all Borel  $e \subset \Sigma_{opt}$ , where  $\psi_{\theta,\pm} := \sin \theta \cdot \psi_{\pm}$ . This means

$$\psi_+(e \cap \{\theta \neq 0\}) = \psi_-(e \cap \{\theta \neq 0\})$$

and exchanging the coordinate axes we prove the above claim.

STEP 2. Fix an arbitrary endpoint  $x \in \Sigma_{opt}$  and an arbitrary  $z \in \Sigma_{opt}$ . Since  $\theta$  is defined  $\psi$ -a.e. over D(x, z), we may apply now Lemma 7.3 and mind

 $\psi^+ = \psi^-$ , thus concluding that for a set of  $y \in D(x, z)$  of positive measure  $\psi$  the angle  $\theta(y)$  is defined and, moreover, y is an endpoint of exactly two transport rays  $R_y^+ \subset T_s^+$  and  $R_y^- \subset T_s^-$  belonging to the same line l, which satisfy

$$l_{v}^{\pm} \geq (\mathcal{H}^{1}(D(x,z)))^{p'\sigma/4}$$

for some  $\sigma > 1$ , where  $l_y^{\pm} := \mathcal{H}^1(R_y^{\pm})$ , while  $p'\sigma/4 < 1$ . Denote  $C_z$  the set of such  $y \in D(x, z)$ . We claim now that  $\psi$ -a.e.  $y \in C_z$  are not endpoints of  $\Sigma_{opt}$ , once  $\mathcal{H}^1(D(x, z))$  is sufficiently small.

To prove this claim, denote

$$C(y') := \{ y \in D(x, z) \text{ endpoint } : [x, y] \cap [x, z] = [x, y'] \}$$

for every branching point  $y' \in [x, z]$ . One clearly has then that every endpoint  $y \in D(x, z)$  belongs to some C(y') for some  $y' \in [x, z]$ , and, moreover,  $C(y'_1) \cap C(y'_2) = \emptyset$  whenever  $y'_1 \neq y'_2$  (otherwise  $\Sigma_{opt}$  would contain a simple closed curve). The claim will be proven, if we show that

(21) 
$$\#\{y \in C(y') : l_y^{\pm} \ge (\mathcal{H}^1(D(x, z')))^{p'\sigma/4}$$
for some  $z' \in [x, z], y \in D(x, z')\} \le 1$ 

provided z is sufficiently close to x. In fact, in view of Theorem VI.7 from [10, Section 51], the set of branching points of  $\Sigma_{opt}$  is at most countable, since  $\Sigma_{opt}$  contains no simple closed curve. This, together with (21) implies that the set  $C_z^{end}$  of endpoints belogning to  $C_z$  is at most countable and hence, due to the assumption on  $\psi$ , one has  $\psi(C_z^{end}) = 0$ . We concentrate therefore on proving (21).

Denote

$$\delta(y) := \inf\{\mathcal{H}^1(D(x, z')) : z' \in [x, z], y \in D(x, z')\}.$$

It is easy to observe that if  $y \in C(y')$ , then

$$\delta(y) := \inf\{\mathcal{H}^1(D(x, z')) : y' <_{\gamma, x} z' \in [x, z]\},\$$

and therefore for all  $y \in C(y')$  one has  $\delta(y) = const$ . We denote the value of the latter constant still  $\delta$ . Let  $y_1 \in C(y') \cap C_z$ . Without loss of generality we consider the origin of the coordinate system to coincide with  $y_1$  and the coordinate axis  $x_1$  to coincide with the line containing the transport rays  $R_{y_1}^{\pm}$ . Then

$$\Sigma_{opt} \cap (B_{\delta^{p'\sigma/4}}((0,\delta^{p'\sigma/4})) \cup B_{\delta^{p'\sigma/4}}((0,-\delta^{p'\sigma/4}))) = \emptyset.$$

Let  $z' \ge_{\gamma,x} y'$  be such that  $\mathcal{H}^1(D(x,z')) \le 2\delta$ . Then for all  $\xi \in D(x,z')$  one has

$$|\xi - y_1| \le \operatorname{diam} D(x, z') \le \mathcal{H}^1(D(x, z')) \le 2\delta,$$

and hence  $D(x, z') \subset B_{2\delta}(y_1)$ .

We assume that z is close enough to y so that  $\delta \leq \mathcal{H}^1(D(x, z))$  be as small as necessary, in particular,  $\delta^{p'\sigma/4} >> 2\delta$  due to our original assumption on p. Also we suppose without loss of generality that x belongs to a lower semiplane  $\{x_2 < 0\}$ , which implies then  $D(x, z') \subset \{x_2 < 0\}$ . In fact, if there were some  $y \in D(x, z')$  belonging to the upper semiplane, then the arc [x, y]would necessarily pass through  $y_1$ , since it has to stay in  $B_{2\delta}(y_1)$  but outside of  $B_{sp'\sigma/4}((\pm \delta^{p'\sigma/4}, 0))$ , and hence  $y_1$  clearly would not be an endpoint of  $\Sigma_{opt}$ .

Suppose that there is another  $y_2 \in C(y') \cap C_z$ ,  $y_2 \neq y_1$ . Then  $\Sigma_{opt}$  must be also outside of the pair of balls with radii  $\delta^{p'\sigma/4}$  centered at  $R_{y_2}^+$  and at  $R_{y_2}^$ respectively and touching  $y_2$ . Now observe that since  $y_2 \in B_{2\delta}(y_1)$  then x must be inside the region bounded by thick arcs on Figure 5. In fact, otherwise, the arc  $[x, y_1]$  would necessarily pass through  $y_2$  contradicting the fact that the latter is an endpoint. But then all  $\Sigma_{opt}$  must belong to this region, because if there were at least one point  $x' \in \Sigma_{opt}$  outside of this region, then [x, x'] would have to pass either through  $y_1$  or through  $y_2$  contradicting the assumption that the latter be endpoints. It is now enough to note that the diameter of this region cannot exceed  $2\delta$ , and hence, diam  $\Sigma_{opt} \leq \delta$ . Letting  $z \searrow_{\gamma} x$  one has  $\delta \to 0$ and therefore diam  $\Sigma_{opt} = 0$  which means that  $\Sigma_{opt}$  consists of just one point, contradicting Theorem 5.1. The latter contradiction completes the proof of the claim.

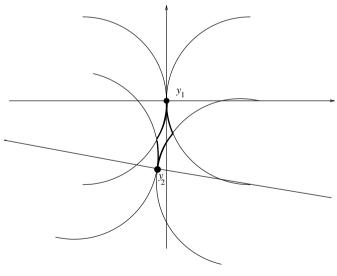


Fig. 5.

STEP 3. Let  $x \in \Sigma_{opt}$  be an endpoint,  $\gamma$  be an arc in  $\Sigma_{opt}$  starting at x. Using the result of Step 2, we deduce that for any sequence  $\{z'_{\nu}\}_{\nu=1}^{\infty} \subset \gamma$  with  $z'_{\nu} \searrow_{\gamma} x$  there is a sequence  $\{y_{\nu}\}_{\nu=1}^{\infty}$  satisfying

- (i)  $y_{\nu} \in D(x, z'_{\nu})$  and are not endpoints of  $\Sigma_{opt}$ ,
- (ii)  $\theta(y_v)$  is defined and, moreover,  $y_v$  is an endpoint of exactly two transport rays belonging to the same line  $l_v$ , both starting from outside of  $B_{r_v}(y_v)$ ,

where

(22) 
$$r_{\nu} := \left(\mathcal{H}^1(D(x, z'_{\nu}))\right)^{p'\sigma/4}.$$

Then for every  $\nu \in \mathbb{N}$  there is an endpoint  $x_{\nu}$  of  $\Sigma_{opt}$  such that  $D(x_{\nu}, y_{\nu}) \subset D(x, z'_{\nu})$ . In fact, either  $y_{\nu} \in \gamma$ , in which case we can take  $x_{\nu} := x$ , or  $y_{\nu} \notin \gamma$ . In the latter case  $\gamma \cap [x, y_{\nu}] = [x, y'_{\nu}]$  for some  $y'_{\nu} <_{\gamma,x} z'_{\nu}$ , and we may take for  $x_{\nu}$  any of the endpoints of  $\Sigma_{opt}$  belonging to  $D(y_{\nu}, y'_{\nu})$ .

We further abbreviate then  $D_{\nu} := D(x_{\nu}, y_{\nu})$  and  $\varepsilon_{\nu} := \text{diam } D_{\nu}$ , omitting the index  $\nu$  for brevity whenever it cannot cause misunderstanding. Note that

$$\varepsilon_{\nu} = \operatorname{diam} D_{\nu} \leq \mathcal{H}^{1}(D_{\nu}) \leq \mathcal{H}^{1}(D(x, z'_{\nu})) \rightarrow 0$$

as  $\nu \to \infty$ . Without loss of generality we consider the system of cartesian coordinates to be situated as follows: the coordinate axis  $x_1$  coincides with  $l_{\nu}$ , while the origin coincides with  $y_{\nu}$ . Let

$$r_{\varepsilon} := \varepsilon_{\nu}^{p'\sigma/4} \le r_{\nu}$$

and consider then the points  $P_{\varepsilon}^{\pm} := (\pm r_{\varepsilon}, 0)$ . Clearly then

$$\Sigma_{opt} \cap (B_{r_{\varepsilon}}(P_{\varepsilon}^{+}) \cup B_{r_{\varepsilon}}(P_{\varepsilon}^{-})) = \emptyset,$$

while  $D_{\nu} \subset B_{\varepsilon}(y_{\nu})$ , and hence

$$D_{\nu} \subset B_{\varepsilon}(y_{\nu}) \setminus (B_{r_{\varepsilon}}(P_{\varepsilon}^{+}) \cup B_{r_{\varepsilon}}(P_{\varepsilon}^{-})).$$

Without loss of generality we assume  $D_{\nu}$  to be situated in the semiplane { $x_2 < 0$ }. Consider the points  $A_{\varepsilon}^{\pm}$  defined by

$$A_{\varepsilon}^{\pm} := \partial B_{\varepsilon}(y_{\nu}) \cap \partial B_{r_{\varepsilon}}(P_{\varepsilon}^{\pm}) \cap Q^{\pm},$$

where  $Q^+$  and  $Q^-$  are the fourth and third quadrants (coordinate angles) respectively. Then  $D_{\nu}$  belongs to the curvilinear triangle with "vertices"  $y_{\nu}$ ,  $A_{\varepsilon}^+$  and  $A_{\varepsilon}^-$  (see Figure 6).

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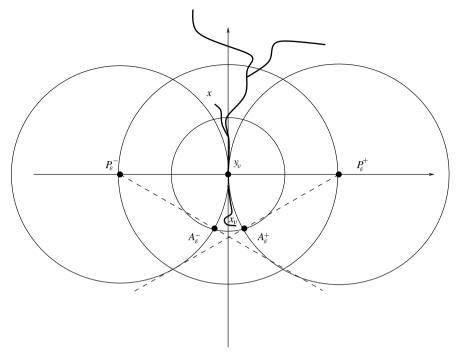


Fig. 6. The original set  $\Sigma_{opt}$ .

A direct calculation shows

$$A_{\varepsilon}^{\pm} = (\pm \varepsilon^2 / 2r_{\varepsilon}, \varepsilon \sqrt{1 - \varepsilon^2 / 4r_{\varepsilon}^2}) = (o(\varepsilon), \varepsilon + o(\varepsilon))$$

due to the choice of  $r_{\varepsilon}$  and to the assumption on p. Let  $R^{\pm}$  stand for the rays starting at  $P_{\varepsilon}^{\pm}$  and passing through  $A_{\varepsilon}^{\pm}$ , while  $C_{\varepsilon}^{\pm}$  stand for the cones with vertices  $P_{\varepsilon}^{\pm}$  and formed by the  $x_1$  axis and the rays  $R^{\pm}$ . Let also

$$D_{\varepsilon}^{\pm} := C_{\varepsilon}^{\pm} \setminus B_{r_{\varepsilon}}(y_{\nu}) \text{ and } D_{\varepsilon}^{0} := \{x_{2} < 0\} \setminus (D_{\varepsilon}^{+} \cup D_{\varepsilon}^{-} \cup B_{r_{\varepsilon}}(y_{\nu})).$$

Define the new measures  $\varphi_s^{\varepsilon}$ ,  $\varphi_{s,\pm}^{\varepsilon}$  by the relationships

$$\varphi_{s,\pm}^{\varepsilon} := \varphi_s \ \bigsqcup(k^{-1}(D_{\nu}) \cap T_s^{\pm}), \qquad \qquad \varphi_s^{\varepsilon} := \varphi_{s,\pm}^{\varepsilon} + \varphi_{s,-}^{\varepsilon} = \varphi_s \ \bigsqcup k^{-1}(D_{\nu})$$

(we recall in fact that  $\varphi_s$  is assumed to be concentrated over the set  $T_s$  where k is injective). Disintegrating the measures  $\varphi^{\varepsilon}_{s,\pm},$  we get

$$\varphi_{s,\pm}^{\varepsilon}(e) = \int_{D_{v}} \varphi_{s,\pm}^{\varepsilon\prime}(t,e) \, d\psi_{\pm}(t),$$

where the Borel probability valued function  $t \in D_{\nu} \mapsto \varphi_{s,\pm}^{\varepsilon'}(t, \cdot)$  is measurable and the probability measures  $\varphi_{s,\pm}^{\varepsilon'}(t, \cdot)$  are concentrated on  $k^{-1}(t) \cap T_s^{\pm}$  for  $\psi_{\pm}$ a.e., and hence, in view of the result of Step 1, for  $\psi$ -a.e.  $t \in D_{\nu}$ . We note then

(23) 
$$\varphi_s^{\varepsilon}(D_{\varepsilon}^0) \leq \varphi_s^{\varepsilon}(B_{r_{\varepsilon}}(y_{\nu})).$$

In fact, for  $\psi$ -a.e.  $t \in D_{\nu}$  the set  $k^{-1}(t)$  is contained in a line which we will denote by  $l_t$ . It is easy to observe that if  $l_t$  passes through  $D_{\varepsilon}^0$ , then either of the rays  $l_t^{\pm} := l_t \cap T_s^{\pm}$  intersects the horizontal segment  $(P_{\varepsilon}^-, P_{\varepsilon}^+)$ . Suppose, without loss of generality, that  $l_t^+ \cap (P_{\varepsilon}^-, y_{\nu}] \neq \emptyset$  (the case  $l_t^- \cap [y_{\nu}, P_{\varepsilon}^+)$  is completely symmetric). Then  $k^{-1}(t) \cap T_s^+ \subset (P_t, t)$ , where  $\{P_t\} := l_t^+ \cap (P_{\varepsilon}^-, y_{\nu}]$ . Since  $\varphi_{s,\pm}^{\varepsilon'}(t, \cdot)$  are concentrated on  $l_t^{\pm}$ , then

$$1 = \varphi_{s,+}^{\varepsilon'}(t, l_t^+) = \varphi_{s,+}^{\varepsilon'}(t, (T_t, t)) = \varphi_{s,+}^{\varepsilon'}(t, B_{r_{\varepsilon}}(y_{\nu})),$$

while

$$1 = \varphi_{s,-}^{\varepsilon'}(t, l_t^-) = \varphi_{s,-}^{\varepsilon'}(t, B_{r_{\varepsilon}}(y_{\nu})) + \varphi_{s,-}^{\varepsilon'}(t, D_{\varepsilon}^0),$$

and hence  $\varphi_{s,-}^{\varepsilon'}(t, D_{\varepsilon}^0) \leq \varphi_{s,+}^{\varepsilon'}(t, B_{r_{\varepsilon}}(y_{\nu}))$ . The latter implies

$$\varphi_{s,-}^{\varepsilon}(D_{\varepsilon}^{0}) \leq \varphi_{s,+}^{\varepsilon}(B_{r_{\varepsilon}}(y_{\nu}))$$

and, by a symmetric argument,  $\varphi_{s,+}^{\varepsilon}(D_{\varepsilon}^{0}) \leq \varphi_{s,-}^{\varepsilon}(B_{r_{\varepsilon}}(y_{\nu}))$ , which together imply (23).

We also remark for further use that (22) implies in view of Lemma 7.2 and the Hölder inequality that

(24) 
$$\varphi_s^{\varepsilon}(B_{r_{\varepsilon}}(y_{\nu})) \le \varphi_s(B_{r_{\varepsilon}}(y_{\nu})) \le C ||\varphi_s||_p \varepsilon^{\sigma/2} \le \beta \psi(D_{\nu})$$

for  $\beta < 1/10$  and for sufficiently large  $\nu$  (i.e. for sufficiently small  $\varepsilon > 0$ ).

We now construct a new set  $\Sigma_{\varepsilon}$  in the following way: we cut from  $\Sigma_{opt}$  the set  $D_{\nu}$  and add a segment  $I_{\varepsilon}$  centered at  $y_{\nu}$  along the  $x_1$  axis and having length  $\varepsilon$  (see figure 7).

The respective set is still closed, connected and satisfies the length constraint, since  $\mathcal{H}^1(D_v) \ge \varepsilon$ . Observe now that

$$\operatorname{dist}(z, \Sigma_{\varepsilon}) \leq \operatorname{dist}(z, \Sigma_{opt}) + \varepsilon$$

for all  $z \in \overline{\Omega}$ . On the other hand, it is a matter of straightforward though tedious calculation that

$$\operatorname{dist}(z, \Sigma_{\varepsilon}) = d(z, z_{\varepsilon}^{\pm}) \leq \operatorname{dist}(z, D_{\nu}) - \varepsilon/4$$

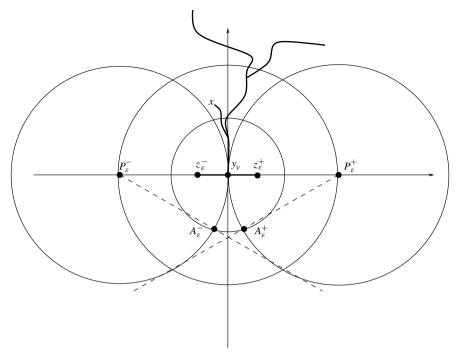


Fig. 7. The modified set  $\Sigma_{\varepsilon}$ .

for all  $z \in D^+_{\varepsilon} \cup D^-_{\varepsilon}$ , where  $z^{\pm}_{\varepsilon}$  are the endpoints of  $I_{\varepsilon}$  in  $Q^+$  and  $Q^-$  respectively. Therefore

$$\int_{\bar{\Omega}} \operatorname{dist}(z, \Sigma_{\varepsilon}) \, d\varphi_s(z) \leq \int_{\bar{\Omega}} \operatorname{dist}(z, \Sigma_{opt}) \, d\varphi_s(z) + \varepsilon \varphi_s^{\varepsilon}(D_{\varepsilon}^0 \cup B_{r_{\varepsilon}}(y_{\nu})) \\ - \varepsilon \varphi_s^{\varepsilon}(D_{\varepsilon}^+ \cup D_{\varepsilon}^-)/4.$$

But

$$\varphi_s^{\varepsilon}(D_{\varepsilon}^+ \cup D_{\varepsilon}^-) + \varphi_s^{\varepsilon}(D_{\varepsilon}^0 \cup B_{r_{\varepsilon}}(y_{\nu})) = \psi(D_{\nu})$$

and with the help of (23) and (24) minding  $\beta < 1/10$  we get

$$\int_{\bar{\Omega}} \operatorname{dist}(z, \Sigma_{\varepsilon}) \, d\varphi_s(z) < \int_{\bar{\Omega}} \operatorname{dist}(z, \Sigma_{opt}) \, d\varphi_s(z).$$

The proof for this case is then concluded since the latter estimate together with Lemma 4.1 gives  $MK(\varphi^+, \varphi^-, \Sigma_{\varepsilon}) < MK(\varphi^+, \varphi^-, \Sigma_{opt})$  for sufficiently small  $\varepsilon$  contradicting the optimality of  $\Sigma_{opt}$ .

## 8. – Branching points

The following result regarding branching points of the optimal set  $\Sigma_{opt}$  is valid.

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THEOREM 8.1. Let n = 2,  $\varphi^{\pm} \in L^p(\Omega)$ , p > 4/3 and  $\varphi^+ \neq \varphi^-$ . Then

- (i) if x is a branching point of Σ<sub>opt</sub>, then ord<sub>x</sub>Σ<sub>opt</sub> = 3 (in other words, all the branching points of Σ<sub>opt</sub> have order three);
- (ii) the number of branching points of  $\Sigma_{opt}$  is at most finite;

In particular,  $\Sigma_{opt}$  is a union of a finite number of simple curves connected by at most finite number of branching points.

Before proving the theorem, we introduce another auxiliary notion which will be used both in the proof of the above theorem and further in the sequel. For a finite set of points  $N \subset \partial B_r(x)$  we call its *centered Steiner connection* the set St(N, x, r) providing the minimum for the length functional

$$\Sigma \mapsto \mathcal{H}^1(\Sigma)$$

among all closed connected  $\Sigma \subset \overline{B}_r(x)$  which satisfy  $N \cup \{x\} \subset \Sigma$  (the existence of such a set is trivial). The following simple assertion is valid.

LEMMA 8.1. Let  $N = \{a, b\} \subset \partial B_1(0)$ , while the minimum arc of  $\partial B_1(0)$  between a and b has angle  $\gamma < 2\pi/3$ . Then

$$\mathcal{H}^{1}(St(N, 0, 1)) \le 2\sin(\gamma/2 + \pi/6).$$

PROOF. It is enough to observe that due to the definition

$$\mathcal{H}^{1}(St(N, 0, 1)) \leq \mathcal{H}^{1}(\Sigma),$$

where  $\Sigma$  stands for the union of three segments connecting *a*, *b* and *O* and having angle  $2\pi/3$  with each other (see Figure 8) and the result follows by a direct calculation of  $\mathcal{H}^1(\Sigma)$ .

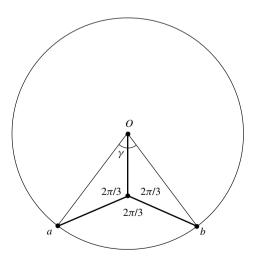


Fig. 8. The set  $\Sigma$  constructed in the proof of lemma (thick lines).

We are able now to prove Theorem 8.1.

PROOF OF THEOREM 8.1: The proof will be achieved in several steps.

STEP 1. We prove first (ii), i.e. that the number of branching points of  $\Sigma_{opt}$  is at most finite.

For the sake of completeness it is worth mentioning that actually  $\Sigma_{opt}$  has no points of order zero since it is connected, and hence all the endpoints have order one. Let k stand for the number of endpoints.

We will say that a point  $x \in \Sigma_{opt}$  has *depth* not exceeding n, where n is a cardinal, if there is an endpoint l and an arc connecting x to l such that the number of branching points of  $\Sigma_{opt}$  on this arc has cardinality n. Moreover, we will say that the depth of  $x \in \Sigma_{opt}$  is equal to n, if n is the least cardinal for which the depth of x does not exceed n.

Let us show first that the depth of each point of  $\Sigma_{opt}$  is at most k - 1. Consider an arbitrary point  $x_0 \in \Sigma_{opt}$  and an arc  $\gamma_0$  connecting it to an arbitrary endpoint  $l_0$ . Proving the claim amounts to showing that the number of branching points on such an arc is finite. If  $x_i \in \gamma_0$  is a branching point, then according to the Menger *n*-Beinsatz (Proposition 2.2) there is an arc  $\gamma'_i$  starting in  $x_i$  and intersecting  $\gamma_0$  only at  $x_i$ . Denote  $x'_i$  an arbitrary internal point of this arc, and consider any connected component of  $\Sigma_{opt} \setminus \{x_i\}$  containing  $x'_i$ . Pick an arbitrary endpoint  $l_i$  of the latter. It is clearly also an endpoint of  $\Sigma_{opt}$  and cannot coincide with  $l_0$  since otherwise  $\Sigma_{opt}$  would contain a simple closed curve contradicting Theorem 6.1. Moreover, for the same reason when  $j \neq i$ , then for the same reason  $l_j \neq l_i$ . Therefore, to each branching point  $x_i \in \gamma_0$ corresponds at least one distinct endpoint  $l_i \neq l_0$  so that  $l_i \neq l_j$  when  $i \neq j$ , which proves that there can be no more that k - 1 distinct endpoints on  $\gamma_0$  (or, in other words, the depth of  $x_0$  doe not exceed k - 1).

We can represent now the set  $\mathcal{B}$  of branching points of  $\Sigma_{opt}$  in the form

$$\mathcal{B} = \bigcup_{i=0}^{k-1} \mathcal{B}_i,$$

where  $\mathcal{B}_i$  stands for the set of branching points of depth *i*. But clearly,  $\#\mathcal{B}_0 \leq k$ , while  $\#\mathcal{B}_{i+1} \leq \#\mathcal{B}_i$ , and hence in the above union all the sets  $\mathcal{B}_i$  are finite. Therefore, the set  $\mathcal{B}$  is finite, which concludes the proof of (ii).

STEP 2. Before showing (i), we prove a slightly weaker assertion, namely, that every branching point of  $\Sigma_{opt}$  has finite order. Consider an arbitrary branching point  $x \in \Sigma_{opt}$ . We claim that its order cannot exceed the number of endpoints k (see notation of Step 1). In fact, otherwise in view of the Menger *n*-Beinsatz there would exist at least k+1 closed arcs  $\gamma_i \subset \Sigma_{opt}$ , i = 1, ..., k+1, starting at x and pairwise disjoint outside of x (i.e.  $\gamma_i \cap \gamma_j = \{x\}$  for  $i \neq j$ ). Taking an arbitrary internal point  $x_i$  of each of the arcs  $\gamma_i$ , we see that each of the connected components of the set  $\Sigma_{opt} \setminus \{x\}$  containing  $x_i$  contains necessarily some endpoint  $l_i$  which is also an endpoint of  $\Sigma_{opt}$ . Further,  $l_i \neq l_j$  when  $i \neq j$  since otherwise  $\Sigma_{opt}$  would contain a simple closed curve in contradiction with Theorem 6.1.

STEP 3. At this point, we are finally able to prove (i). Let us suppose the contrary, namely that there is an  $x \in \Sigma_{opt}$  with  $\operatorname{ord}_x \Sigma_{opt} > 3$ . Then according to the Menger *n*-Beinsatz, there are at least 4 closed arcs  $\gamma_i \subset \Sigma_{opt}$ ,  $i = 1, \ldots, 4$ , starting at *x* and pairwise disjoint outside of *x* (i.e.  $\gamma_i \cap \gamma_j = \{x\}$  for  $i \neq j$ ). We choose an  $\varepsilon > 0$  small enough so that the closed ball  $\overline{B}_{\varepsilon}(x)$  does not contain other noncut or branching points (this is possible since both the former and the latter are finite) and so as to have also

$$\gamma_i \cap \partial B_{\varepsilon}(x) \neq \emptyset, \qquad i = 1, \dots, 4.$$

Let each  $a_{\varepsilon}^{i} \in \gamma_{i} \cap \partial B_{\varepsilon}(x)$  stand for the first point where  $\gamma_{i}$  hits  $\partial B_{\varepsilon}(x)$ , i.e. such that for all  $y \in (x, a_{\varepsilon}^{i})$  one has  $y \in B_{\varepsilon}(x)$ , i = 1, ..., 4. Among these four points there are at least two (without loss of generality, up to renumbering, we assume that the latter are  $a_{\varepsilon}^{1}$  and  $a_{\varepsilon}^{2}$ ) such that the minimum arc of  $\partial B_{\varepsilon}(x)$ has angle  $\delta \leq \pi/2$  (see Figure 9).

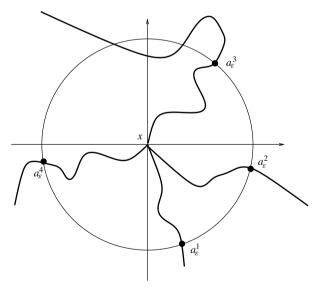


Fig. 9. The points  $a_{\varepsilon}^{i}$ , i = 1, ..., 4.

Assume without loss of generality that  $\Omega$  is large enough so as to satisfy

$$\overline{\operatorname{co}}(\operatorname{supp}\varphi^+\cup\operatorname{supp}\varphi^-)\subset\subset\Omega$$

(we may do it according to Proposition 5.1), and set

$$\Sigma^1_{\varepsilon} := \left( \Sigma_{opt} \setminus ((x, a^1_{\varepsilon}) \cup (x, a^2_{\varepsilon})) \right) \cup St(\{a^1_{\varepsilon}, a^2_{\varepsilon}\}, x, \varepsilon).$$

Note that  $\Sigma_{\varepsilon}^{1}$  is still connected, since the arcs erased did non contain any branching point of  $\Sigma_{opt}$ , and is obviously closed. We estimate then

$$\mathcal{H}^{1}(\Sigma_{\varepsilon}^{1}) \leq \mathcal{H}^{1}(\Sigma_{opt}) - \mathcal{H}^{1}((x, a_{\varepsilon}^{1})) - \mathcal{H}^{1}((x, a_{\varepsilon}^{2})) + \mathcal{H}^{1}(St(\{a_{\varepsilon}^{1}, a_{\varepsilon}^{2}\}, x, \varepsilon)).$$

Observe now that  $\mathcal{H}^1((x, a_{\varepsilon}^i)) \geq \varepsilon$ , i = 1, 2, while

$$\mathcal{H}^{1}(St(\{a_{\varepsilon}^{1}, a_{\varepsilon}^{2}\}, x, \varepsilon)) = \varepsilon \mathcal{H}^{1}(St(\{(a_{\varepsilon}^{1} - x)/\varepsilon, (a_{\varepsilon}^{2} - x)/\varepsilon\}, 0, 1)).$$

Lemma 8.1 implies then

$$\mathcal{H}^{1}(St(\{(a_{\varepsilon}^{1}-x)/\varepsilon, (a_{\varepsilon}^{2}-x)/\varepsilon\}, 0, 1) \leq 2-\beta$$

for some constant  $\beta > 0$  depending only on  $\delta$ . Putting the above estimates together, we get

$$\mathcal{H}^{1}(\Sigma_{\varepsilon}^{1}) \leq \mathcal{H}^{1}(\Sigma_{opt}) - \beta \varepsilon.$$

Moreover, one has

(25) 
$$\int_{\bar{\Omega}} \operatorname{dist}(z, \Sigma_{\varepsilon}^{1}) d\varphi_{\varepsilon}(z) \leq \int_{\bar{\Omega}} \operatorname{dist}(z, \Sigma_{opt}) d\varphi_{\varepsilon}(z) + \varepsilon \psi(B_{\varepsilon}(x) \setminus \{x\}).$$

Let now

$$\Sigma_{\varepsilon}^2 := \Sigma_{\varepsilon}^1 \cup \partial B_{\beta \varepsilon/2\pi}(y),$$

where y is some noncut point of  $\Sigma_{opt}$ . Using Theorem 7.1, one arrives at the estimate

(26) 
$$\int_{\bar{\Omega}} \operatorname{dist}(z, \Sigma_{\varepsilon}^{2}) d\varphi_{s}(z) \leq \int_{\bar{\Omega}} \operatorname{dist}(z, \Sigma_{\varepsilon}^{1}) d\varphi_{s}(z) - C\varepsilon$$

for some C > 0. Since  $\psi(B_{\varepsilon}(x) \setminus \{x\}) = o(1)$  as  $\varepsilon \to 0$ , then combining (25) and (26), one arrives at the estimate

$$\int_{\bar{\Omega}} \operatorname{dist}(z, \Sigma_{\varepsilon}^2) \, d\varphi_s(z) < \int_{\bar{\Omega}} \operatorname{dist}(z, \Sigma_{opt}) \, d\varphi_s(z),$$

and hence in view of Lemma 4.1, one has

$$\begin{split} MK(\varphi^+, \varphi^-, \Sigma_{\varepsilon}^2) &\leq MK(\varphi_r^+, \varphi_r^-) + \int_{\bar{\Omega}} \operatorname{dist}(z, \Sigma_{\varepsilon}^2) \, d\varphi_s(z) \\ &< MK(\varphi_r^+, \varphi_r^-) + \int_{\bar{\Omega}} \operatorname{dist}(z, \Sigma_{opt}) \, d\varphi_s(z) \\ &= MK(\varphi^+, \varphi^-, \Sigma_{opt}), \end{split}$$

contradicting the optimality of  $\Sigma_{opt}$ .

## 9. – Triple points and curvature measure

The goal of this section is to characterize the nature of branching points of the optimal set  $\Sigma_{opt}$ . In fact, we expect, as the numerical results from [5] suggest, that at least when the measures  $\varphi^{\pm}$  are sufficiently nice (i.e. they have densities with restpect to the Lebesgue measure summable with sufficiently large exponent), then all the branching points of  $\Sigma_{opt}$  are *regular tripods*, i.e. triple points where three smooth branches meet with angles of 120 degrees. However since we know nothing about the regularity of  $\Sigma_{opt}$  up to branching points, we will be only able to prove a weaker formulaton of the desired statement. For this purpose we recall the notion of a generalized mean curvature from [3]. The generalized mean curvature  $H_{\Sigma}$  of a  $(\mathcal{H}^k, k)$ -rectifiable set  $\Sigma \subset \mathbb{R}^n$  (or, in terms of [3], of the measure  $\mathcal{H}^k \sqcup \Sigma$ ) is the vector-valued distribution defined by the relationship

$$< X, H_{\Sigma} > := \int_{\Sigma} \operatorname{div}^{\Sigma} X \, d\mathcal{H}^k$$

for all  $X \in C_0^{\infty}(\mathbb{R}^n, \mathbb{R}^n)$ . Of course,  $H_{\Sigma}$  is a (signed) Radon measure, if the quantity

$$|H_{\Sigma}|(D) := \sup\left\{\int_{\Sigma \cap D} \operatorname{div}^{\Sigma} X \, d\mathcal{H}^k : X \in C_0^{\infty}(D; \mathbb{R}^n), ||X||_{\infty} = 1\right\},\$$

is finite for every open set  $D \subset \mathbb{R}^n$ . In the sequel let H stand for the generalized mean curvature of  $\Sigma_{opt}$ . The following statement is valid.

PROPOSITION 9.1. Let n = 2,  $\varphi^{\pm} \in L^{p}(\Omega)$ , where p > 4/3, and  $\varphi^{+} \neq \varphi^{-}$ . Then H is a signed Radon measure satisfying  $H \ll \psi$ .

PROOF. We show that there exists a constant C > 0 such that

$$|H|(D) \le C\psi(D)$$

for all open  $D \subset \overline{\Omega}$  which does not contain noncut points of  $\Sigma_{opt}$ , from which the statement follows immediately. For this purpose suppose  $|H|(D) \neq 0$  (otherwise there is nothing to prove) and for every  $\nu \in \mathbb{N}$  consider the vector field  $X_{\nu} \in C_0^{\infty}(D; \mathbb{R}^2)$  such that  $||X_{\nu}||_{\infty} = 1$  and

$$\left|\int_{\Sigma_{opt}\cap D}\operatorname{div}^{\Sigma_{opt}}X_{\nu}\,d\mathcal{H}^{1}-|H|(D)\right|\leq 1/\nu.$$

For every  $\varepsilon \in \mathbb{R}$  and  $\nu \in \mathbb{N}$  define the diffeomorphism  $\Phi_{\nu}^{\varepsilon}$  by

$$\Phi_{\nu}^{\varepsilon}(x) := x - \varepsilon X_{\nu}(x).$$

As usual, we assume without loss of generality, referring to Proposition 5.1, that  $\Omega$  is large enough so as to satisfy

$$\overline{\operatorname{co}}\,(\operatorname{supp}\varphi^+\cup\operatorname{supp}\varphi^-)\subset\subset\Omega.$$

Let  $\Sigma_{\varepsilon} := \Phi_{\nu}^{\varepsilon}(\Sigma_{opt})$ . According to the Theorem 7.31 of [1] one has then

$$\frac{d}{d\varepsilon}\mathcal{H}^{1}(\Sigma_{\varepsilon}) = \int_{\Sigma_{opt}\cap D} \operatorname{div}^{\Sigma_{opt}} X_{v} \, d\mathcal{H}^{1}.$$

Hence,

$$\delta := \mathcal{H}^1(\Sigma_{opt}) - \mathcal{H}^1(\Sigma_{\varepsilon}) = \varepsilon \int_{\Sigma_{opt} \cap D} \operatorname{div}^{\Sigma_{opt}} X_{\nu} \, d\mathcal{H}^1 + o(\varepsilon).$$

We suppose  $\nu$  to be sufficiently large. In this case  $\delta \ge \varepsilon(|H|(D) - 1/\nu) + o(\varepsilon) > 0$  for small  $\varepsilon$ .

Let now  $\Sigma'_{\varepsilon} := \Sigma_{\varepsilon} \cup \partial B_{\delta/2\pi}(x)$ , where  $x \in \Sigma_{opt}$  is some noncut point. Note that  $\Sigma'_{\varepsilon}$  is closed, connected and satisfies the length constraint. One has then

$$\int_{\bar{\Omega}} \operatorname{dist}(z, \Sigma_{\varepsilon}) \, d\varphi_{s}(z) \leq \int_{\bar{\Omega}} \operatorname{dist}(z, \Sigma_{opt}) \, d\varphi_{s}(z) + |\varepsilon| \psi(D),$$

while on the other hand

$$\int_{\bar{\Omega}} \operatorname{dist}(z, \Sigma_{\varepsilon}') \, d\varphi_s(z) \leq \int_{\bar{\Omega}} \operatorname{dist}(z, \Sigma_{\varepsilon}) \, d\varphi_s(z) - \delta\left(\psi(\{x\}) - \varphi_s(B_{\delta/2\pi}(x))\right) / 2\pi.$$

Minding  $\varphi_s(B_{\delta/2\pi}(x)) = o(\varepsilon)$  for  $\varepsilon \to 0$ , one has that the above estimates do not lead to a contradiction for small  $\varepsilon$  unless

$$(|H|(D) - 1/\nu)\psi(\{x\})/2\pi \le \psi(D).$$

Minding that  $\psi({x}) > C$  for some C > 0 according to Theorem 7.1, and letting  $\nu \to +\infty$ , we get the desired result.

With the help of the above proposition one can prove the following result regarding further characterization of branching points of  $\Sigma_{opt}$ .

THEOREM 9.1. Let n = 2,  $\varphi^{\pm} \in L^{p}(\Omega)$ , where p > 4/3, and  $\varphi^{+} \neq \varphi^{-}$ . Then every branching point  $x \in \Sigma_{opt}$  is a triple point (i.e. has order three) satisfying  $H(\{x\}) = 0$ .

PROOF. Let  $x \in \Sigma_{opt}$  be a branching point. According to Theorem 8.1 it is a triple point. The result regarding the curvature measure will follow from Proposition 9.1 once we show that if  $\psi(\{x\}) = 0$ . We will now concentrate on proving the latter assertion.

Suppose the opposite, i.e. that  $\psi({x}) \neq 0$ .

Then there is a piece of the cone  $C \subset \Omega$  with vertex x and nonzero aperture angle (i.e. not reduced to a ray) such that k(C) = x. Note that clearly  $C \cap B_{\varepsilon}(x) \cap \Sigma_{opt} = \{x\}$ . Moreover, let C' stand for the cone with vertex x,

coaxial with C and with aperture angle  $\gamma + 2\pi/3$ , where  $\gamma > 0$  is the aperture angle of the cone C, and  $C \subset C'$ . Then

$$C' \cap B_{\varepsilon}(x) \cap \Sigma_{opt} = \{x\},\$$

since for every  $z \in C$  there is a  $z' \in C'$  such that  $d(z, z') \leq d(z, x)$  (see Figure 10). We apply now a construction almost identical to the one used at Step 3 of the proof of Theorem 8.1. In fact, since x is assumed to be a triple point, then according to the Menger *n*-Beinsatz, there are 3 closed arcs  $\gamma_i \subset \Sigma_{opt}$ , i = 1, ..., 3, starting at x and pairwise disjoint outside of x, i.e.  $\gamma_i \cap \gamma_j = \{x\}$  for  $i \neq j$ . We suppose  $\varepsilon > 0$  to be small enough so that the closed ball  $\overline{B}_{\varepsilon}(x)$  does not contain other branching points of  $\Sigma_{opt}$  (which is possible since the number of braching points is finite) and so as to have

$$\gamma_i \cap \partial B_{\varepsilon}(x) \neq \emptyset, \qquad i = 1, \dots, 3.$$

Let  $a_{\varepsilon}^{i} \in \gamma_{i} \cap \partial B_{\varepsilon}(x)$  stand for the first point where  $\gamma_{i}$  hits  $\partial B_{\varepsilon}(x)$ , i.e. such that for all  $y \in (x, a_{\varepsilon}^{i})$  one has  $y \in B_{\varepsilon}(x)$ , i = 1, ..., 3. But since all  $a_{\varepsilon}^{i}$  must be outside of C', then there is a couple of points among them (which without loss of generality, up to renumbering, we may assume to be  $\{a_{\varepsilon}^{1}, a_{\varepsilon}^{2}\}$ ) such that the minimum arc of  $\partial B_{\varepsilon}(x)$  connecting it has an angle not exceeding  $2\pi/3 - \gamma/2$ .

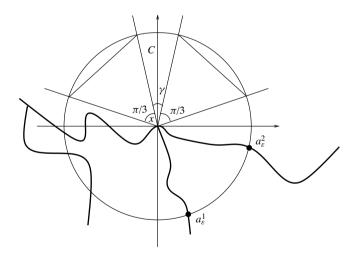


Fig. 10. The cone C and the points  $a_{\varepsilon}^1, a_{\varepsilon}^2$ .

We assume, as usual, in view of Proposition 5.1, without loss of generality  $\Omega$  to be large enough so as to satisfy

$$\overline{\operatorname{co}}\,(\operatorname{supp}\varphi^+\cup\operatorname{supp}\varphi^-)\subset\subset\Omega.$$

Set then

$$\Sigma_{\varepsilon}^{1} := \left(\Sigma_{opt} \setminus ((x, a_{\varepsilon}^{1}) \cup (x, a_{\varepsilon}^{2}))\right) \cup St(\{a_{\varepsilon}^{1}, a_{\varepsilon}^{2}\}, x, \varepsilon).$$

We observe that  $\Sigma_{\varepsilon}^{1}$  is still connected, since the arcs erased did non contain any branching point of  $\Sigma_{opt}$ , and closed. The estimate

$$\mathcal{H}^{1}(\Sigma_{\varepsilon}^{1}) \leq \mathcal{H}^{1}(\Sigma_{opt}) - \mathcal{H}^{1}((x, a_{\varepsilon}^{1})) - \mathcal{H}^{1}((x, a_{\varepsilon}^{2})) + \mathcal{H}^{1}(St(\{a_{\varepsilon}^{1}, a_{\varepsilon}^{2}\}, x, \varepsilon)).$$

combined with that  $\mathcal{H}^1((x, a_{\varepsilon}^i)) \geq \varepsilon$ , i = 1, 2, and

$$\mathcal{H}^{1}(St(\{a_{\varepsilon}^{1}, a_{\varepsilon}^{2}\}, x, \varepsilon)) = \varepsilon \mathcal{H}^{1}(St(\{(a_{\varepsilon}^{1} - x)/\varepsilon, (a_{\varepsilon}^{2} - x)/\varepsilon\}, 0, 1)) \ge \varepsilon(2 - \beta)$$

for some constant  $\beta > 0$  depending only on  $\gamma$  (the latter estimate being valid in view of Lemma 8.1), implies

$$\mathcal{H}^{1}(\Sigma_{\varepsilon}^{1}) \leq \mathcal{H}^{1}(\Sigma_{opt}) - \beta \varepsilon.$$

Now define

$$\Sigma_{\varepsilon}^{2} := \Sigma_{\varepsilon}^{1} \cup \partial B_{\beta \varepsilon/2\pi}(y),$$

where y is some noncut point of  $\Sigma_{opt}$ . Note that  $\Sigma_{\varepsilon}^2$  is still closed, connected and satisfies the length constraint. Using Theorem 7.1, one has

$$\int_{\bar{\Omega}} \operatorname{dist}(z, \Sigma_{\varepsilon}^{2}) \, d\varphi_{s}(z) \leq \int_{\bar{\Omega}} \operatorname{dist}(z, \Sigma_{\varepsilon}^{1}) \, d\varphi_{s}(z) - C\varepsilon$$

for some C > 0. But

$$\int_{\bar{\Omega}} \operatorname{dist}(z, \Sigma_{\varepsilon}^{1}) \, d\varphi_{s}(z) \leq \int_{\bar{\Omega}} \operatorname{dist}(z, \Sigma_{opt}) \, d\varphi_{s}(z) + \psi(B_{\varepsilon}(x) \setminus \{x\}),$$

and since  $\psi(B_{\varepsilon}(x) \setminus \{x\}) = o(1)$  as  $\varepsilon \to 0$ , then combining the above estiates one arrives at

$$\int_{\bar{\Omega}} \operatorname{dist}(z, \Sigma_{\varepsilon}^2) \, d\varphi_s(z) < \int_{\bar{\Omega}} \operatorname{dist}(z, \Sigma_{opt}) \, d\varphi_s(z),$$

and hence  $MK(\varphi^+, \varphi^-, \Sigma_{\varepsilon}^2) < MK(\varphi^+, \varphi^-, \Sigma_{opt})$ , in view of Lemma 4.1, contradicting the optimality of  $\Sigma_{opt}$ .

It is worth emphasizing that the result of the above Theorem 9.1 automatically implies that every branching point of  $\Sigma_{opt}$  is a regular tripod, provided  $\Sigma_{opt}$  is sufficiently regular (i.e. sufficiently smooth up to a branching point).

## 10. – Regularity

We expect the optimal set  $\Sigma_{opt}$  to be rather regular away from branching points and endpoints. However, we are able to prove only the following rather weak regularity statement.

PROPOSITION 10.1. Let n = 2,  $\varphi^{\pm} \in L^{p}(\Omega)$ , where p > 4/3, and  $\varphi^{+} \neq \varphi^{-}$ . Then  $\Sigma_{opt}$  is Ahlfors regular.

PROOF. It is enough to show the existence of an  $r_0 > 0$  and a C > 0 such that  $\mathcal{H}^1(\Sigma_{opt} \cap B_r(x)) \leq Cr$  for all  $x \in \Sigma_{opt}$  and for all  $r < r_0$ . We show that one can take  $C = 2\pi + \varepsilon$ , where  $\varepsilon > 0$  is an arbitrary positive number. Suppose the contrary, namely, the existence of a sequence  $\{x_{\nu}\} \subset \Sigma_{opt}$  and of a sequence  $r_{\nu} \to 0$  such that

$$l_{\nu}(x) := \mathcal{H}^{1}(\Sigma_{opt} \cap B_{r_{\nu}}(x_{\nu})) > (2\pi + \varepsilon)r_{\nu}.$$

Up to choosing a subsequence of  $\{x_{\nu}\}$ , we assume  $x_{\nu} \to x \in \Sigma_{opt}$ . Further, we will write r instead of  $r_{\nu}$  omitting the index  $\nu$  whenever this cannot cause confusion.

According to Proposition 5.1 we may assume without loss of generality that

$$\overline{\operatorname{co}}(\operatorname{supp}\varphi^+\cup\operatorname{supp}\varphi^-)\subset\subset\Omega.$$

Letting  $\Sigma_r := (\Sigma_{opt} \setminus B_r(x_v)) \cup \partial B_r(x_v)$ , one has that the latter is closed and connected, while still  $\mathcal{H}^1(\Sigma_r) \leq \alpha - \varepsilon r$ . But then

$$\int_{\bar{\Omega}} \operatorname{dist}(x, \Sigma_r) \, d\varphi_s(x) \leq \int_{\bar{\Omega}} \operatorname{dist}(x, \Sigma_{opt}) \, d\varphi_s(x) + 2r\varphi_s(B_r(x_v)).$$

We would like to apply now Lemma 5.2. For this purpose consider a  $\rho > 0$  such that

$$\psi(\Omega) > \psi(B_{\rho}(x)).$$

Such a  $\rho$  exists since otherwise one would have  $\psi(\bar{\Omega}) = \psi(B_{\rho}(x))$  for all  $\rho > 0$ , and hence, taking a limit in the latter relationship as  $\rho \to 0$ ,  $\psi(\bar{\Omega}) = \psi(\{x\})$ , which would mean that the one-point set  $\{x\}$  is optimal, in contradiction with Theorem 5.1. Then  $\Sigma_r \cap B = \Sigma_{opt} \cap B$ , where  $B := \bar{\Omega} \setminus B_{\rho}(x)$ , for all sufficiently large  $\nu$ . What is more, for all  $y \in k^{-1}(\Sigma_{opt} \cap B)$  (i.e. y has unique projection on  $\Sigma_{opt}$ , and, moreover, the latter belongs to B) one has

(27) 
$$\operatorname{dist}(y, \Sigma_{opt} \cap B) = \operatorname{dist}(y, \Sigma_{opt}) < \operatorname{dist}(y, \Sigma_r \setminus B)$$

for all  $\nu \ge \overline{\nu}$ , where  $\overline{\nu} = \overline{\nu}(x)$  is some number which may depend on x. In fact, otherwise one would have

(28) 
$$\operatorname{dist}(y, \Sigma_{opt} \cap B) = \operatorname{dist}(y, \Sigma_{opt}) \ge \operatorname{dist}(y, \Sigma_r \setminus B)$$

for a subsequence of  $\nu$  (not relabeled). The latter can only happen, if there is a  $x'_{\nu} \in \partial B_{r_{\nu}}(x_{\nu})$  such that

(29) 
$$\operatorname{dist}(y, \Sigma_r \setminus B) = d(y, x'_y).$$

Combining the above two relationships (28) and (29), one gets

$$\operatorname{dist}(y, \Sigma_{opt} \cap B) = \operatorname{dist}(y, \Sigma_{opt}) \ge d(y, x'_y)$$

and taking then a limit as  $\nu \to \infty$  in the resulting estimate one has,

$$\operatorname{dist}(y, \Sigma_{opt}) \ge d(y, x),$$

which can only happen when y has a nonunique projection on  $\Sigma_{opt}$ , while this case is ruled out by our construction. Hence,  $k^{-1}(\Sigma_{opt} \cap B) \subset T'$  and

$$\varphi_s(T') = \psi(B) = \psi(\Omega) - \psi(B_\rho(x)) > 0.$$

We may use then Lemma 5.2 with  $\varphi := \varphi_s$  and  $\Sigma_{\nu} := \Sigma_r$  to find a new closed and connected set  $\Sigma_{r,\varepsilon} \subset \overline{\Omega}$  satisfying  $\mathcal{H}^1(\Sigma_{r,\varepsilon}) \leq \alpha$ , such that

$$\int_{\bar{\Omega}} \operatorname{dist}(x,\,\Sigma_{r,\varepsilon})\,d\varphi_s(x) \leq \int_{\bar{\Omega}} \operatorname{dist}(x,\,\Sigma_r)\,d\varphi_s(x) - C_{\varepsilon}r^{3/2},$$

where  $C_{\varepsilon}$  stands for a positive constant depending on  $\varepsilon$  but not on r. Since  $\varphi_s \neq 0$  in view of Lemma 4.2, then using Hölder inequality one has  $\varphi_s(B_r(x_{\nu})) \leq Cr^{2/p'}$  for some C > 0. It is now enough to note that with p > 4/3 one has 2/p' + 1 > 3/2 and hence

$$\int_{\bar{\Omega}} \operatorname{dist}(x, \Sigma_{r,\varepsilon}) \, d\varphi_s(x) < \int_{\bar{\Omega}} \operatorname{dist}(x, \Sigma_{opt}) \, d\varphi_s(x)$$

for sufficiently small r > 0. Therefore, in view of Lemma 4.1, for such r one has

$$MK(\varphi^+, \varphi^-, \Sigma_{r,\varepsilon}) < MK(\varphi^+, \varphi^-, \Sigma_{opt})$$

contradicting the optimality of  $\Sigma_{opt}$ .

We remark that Ahlfors regularity of the optimal set  $\Sigma_{opt}$  implies in view of its connectedness another mild regularity condition on  $\Sigma_{opt}$  called *uniform rectifiability*. The latter condition, which has been extensively studied in [9], provides a lot of nice analytical properties of the set and can be considered as a kind of "quantitative rectifiability" condition as opposed to the classical "qualitative" rectifiability which is one of the basic concepts of the geometric measure theory.

## REFERENCES

- L. AMBROSIO N. FUSCO D. PALLARA, "Functions of Bounded Variation and Free Discontinuity Problems", Oxford mathematical monographs. Oxford University Press, Oxford, 2000.
- [2] L. AMBROSIO P. TILLI, 'Selected Topics on "Analysis in Metric Spaces", Quaderni della Scuola Normale Superiore, Pisa, 2000.
- [3] G. BOUCHITTÉ G. BUTTAZZO I. FRAGALÀ, *Mean curvature of a measure and related variational problems*, Ann. Scuola Norm. Sup. Pisa Cl. Sci. (4) **25** (1997), 179–196.
- [4] G. BUTTAZZO G. BOUCHITTÉ, Characterization of optimal shapes and masses through Monge-Kantorovich equation, J. European Math. Soc. 3 (2001), 139–168.
- [5] G. BUTTAZZO E. OUDET E. STEPANOV, Optimal transportation problems with free Dirichlet regions, Progress Nonlinear Differential Equations Appl. 51 (2002), 41–65.
- [6] G. BUTTAZZO A. PRATELLI S. SOLIMINI E. STEPANOV, *Mass transportation and urban planning problems*, forthcoming.
- [7] G. BUTTAZZO E. STEPANOV, *On regularity of transport density in the Monge-Kantorovich problem*, Preprint del Dipartimento di Matematica, Università di Pisa, 2001.
- [8] L. CAFFARELLI M. FELDMAN R. J. MCCANN, Constructing optimal maps for Monge's transport problem as a limit of strictly convex costs, J. Amer. Math. Soc. 15 (2002), 1–206.
- [9] G. DAVID S. SEMMES, "Analysis of and on uniformly rectifiable sets", Vol. 38 of Math. Surveys Monographs. Amer. Math. Soc., Providence, RI, 1993.
- [10] C. KURATOWSKI, "Topologie", Vol. 1, Państwowe Wydawnictwo Naukowe, Warszawa, 1958, in French.

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