FOUNDATIONS OF TRANSPORTATION RESEARCH REVISED

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ABSTRACT

Is everything that has been said about Transportation enough? What is Transportation? What is its nature? What is a Transportation System? Is Transportation Science reducible to other hardcore science (such as Physics)? In a context of a myriad of new terms and definitions, how can we reduce confusion and misinterpretations and distinguish shallow semantic operation from authentic theoretical advancements? This paper aims to revisit these fundamental questions trying to bring new air to this discussion, while we also try to clarify some crucial definitions of the field of research such as transportation, accessibility and mobility. Also, we aim to provide arguments to legitimate Transportation Science as a science itself and not a subarea of another research field (such as Economics, Physics, Psychology). Specifically, by discussing the notions of transportation, we provide a new (but not so new) definition of transportation from which we derive specific formalized general definitions of accessibility and mobility, less vulnerable to ambiguity of natural language.

Keywords: Transportation, Systems Theory, Accessibility, Mobility, Science.

INTRODUCTION

Commonly, we use the term 'transportation' (or 'transport') to refer to the movement of people and goods. This is the very etymological definition of 'to transport'. The phenomena denoted by this term are of utmost importance to our day-to-day life. The concern regarding the development of new ways to allow such movements is known since Ancient times when men tried to build new commercial routes, to allow army's mobility, and to provide water and other natural resources supply (Mumford, 1998). Because transportation has increasingly gained importance in modern society, a specific field of research has been developed to deal with the complex problems related to such movements. However, the scientific development of this research field on the very subject is recent, dated from the beginning of the 20th century.

With the passing of time, it is expected that any field of research would improve its maturity and formalization. At this time, it is not acceptable to proceed exclusively on definitions provided by common sense as we do today. The community dedicated to research on the subject of transport, or transportation, has grown considerably. This very community needs to communicate, share and discuss ideas in a precise and productive manner. In this context, how to identify and to distinguish an authentic novelty from the myriad of shallow semantic definitions? To answer that, we need to remove the ambiguity of the natural language for the sake of precision, a distinctive character of science.

Also, for the sake of the legitimacy of our research field, some basic questions need to be addressed. At first, questions will emerge, such as 'what is transport? 'What is the distinction between transport and the other kinds of movements? (I.e. a chuck of wood carried by the force of a river)'. If not adequately answered, one might argue that other mature sciences would be sufficient to deal with the problems of transportation phenomena. Many authors have tried to address those questions, such as Cox (19972), Taaffe et al. (1994), Morlock (1978), Hay (1977), Sussman (2000). However, they've limited themselves to use only natural language, which is essentially ambiguous.

Thus, it is of fundamental importance to revisit the foundations of transport research and to distinguish 'transport' from the other events that shape the reality lived by men. We need to put forward a proper and sound language to express concepts. This paper addresses this problem. Also, we try to break barriers to creativity in future theoretical and technological developments in the field.

To undertake that challenge, our main tool will be Mario Bunge's Theory of Concrete Systems (Bunge, 1979) and its ontology (Bunge, 1978) as metatheories to analyze, to criticize, and to rebuild the main definitions of transportation research. After presenting its main concepts, we will address the definition of 'transportation' as a phenomenon, starting from its etymology and classical definitions on popular manuals, to the inquiry of its nature. By then, we will have a general framework of transportation, which will lead us to the formalization of the notions of 'accessibility' and 'mobility', using both elements of Bunge's Theory and formal logic.

THEORETICAL BACKGROUND: BUNGE'S THEORY OF CONCRETE SYSTEMS

On transportation research, a notion historically relevant is that of systems. Different authors have proposed many definitions to "system" and its components. Bunge (1979:16) commented that there are many works on the subject and they can all be reduced to three basic definitions: (I) 'system' as a 'set of interrelated elements'; (ii) 'system' as a 'black box' with inputs and outputs; (iii) 'system' as binary relations. He takes them all for inadequate.

To understand why Mario Bunge judges those definitions as inadequate, we have to refer to his ontological model and his theory of concrete systems. The first core notion is the distinction between an 'aggregate' and a 'system'.

According to Bunge (1979:4), an aggregate is "(...) a collection of items not held together by bonds, and therefore lacks integrity or unity. Aggregates can be either conceptual or concrete (material). A conceptual aggregate is a set. (But not every set is a conceptual aggregate: a set equipped with a structure is a conceptual system.) A concrete or material aggregate, on the other hand, is a compound thing, the components of which are not coupled, linked, connected, or bonded, such as a field constituted by two superposed fields (...)". A 'system', on the other hand, is "(...) a complex object, the components of which are interrelated rather than loose. If the components are conceptual, so is the system; if they are concrete or material, then they constitute a concrete or material system. A theory is a conceptual system, a school a concrete system of the social kind".

If we relate these definitions to those of system, we notice that: (i) the previously mentioned definitions that take 'system' as a 'set of interrelated' or as 'binary relations' are inadequate as they refer to mental constructions (sets) rather than concrete objects (things); (ii) the 'black box' model is inadequate because it does not look into the internal structure of a system.

To better understand this last objection, we should take a further look on Bunge's concept of concrete system.

Bunge's Definition of System

In non-formalized discourse, Bunge (1979:4) asserts that any system has a definite composition, an environment and a structure. The composition is the set of all of system's components; the environment is the set of all things to which the system's components are connected; and the structure is the set of all relations between system's components and between system's components and thing on system's environment.

The initial formalization of system under Bunge's theory is as follows. Let *T* be a non-empty set. Then, the ordered triple $\sigma = \langle \mathscr{C}, \mathscr{E}, \mathscr{S} \rangle$ is (or represents) a systems over *T*, $\mathscr{C}$ and $\mathscr{E}$ are mutually excluding subsets of *T* ($\mathscr{C} \cap \mathscr{E} = \varnothing$), and $\mathscr{S}$ is a non-empty set of relations on the union of $\mathscr{C}$ and $\mathscr{E}$. A system is conceptual if *T* is a set of conceptual items, and concrete (or substantial) if $T \subseteq \Theta$ is a set of concrete entities, e.g. things (for a precise definition of thing, see Bunge, 1977, chapter 1 to 3).

However, in order to have a fully definition of system, we need to formalize the notions of Composition ($\mathscr{C}$), environment ($\mathscr{E}$) and structure ($\mathscr{S}$). Such formalization, as proposed by Bunge, is presented in the following subsection.

Bunge's definition of concrete System

For us to understand the definition of system provided by Bunge, it is necessary to have the specification of the concepts of A-Composition, A-Environment and A-Structure – 'A' stands for 'Atomic'. Here, we use the same notation used by Bunge.

According to the author, the composition of a system is not merely a collection of its parts, but a set of its 'atoms'. So, he expresses the absolute composition and the A-Composition as follows.

Let $A \subseteq \Theta$ be a class of things and *x* a given thing (i.e. $x \in \Theta$). The composition (absolute) of *x* is the set of its parts:

$$\mathscr{C}(x) = \{x \in \Theta \mid y \sqsubset x\} \qquad (1)$$

where:

$\mathscr{C}(x)$: absolute composition of *x*

'$y \sqsubset x$' denotes "*y* is part of *x*"

And the A-composition of *x* is the set of its A-parts (things of the type 'A'):

$$\mathscr{C}_A(x) = \mathscr{C}(x) \cap A = \{y \in A \mid y \sqsubset x\} \qquad (2)$$

where:

$\mathscr{C}_A(x)$: A-composition of *x*

It is important to notice that the latter definition of composition (A-composition) is ingenious as it provides us with a practical logical limitation to analysis. In other words, we can set what we take as the atom of our analysis (e.g. Biology would set its atom as cells). This is useful to avoid infinite recursive references that happen on 'holistic' approaches.

To explain the notion of environment, Bunge also introduces another concept that is required to his model: the concept of bounding, connecting or coupling, among a thing's component (Bunge, 1979:6). According to him, such concept is diverse from relations such as "be older than", "be beside something", etc. Two things are connected if at least one of them acts on another. And, if a thing acts on another, it modifies its behavior line, trajectory or history. The action relation is symbolized in the following manner: if thing *a* acts upon thing *b*, we write '$a \rhd b$'.

The notion of A-Environment of a thing *x* with a A-Composition $\mathscr{C}_A(x)$ is defined as the set of all things that are not contained in $\mathscr{C}_A(x)$, and that act upon, or receive the action of, $\mathscr{C}_A(x)$. In formal terms, such concept is expressed as:

$$\mathscr{E}_A(x) = \{y \in \Theta \mid \neg(y \in \mathscr{C}_A(x)) \,\&\, (\exists x)(z \sqsubset x \,\&\, (y \rhd z \vee z \rhd y))\} \qquad (3)$$

where

$\mathscr{E}_A(x)$: A-Environment of *x*

$\mathscr{C}_A(x)$: A-Composition of *x*

Finally, structure is the set of all relations between the components of a thing, as well as the relations between the components and the things in the environment.

Bunge's Formalization of the characteristics of a Concrete System

An object is a concrete system if, and only if, it is composed by at least two different connected things (Bunge, 1979:6).

The three basic characteristics of a system where introduced previously. They are (Bunge, 1979:7): A-Composition, A-Environment e A-Structure.

Let $\sigma \in \Sigma$ be a concrete system and $A \subset \Theta$ a class of things. The *A-composition* of σ at time *t* is the set of all its A-parts, in *t.* In formal terms it is expressed as:

$$\mathscr{C}_A(\sigma,t) = \{x \in A \mid x \sqsubset \sigma\} \qquad (4)$$

The *A-environment* of σ at time *t* is the set of all A-things, which are not components of *x*, but act upon, or receive the action of, components of σ at time *t.* Its formalization should read:

$$\mathscr{E}_A(\sigma,t) = \{x \in A \mid x \notin \mathscr{C}_A(\sigma,t) \,\&\, (\exists y)(y \in \mathscr{C}_A(\sigma,t)) \,\&\, (x \rhd y \vee y \rhd x)]\} \qquad (5)$$

The *A-structure* of σ at time *t* is the set of relations, especially bounding relations, between components of σ, and between components and things in the *A-environment* of σ at time *t.* In formal notation it is expressed as:

$$\mathscr{S}_A(\sigma,t) = \{R_i \in \mathbb{B}_A(\sigma,t) \cup \overline{\mathbb{B}}_A(\sigma,t) \mid \mathbb{B}_A(\sigma,t) \neq \varnothing \,\&\, 1 \leq i \leq n\} \qquad (6)$$

Where:
$\mathbb{B}_A(\sigma,t)$: set of bounding relations (connections)
$\overline{\mathbb{B}}_A(\sigma,t)$: set of non-bounding relations
R_i: a relation

Technosystem

The main distinction of a technosystem is the use and production of artifacts, which is aimed to members of a society. Considering the naïve notion of transportation system in which the image of vehicles comes immediately to mind, this seems to offer a grasp of such idea of a technosystem.

Bunge (1979:202) gives more information on this notion:

A system τ is a technosystem, iff:
(i) the composition of τ includes rational beings and artifacts;
(ii) the environment of τ includes components of a society;
(iii) the structure of τ includes production, maintenance and use of artifacts.

From here, we can derive that a technosystem is a subsystem of a human society, but not the other way around.

All these theoretical notions will be of some use for us to address the notions of Transportation and Transportation Systems.

TRANSPORTATION AND ITS NATURE

Definitions in Dictionary: The Common Sense

The verb 'to transport' derive from the latin word 'transportare' and it can bear the following meaning, according to the Oxford New American Dictionary: "*take or carry (people or goods) from one place to another by means of vehicle, aircraft, or ship".*

Based on this definition, we can point some important aspects: (I) it considers the changing of place; (ii) the action has objects (i.e. people and goods); (iii) it has means, or the process is mediated. It is important to note that in other languages, such as Portuguese, the verb has a reflexive form, meaning that the subject and the object are the identical.

Yet, the term can also assume a substantive form ('transport' or 'transportation') meaning: *"the action of transporting someone or something or the process of being transported*". So, it can denote a particular class of phenomena.

These features will be useful on discussing the concept of transportation.

Definitions in Specialized Manuals

A paradigm synthesizes the most important features of a field of studies. It bears ontologies, theories, and methods. The paradigms of a research field can be identified by the scrutiny of manuals and textbooks used to present the subject to students and new researchers (Kuhn, 2005). Thus, by consulting those materials we should find a more specialized definition of transportation, enriching our inquiry on the nature of the phenomenon.

Aside from the general definition provided by common dictionary (that includes circular references), Morlock (1978:5) provide us with a definition of Transportation Engineering: "The application of science and mathematics by which the properties of matter and the sources of energy in nature are utilized to convey passengers and goods in a manner useful to mankind".

Before we start discussing Morlock's definition, it is proper to take another definition. This one provided by Papacostas & Prevedouros (1993:1) refers to 'transportation system' as "The fixed facilities, the flow entities, and the control system that permit people and goods to overcome the friction of geographical space efficiently in order to participate in a timely manner in some desired activity."

For now we focus on discussing the definition of 'transportation' rather than the proper definitions of 'engineering' or 'transportation system'. So, we shall address those previous definitions in order to identify useful ideas to explore the concept of transportation.

As seen beforehand, we should point a worthy idea: the notion that transportation serves a purpose, a desire (as expressed in "useful to mankind" and "in order to participate in a timely manner in some desired activity"). In other words, one of the distinctive properties of transportation is intentionality. Despite of its importance, this feature passes almost unnoticed in those definitions. This could and can lead to the assumption that transportation and the other kinds of movements share the same nature. However, such interpretation is not fertile to transportation research.

Transportation and intentional action

As a corollary of the ideas presented in the previous subsection, we can assert that transportation is an intentional human process. The phenomena witnessed everyday, such as: people moving from place to place, vehicles crowing the streets and a myriad of other examples are just a external layer of a deeper and more complex process whose wholeness cannot be grasped by those shallow "appearances". Andler provides us with an analogy to better illustrate the difficulties related to observation of intentional action/phenomenon:

"Imagine Peter crossing the streets when he meets the principal of the elementary school his children study in. At that time, they'd had an argument and Peter wonders if he shouldn't propose reconciliation. What he imagines and then decides to do, it is not to move his arm and his hand in such way that he raises his hat in precisely 5cm over his head; also it is not to give a casual photographer the opportunity to illustrate a story on old-fashioned customs of a small city. (…) What Peter does deliberately (…) is to greet the principal of the elementary school his children study in. The agent chooses to do X, and performs his choice by doing Y: the former has a meaning apparently different from the latter – in short, X is performed by the agent, while Y is performed by a part of agent's body (Andler *et al.*, 2005:6)*."*

This is a sound analogy for thinking transportation. Phenomena observed and usually called "transportation" are in fact only part of the intentional action. This comprehends the choice of subject (X), which is materialized by, among other things, the movement of object (Y). Let us provide a example: (1) a commodity supplier in South America wants to sell its products in

China and materializes this by exporting its goods through a port in Santos/Brazil; or (2) a student that desires to participate in educational activities and materializes this by going to school. It would be possible to enumerate a series of actions that falls on category Y. However, the main issue here is the notion that the process of transportation holds two dimensions: one explicit, observable, and not determinant – a mere realization of the choice; and the other hidden, the intentional action that is the determinant factor. In other words, the reasons (determinants) for transportation can only be known by the 'transportation's subject'. An external observer can only pose conjectures about the reasons, or it can question the agent directly.

As a consequence, by taking transportation as an intentional action operates a deep change in the fundamentals of transportation research by demanding methodological revision, adoption of new tools still not fully understood and explored in the area.

Now we should take a closer look on the support for the intentional interpretation of the transportation phenomenon.

Supporting the intentional nature of transportation: Some hints from traditional research

The assertion that transportation is a human phenomenon does not come from nothing. It derives from reflection and from the scientific community itself. Our intention here is to bring into consideration some evidence taken from past studies, which can contribute to corroborate our proposal.

On the intentional nature of transportation, in transportation planning we always refer do 'desire lines' that are proposed to represent the very desire for movement (be it inferred or declared) by the inhabitants of a given region. Those 'desire lines' are produced based on data provided by field surveys, especially from interviews. Furthermore, we usually use categories to sort different trips (i.e. purposes). There are a huge number of papers and technical reports that could be referred as examples of such approach. Just to name some of them: Papacostas & Prevedouros (1993:310-312), Mello (1975:51-51), Hensher & Button (2005) and Stopher & Greaves (2007). This last paper should be given a special attention as it provides a good overview of the most used data-collection methods used in Transportation Research and also discusses the challenges and suggestions on that subject.

Stopher & Greaves (2007) asserts that the state-of-the-practice has not evolved much in the last 30 years of research, especially on trying to explain the demand for transportation. According to them, models and results are just descriptive and they lack on providing useful knowledge to explain how transportation phenomena are determined. Despite of focusing on the problem of data collection, the authors address issues directly related to the intentionality of transportation. Example of that is the following passage:
"An emerging area in travel demand modeling is that of process models, rather than outcome models. Process models are models that are based on the processes by which people make choices, rather than being focused on observed choices, which may have come about

through the operation of a range of opportunities and constraints, as well as underlying behavioral processes (Stop her & Greaves, 2007:369)”.

We are not concerned on assessing the adherence of each model, but we are trying to support the argument that both research and practice in the field of transportation have acknowledged the intentional nature of transportation phenomena, even if in an intuitive manner. We can add to that studies that make use of methods such as stated preferences as a way to provide better understanding of the phenomenon. The previous passage’s put into evidence elements such as decision process, people’s choice. These are contained as we see in the Transportation’s Subject dimension.

Analyzing Transportation Phenomena: a General Model

In order to analyze transportation phenomena, we postulate that a transportation process exists and it is composed of different moments as described bellow:

- Moment 01: A person (or group of people) has to develop some activity in order to satisfy some need. He/she knows, or believe, based in common sense (or other source of knowledge) that in order to participate in that activity he/she is required to perform a chain of actions, including those that will result in the movement of a specific material object;
- Moment 02: The person (or group of people) searches for available means that will allow the chain of actions to be performed, especially those that imply movement.
- Moment 03: If the person (or group of people) finds a suitable mean, then he/she can decide whether to use it or not;
- Moment 04: If the person (or group of people) chooses to use a suitable mean, this will perform (in case of transportation) the movement of the specified object according with the requirements set;
- Moment 05: Movement is over. The person (or group of people) can participate in the activity it intended from start and satisfy its expectations.

We can illustrate the process described above in the following manner (Figure 01).

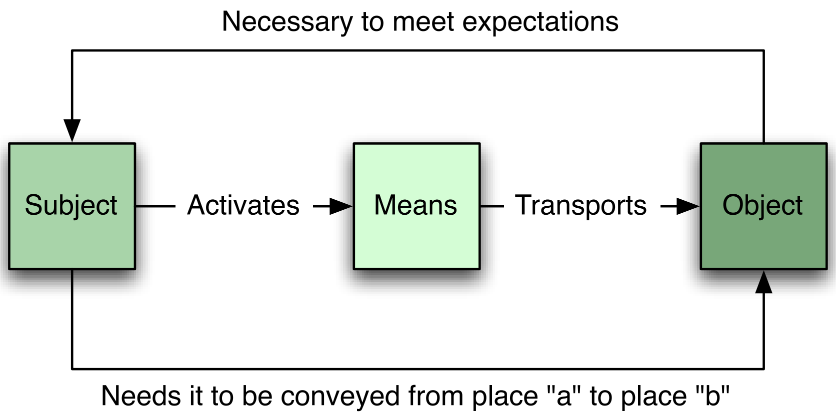

Figure 01: General Model of Transportation Process

In other words, transportation depends of three elements for its realization: Transportation's Subject, Transportation's Means and Transportation's Object. Transportation's Subject is that entity that has some necessity, or desire, whose satisfaction requires the moment (displacement) of a given object. The Transportation's Object is that things whose moment (displacement) is required to satisfy Transportation's Subject expectations. An example would be a factory that needs to produce its goods and requires that some raw material be taken to its plant. The factory is the Transportation's Subject and the raw material, the Transportation's Object.

But in the transportation action the relation between Transportation's Subject and Object is mediated by another entity: the Mean of Transportation. Mean of Transportation (or of Transport) is the entity (be it simple or complex) that effectively displaces (or moves) the object. Continuing the factory's example, the factory does not have to be the direct responsible for conveying the raw material, but it can contract some service provider that would be liable for picking the cargo up and for delivering it at the desired location. Therefore, the mean of transportation is the effective cause of the observable displacement (movement) phenomena.

However, caution is required for we are not supposed to take a river that accidentally carries a fallen leaf throughout its course for a mean of transportation. As we discussed previously, transportation is an intentional phenomenon and this intentional dimension is precisely what is missing in the case of river – as we do not assume a metaphysical position that recognizes that to everything that happen there is a divine intention underlying.

Besides, the proposed schema can be misinterpreted sometimes, so attention is required. To help on that, we shall provide some model cases:

- Case 01: An automobile factory hires a contractor to convey its goods to another region.
    - Transportation's Subject: the automobile factory;
    - Means of Transportation: the system that comprehends all existing transportation infrastructure (i.e. vehicles, roadways, railways, waterways, ducts, buildings, equipment, etc.), the service provider and other agents;
    - Transportation's Object: the automobiles produced by the factory.

- Case 02: A student walking to school.
    - Transportation's Subject: the student;
    - Means of Transportation: the system that comprehends all existing transportation infrastructure (i.e. walkways, sidewalks, streets, stairs, ramps, crossings, buildings, equipment, etc.), part of the student's body;
    - Transportation's Object: the student (his body and self).

Transportation *versus* Other kinds of Movements

Common sense, based on classic Physics, teaches us that a displacement is a change of spatial position over time. So, the flow of river water, the fall of an apple, the fight of a birds, the automobile traffic are all examples of movements. In that way, why do not rely on Physics to deal with all movement?

Physics assumes a force to be the cause of movement. So, its approach limits itself to relate displacement and forces. Therefore, there is no concern to explain the end of such movement (in the sense of its goals), nor their reasons or purposes. This would be equivalent to a teleological explanation. To Physics movements (displacements) are not intentional and they have no purpose. This is an assumption that demarcates physical phenomena.

We have argued so far that transportation phenomena have the distinctive characteristic of being intentional. And with reference to the material presented to this point, we provide the following definition to transportation: *it is the INTENTIONAL displacement of a material object.* So, intentionality becomes the distinctive character of such phenomena.

By defining this way we take transportation out of the strict domain of Physics and put it also in the realm of human/social sciences. And, in this sense, we cannot rely solely on the theories and instruments provided by Physics (e.g. gravitational models) but we also need to use theories and instruments that are able to unveil and explain the intentional dimension. Transportation is a human phenomenon and, therefore, opened to teleological scrutiny. Natural sciences are blind to such dimension: they do not have the proper means to address this facade. This is one of the most crucial consequences of our definition of transportation.

By this point we come to question: what is the end (reason or purpose) of transportation? Morlock (1978:5) and Papacostas & Prevedouros (1993:1) have provided us with a good hint: *satisfaction of an expectation.* Parting from that, we put that the end (purpose or reason) of transportation is *the satisfaction of an expectation of a person or a group of people.* Thus, there resides its *telos.*

Exploring relations among the fundamental elements of Transportation Process: in the search of a mechanism

Previously we have discussed the general model of transportation phenomenon and its main elements: Transportation's Subject, Mean of Transportation and Transportation's Object. For transportation to happen it is required a relation between Transportation's Object and the Mean of Transportation, and between the Mean of Transportation and the Transportation's Object. As shown on our model, the relation Subject-Mean is 'activate' and Mean-Object is 'transported'. If such relations are possible to happen, we say that the object is mobile or that it has 'mobility' as a property. Accessibility is, by definition, a property of the Mean of

Transportation that is able to interact with the Subject or the Object. Therefore, it can be decomposed in two ways: Subject-Mean Accessibility and Mean-Object Accessibility.

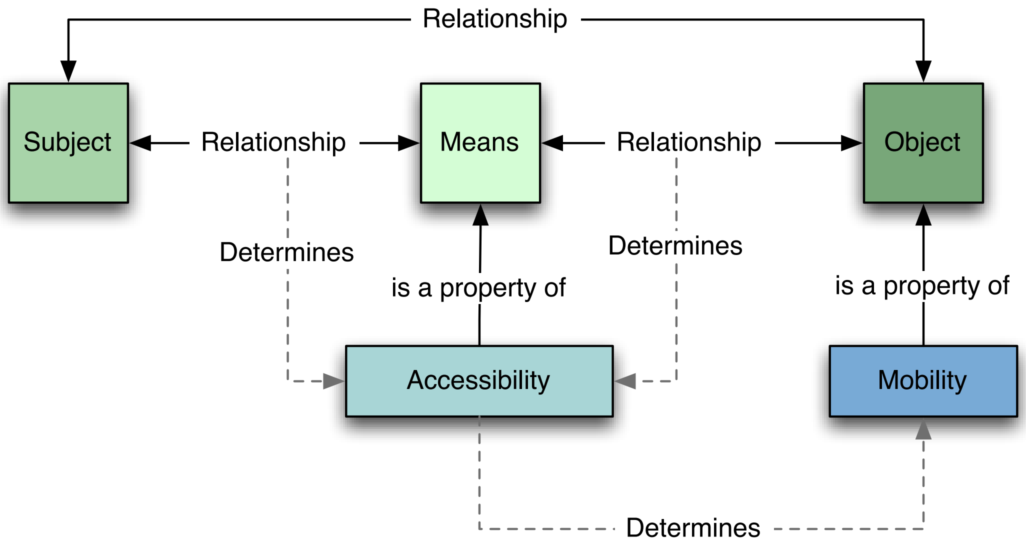

Figure 02: Relations between the fundamental elements of transportation and the fundamental properties of Mean of Transportation and of Transportation's Object.

To study and analyze transportation is, on that way, to address those elements, properties and relations. Further, it is the theoretical inquiry on transportation systems and the determination of its mechanism. The object of Transportation Studies should be, therefore, the Transportation Systems. The goal of a transportation system is to move objects in such way outcome of transportation tends tries to satisfy to its intention, which is, by its turn, derived from other societal subsystems. And the understanding of the outcomes of transportation requires, obviously, knowledge about these other society´s subsystems and its intentions.

So we assert that:

The main goal of the Transportation Research is to produce models of Transportation Systems whose minimal form is:

$$\sigma_t = \langle \mathscr{C}_t, \mathscr{E}_t, \mathscr{S}_t \rangle \qquad (7)$$

where:

σ_t: Transportation System
$\mathscr{C}_t$: Composition of the Transportation System
$\mathscr{E}_t$: Environment of the Transportation System
$\mathscr{S}_t$: Structure of the Transportation System

Based on this theoretical background, Transportation Research should make use of methods and instruments for complex systems analysis. Its job is to conjecture components, environment and, more important, structure of the transportation system, from simple propositions to more complex ones. To make it operational, however, the notions of A-Composition, A-Environment and A-Structure are needed, and by setting the atomic level used in the analytical process, they avoid infinite recursive analysis – a trap of Holism.

A transportation system is, according to our ontology, a technosystem – a system in which artifacts and technology play a very important role. Its *inputs* are people and things to transport, along with energy and artifacts. Its *outputs* are transported things and residuals (non-intended produced things as consequence of the activities of the system). On the next figure we present a general black-box model of a Transportation System. Arrows on left, right and top sides mean 'inputs', 'outputs' and 'constraints' (or guidelines), respectively. This should be used as a startup for analyzing a transportation system.

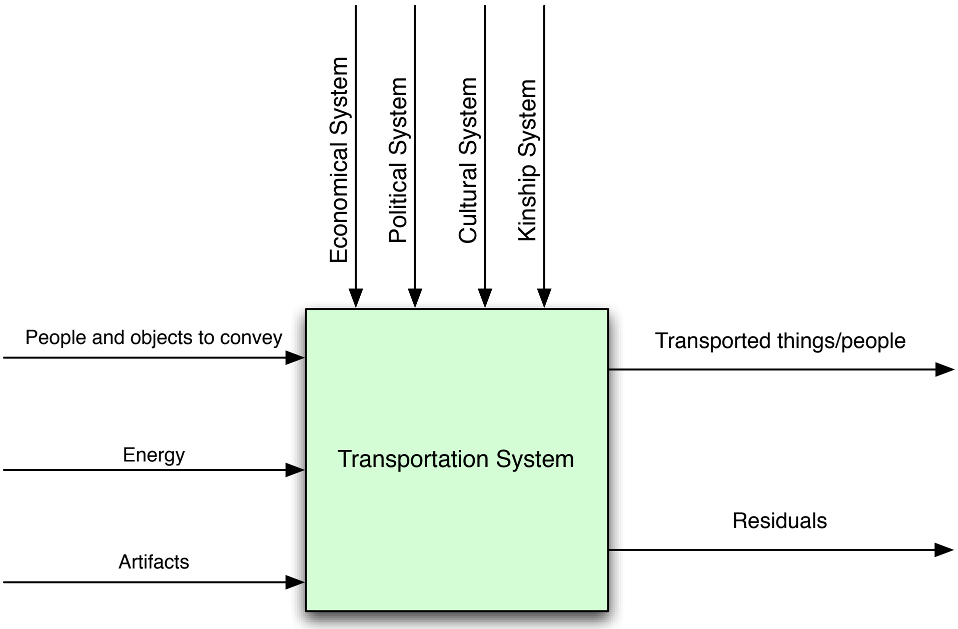

Figure 03: Black-Box model of a Transportation System

FORMAL GENERAL DEFINITION OF ACCESSIBILITY

In the context of a system (as defined by Bunge, 1979), we can formalize the notion of accessibility. This would help researches to analyze the growing number of definitions available today and to help them find if they carry any theoretical novelty.

Let $C \subset \mathscr{C}_A(\sigma,t)$, $E \subset \mathscr{E}_A(\sigma,t)$, $S \subset \mathscr{S}_A(\sigma,t)$ be sets and let $r \in S$ be a relation $r : \mathscr{E}_A(\sigma,t) \rightarrow \mathscr{C}_A(\sigma,t)$ that belongs to the A-Structure of a transportation system $\sigma \in \Sigma$.

Also, let $x \in E$ be an element of a subset of the A-Environment and $y \in C$ be an element of a subset of A-Composition of a transportation system.

We say that x has access to system σ (or system σ is accessible to x), or "$A_\sigma x$", iff, there exists an element x, an element y, and a relation r, such that $(x,y) \in r$. This can be formalized as:

$$A_\sigma x \leftrightarrow \exists x \exists y \exists r (x \in E \wedge y \in C \wedge \Diamond \langle x,y \rangle \in r) \tag{8}$$

The signal '◊' is the modal operator of possibility. For more detail on notation, syntax and semantics, systems and specific properties of modal logic refer to Hughes & Cresswell (1996).

For instance, let x be a food factory, let y be a cargo company (in the composition of a transportation system) and let r be a relation "x hires y". We say that, in this case, the transportation system is accessible to the food factory if, and only if, it is possible to the factory to hire the cargo company (i.e. there are local offices, or means of contacting the service provider, and the factory can afford the cost of cargo service, etc.). Thus, accessibility is always relative to the entities analyzed. And it is important to notice, that possibility of something to happen does not imply the realization of that thing (refer to Possible Worlds Metaphysics notions in Lewis, 1998).

It is important to say that here we are concerned about the formal general definition of accessibility and not on exhausting the list of all material conditions for that to happen. This last task would be a continuous challenge for the researches to undertake.

Now, based on the general definition of accessibility, we can provide a general definition of mobility.

FORMAL GENERAL DEFINITION OF MOBILITY

The aforementioned definition of mobility will be developed on that of accessibility. But first, let us briefly discuss the idea of mobility.

Mobility is the property of what is able to move, or be moved. So, in the context of transportation systems, for us to say that something is mobile, or has 'mobility', there must exist a transportation system that: (i) can be accessed (i.e. hired, contacted, paid, etc.); (ii) can receive, convey and deliver the object (i.e. goods or people). Figure 02 illustrated that notion: an object is mobile (has mobility as property) if, and only if, the transportation system (Mean of Transportation) is accessible to both Transportation's Subject and Transportation's Object.

In formal terms we could say:

Let $C \subset \mathscr{C}_A(\sigma,t)$, $E \subset \mathscr{E}_A(\sigma,t)$, $S \subset \mathscr{S}_A(\sigma,t)$ be sets and let $r \in S$ be a relation $r : \mathscr{E}_A(\sigma,t) \to \mathscr{C}_A(\sigma,t)$ that belongs to the A-Structure of a transportation system $\sigma \in \Sigma$. Also, let $r_1 : \mathscr{E}_A(\sigma,t) \to \mathscr{E}_A(\sigma,t)$ be a Subject-Object relation (see figure 02) and let $x_1, x_2 \in E$, such that x_1 is Transportation's Subject and x_2 is Transportation's Object.

We say that the thing x_2 is mobile (or has mobility as property) under a transportation system σ, or $M_\sigma x_2$, iff the transportation system σ is accessible to both x_1 and x_2.

$$M_\sigma x_2 \leftrightarrow (\Diamond \langle x_1, x_2 \rangle \in r_1 \wedge A_\sigma x_1 \wedge A_\sigma x_2) \qquad (9)$$

The notation $A_\sigma x$, as defined in (8), means "system σ is accessible to x".

Another example: let x_1 be a food factory, let *y* be a cargo company (in the composition of a transportation system) and let *r* be a relation "*x* hires *y*". Also, let r_1 be a relation "x_1 need x_2 to be delivered at a retail store", and let x_2 be a cargo of ice cream. In this case, we say that the ice-cream is mobile (or has mobility as property) under this transportation system if, and only if: it is possible to have an intention, or necessity, (remember, transportation is an intentional phenomenon), and it is possible for the factory to hire the cargo company, and it is possible for the cargo company to convey the ice-cream (i.e. refrigerated trucks, freezers to store the product, roadways to reach both origin and destination, etc.).

In the previous example, we did not approach a special case: a person who intends to go out for shopping, and chooses to do it by foot. In such situation, x_1 would be the person; *y* would be the system composed by parts of the person's musculoskeletal system, streets, stairs, elevators, sidewalks, ramps, etc.; and x_2 would be the person's body and self. Although it is a conceptual exercise and it would seem awkward to analyze the situation in this manner, this exercise shows how fertile this approach is: it helps us to bring/include new elements to our analysis of transportation systems. Also, it puts the matter of transportation in relation to a far more comprehensive context of social systems.

EXAMPLE OF APPLICATION: A SIMPLE TRANSPORTATION SYSTEM MODEL

Parting from the theory outlined in the previous sections, we can provide an example of application by developing a simple model of a transportation system. In this paper, we do not intend to fully develop such model, but solely demonstrate how those concepts (specially those from Bunge's Ontology) can be applied.

We will start from a study, undertaken by University of Brasilia and the Education Development National Fund in Brazil (FNDE), which addressed the problem of rural pupil transportation (CEFTRU&FNDE, 2009). This study tried to uncover the complexity of this service. Although its methodology was based on a whole different theoretical basis, thus leading to a different form of modeling the problem, we shall demonstrate how our proposed theory can provide analytical tools for interpreting, or reinterpreting different studies.

According to propositions (4), (5) and (6), a minimum model of a system, at time *t*, is given by its A-Composition, A-Environment and A-Structure. Also, as we have proposed, a transportation system is a technosystem, whose definition poses some special features.

Based on those notions, we can start modeling our example of rural pupil transportation system, based on the aforementioned study (CEFTRU&FNDE, 2009).

Modeling Complex Systems with no clearly defined boundaries: Transportation System

According to Bunge's Theory, we should specify the composition and the environment of a system. Note that those sets are mutually exclusive, meaning that if an element belongs to one of those sets, it cannot belong to the other.

In the case of a simple object, such as a watch, we can clearly see its boundaries, thus differentiating it from "everything else". However, this is not the case of complex systems whose boundaries are not easily distinguished and, in our case, a transportation system.

Thus, how can we model a transportation system using Bunge's concepts?

Our methodological guideline is to start from its consensual components (artifacts), as present in most theories of transportation systems (Morlock, 1978; Hay, 1977; Sussman, 2000; Papacostas & Prevedouros, 1993): vehicle, links (roads, sidewalks, etc.) and terminals (bus stops, terminals, etc.). Also, a small set of core relations (taken from the definition of technosystem): production, maintenance and use (operation). Now, we can start formalizing our A-Composition and A-Structure as following.

$$\mathscr{C}_A(\sigma,t) = \{\text{vehicle, links, terminals}\} \tag{10}$$

$$\mathscr{S}_A(\sigma,t) = \{\text{produce, maintain, operate}\} \tag{11}$$

From this point, we start expanding the A-Composition by searching entities that are valid for the first position of each relation (eg. in '____*produces* vehicles'). Parting from information contained in the CEFTRU (2009) document, we, then, get to the following A-Composition:

$$\mathscr{C}_A(\sigma,t) = \{\text{vehicle, links, terminals, drivers, mechanic, transportation secretary, monitor, fleet manager, manufacturer, certification authority, service operator, public works secretary, designer, planner}\} \quad (12)$$

Now, we can focus on the A-environment. To do that, we need to expand the A-Structure to cover new relations. A sketch of these relations where put forward in Figures 01 and 03. After expanding the set to comprehend part of those relations we have the following set:

$$\mathscr{R}_A(\sigma,t) = \{\text{produce, maintain, operate, supply, transport, pay, supervise, use}\} \quad (13)$$

Parting from that new relation set (and ignoring the first three relations), we can define the A-Environment:

$$\mathscr{E}(\sigma,t) = \{\text{student, teacher, school principal, education secretary, fuel, sponsor, hitchhikers, parts, city mayor, parts manufacturer, school, people with disabilities}\} \quad (14)$$

All things that belong to the A-Environment are, then, components of other systems that are not identical to the modeled system. They might belong to political, economic, cultural systems, or even other technosystems within a society. An A-Environment with greater cardinality (number of elements) indicates a system with richer interrelations with the surrounding world.

These steps do not show, however, the most important information about this system's model: how the relations are set. In fact, to define the A-Composition and the A-Environment, we needed to specify for each binary relation its corresponding ordered pairs. But presenting them only by extensively defined sets is not very interesting.

In our proposed framework, the most adequate form for visualizing a transportation system modeled is to present it in the form of its defined A-Composition, A-Environment and A-Structured, along with the corresponding network. In our example, the network is presented in the following image.

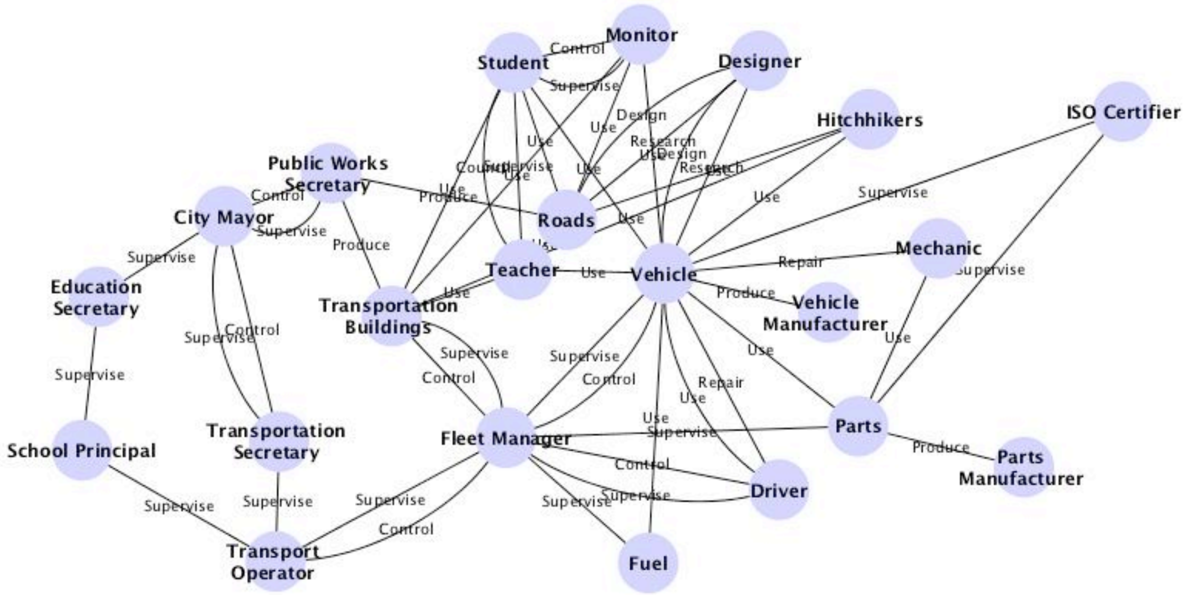

Figure 04: The network (directed) representation for the modeled transportation system. Software: Cytoscape.

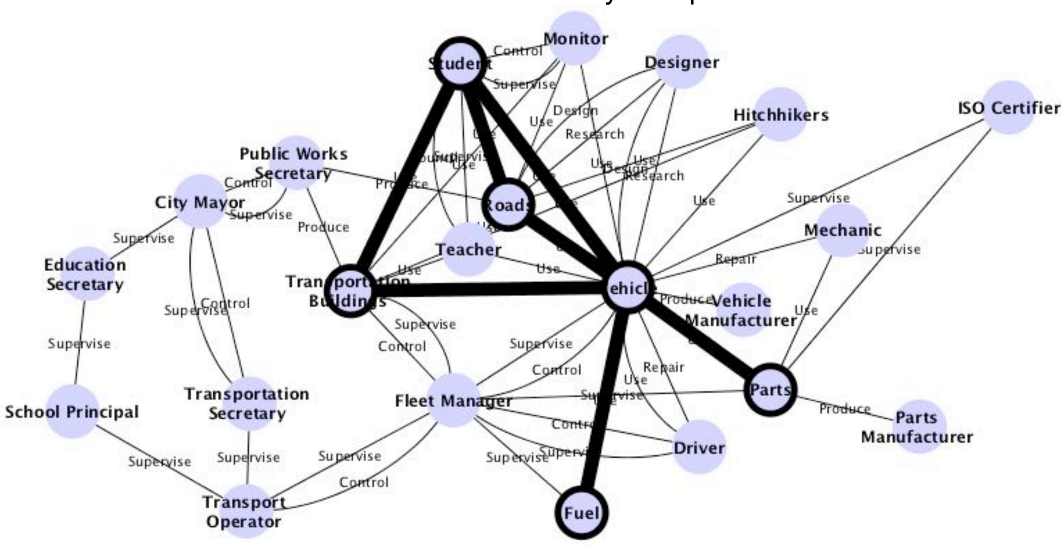

Figure 05: Paths drawn from 'Student' node – determinants for the accessibility object->mean. Software: Cytoscape.

In the Figure 05, we can see, by applying a path tracer from node 'Students' in the direct graph that represents our modelled system, the main nodes related to the notion of Accessibility (Object->Mean). The result path seems to be sound with the theory as their direct links connect to elements in the A-Composition of the system. As said before, we did not intend to perform a full analysis but to provide examples and elements to show that our proposed approach is fertile and interesting to transportation research.

CONCLUSIONS

The intention of this paper was to revise the fundamentals of transportation research. This does not mean that we intended to start from scratch. In truth, we tried to uncover the foundations of our field of study, to revisit them, and to question whether they are still suitable or not.

The transportation research community has increased enormously in the last decade. Complexity have expanded, new technologies have become available. With that increment, we have witnessed remarkable contributions but also a lot of not-so-remarkable ones. Many researchers have been questioning the effectiveness of traditional methods and trying to solve those problems by adopting new technology and methods. But, among all those initiatives, few people have explored the level of science that prepares for the most creative revolution: the hard core (Lakatos, 2001), or the paradigm (Kuhn, 2005), or scientific ontology (Bunge, 1978).

Remembering Quine (1953:199-200): "As scientists we accept provisionally our heritage from the dim past, with intermediate revisions by our more recent forebears; and then we continue to warp and revise. As Neurath has said, we are in the position of a mariner who must rebuilt his ship plank by plank while continuing to stay afloat on the open sea. How do we decide on such retentions and revisions? (...) How do we decide, apropos the real world, what things there are? (...) By considerations of simplicity plus pragmatic guess as to how the overall system will continue to work in connection with experience"

Thus, we have tried to "look under the hood" or, to better fit Neurath's and Quine's nautical analogy, we have tried "to inspect the keel".

Bunge's Theory was demonstrated to be very fertile as metatheory for analyzing transportation systems and to provide some core notions for formalizing some crucial definitions such as accessibility and mobility. Also, it opens a way to eliminate some ambiguity that comes from the natural language.

By ontologically bringing transportation phenomena into the human realm, we legitimate our research field as been irreducible to any other science. Yet, give theoretical foundations to the increasing initiatives that use methods such as multi-agent systems from Computation Sciences, Game Theory from Economics, social network analysis (Nook *et al. 2005) from Sociometry.* Also, many methods from Psychology (i.e. human behavior, Social psychology) can be now theoretically supported.

Furthermore, the proposed formalization of accessibility and mobility, in spite of its generality, are useful to distinguish theoretical novelty from shallow semantic operations in natural language. For instance, "in what aspects definition of mobility from author 1 differs from author 2?" Also: (i) they separate the notion of mobility and accessibility from their material conditions for effective realization; (ii) they bring the notion of possibility in such way that we deconstruct the myth that the more travels a person make more mobility it has (it is false as we can only say that it HAD mobility in such occasions – refer to the intentional nature of transportation).

Therefore the results of this paper pose new questions and research agenda. As a research agenda, we have:

- To reorganize and integrate the present and past research initiatives, rationally assigning them to a precise object of knowledge inside our framework (be it a entity or a relation). For instance, what the recent and past research on transport demand can teach us about the entities and relations mapped in our framework (subjects, means and objects, and the relations among them)?
- To study the coupling of functional models (such as organizational structures of municipalities) and social networks. For instance, 'Mayor' is a role played by a person, such as 'John'. What does it happen when we couple John's personal network with the functional network in which the role 'mayor' is a node? What insights and information can we depict from that association?
- To improve the method for modeling systems without clearly defined boundaries;
- To study the properties of the relevant relations: symmetry, reflexivity and transitivity. For example, are 'control' relations transitive? Is it sound to assert that: If *a* controls *b,* and *b* controls *c,* then *a* controls *c?*
- To develop analysis software better suitable to our theory requisites. In this paper, we used software developed for modeling bio systems (Cytoscape).

Therefore, we are in a very initial moment in the development of this theory and we still cannot claim it as a replacement for our most established paradigms. However, we can claim that the proposed framework is a candidate for unifying the field, as it does places transportation in an authentic multidisciplinary perspective while providing some constructs for building a more specialized language for expressing our concepts and propositions. The increasing complexity of our sociosystems have been presenting new challenges to our research field, most of them requiring deep revision of our most dear and established beliefs.

Remembering Karl Popper (2002): "The game of science is, in principle, without end. He who decides one day that scientific statements do not call for any further test, and that they can be regarded as finally verified, retires from the game."

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