Evidences of communicating vessels principle in results of a regional land use and transport integrated modeling application

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RESUME. Cet article présente une partie des résultats obtenus à partir d'une modélisation intégrée d'usage du sol et des transports à l'échelle d'une région, en utilisant le logiciel de simulation Tranus. Plus précisément, le travail visait à analyser les effets d'un plan régional de Transit Oriented Development, appliqué à la région française du Nord-Pas-de-Calais, en référence à l'évolution de la répartition modale entre voiture privée et transports en commun et des dynamiques de localisation résidentielle et des activités.
En particulier, le modèle donne des résultats qui montrent l'existence d'un système d'interdépendance mutuelle dans l'évolution des parts modales. Cette interaction entraîne l'activation d'un effet de substitution dans la distribution de la demande de transport, comme conséquence de l'application d'interventions défavorables à l'utilisation des voitures et de renforcement des performances relatives à l'offre de transport en commun.
En outre nous avons observé quelques évidences attribuables à un processus correspondant au principe des vases communicants. En particulier à la fin de la simulation l'augmentation de la part modale liée aux transports en commun, résultant de l'application des politiques de TOD, a produit dans certaines zones du modèle, une désaturation et décongestion progressive du réseau routier et donc un retour progressif d'attractivité pour la voiture. Ce phénomène de vases communicants lié à l'évolution de la demande de transport, indique la présence d'un état de tension permanente dans le processus de répartition modale, qui se révèle en fonction de certains facteurs particuliers (segments de demande concernés; contexte temporel et territorial; structure du réseau de transport) et généralement tendant à un équilibre temporaire.
Ces résultats démontrent la pertinence du modèle implémenté et sa capacité de reproduire des dynamiques complexes ; en invitant également à observer comment des politiques qu'encouragent l'utilisation des transports en commun peuvent avoir, dans certains contextes particuliers, des effets controversés et parfois contraires aux attentes, en particulier dans le long terme. L'article explique les principes à la base de la recherche, qui ont permis ces résultats, en analysant les causes et les conséquences relatives à l'observation du phénomène de vases communicants appliqué aux dynamiques de mobilité et transports.

ABSTRACT. This article presents part of results obtained from an integrated land use and transport regional modeling, using the simulation software Tranus. Specifically, this research aimed to analyze effects of a regional Transit Oriented Development plan, applied to the French region of Nord-Pas-de-Calais, with reference to the evolution of modal share between private car and public transport and of residential and activity location dynamics.

In particular the model has provided results that show the existence of a system of mutual interdependence in transport modal share evolution. This interaction entails the activation of a substitution effect in transport demand distribution, as a consequence of the application of interventions discouraging car use and reinforcing public transport supply performance.

Furthermore we also observed some evidences referable to a process proper of the physical principle of communicating vessels. In particular the increase over simulation times of modal share related to public transport, resulting in the application of TOD policies, produces in some zones of the model, a progressive desaturation and decongestion of the road network and therefore a gradual return of attractiveness for private cars. This phenomenon of communicating vessels related to transport demand evolution, indicates the presence of a permanent state of tension in modal share, depending on some particular factors (segment of demand; temporal and territorial context; structure of transport network) and generally tending to a temporary equilibrium.

These results invite therefore to observe how policies that promote and encourage the use of public transport may have, in some particular contexts, controversial effects and sometimes contrary to expectations, especially in the long term.

The article explains the principles behind the research that have allowed achieving these results, analyzing causes and consequences related to the observation of the phenomenon of communicating vessels applied to dynamics of mobility and transport.

MOTS-CLES : Modèles d'usage du sol et transport, Tranus, TOD, répartition modale, urbanisme, aménagement du territoire.

KEYWORDS: Land Use and Transport Integrated models; Tranus, TOD, modal share, urbanism, urban planning.

1. Land Use and Transport Integrated modeling

Land Use and Transport Integrated (LUTI) modeling intends the ability to model interactions between supply and demand of a transportation system and the socio-economic functioning of a specific territory. These models are able to simulate regional and urban systems, reproducing economic equilibrium between supply and demand and dynamics of competition related to localization choices of households and activities, depending on certain key factors: accessibility, generalized transport costs, land and housing prices (Nguyen-Luong, 2012).

Several researchers, including F. Leurent (2012), observe that LUTI modeling is a tool that allows answering to typical questions of developers and planners; thanks in particular to its potential and ability in space-time decomposition and in analyzing different behavioral aspects of multiple actors and factors contributing to evolution of territories. This type of modeling can provide a comprehensive and inclusive analysis, particularly during the decision-making process relating to relocation of services, resources or activities, as well as for identification of new spatial development configuration.

Modeling research introduced in this article intends to analyse effects of urban densification and transit oriented policies applied in correspondence of main regional railway corridors and nodes of the study area. In particular such hypotheses, detailed later, have activated an unexpected mechanism of substitution, and subsequently of complementarity among transport demand segments related to private car and public transports. Results show that car has a return of attractiveness caused by reduction of road congestion, produced in turn by an increase in public transport rate of frequentation due to effects of modeling hypothesis.

This unexpected substitution effect in favour of car occurred in two zones of the model, in the simulation scenario more favourable to public transport. That situation induced to develop further reflections, more oriented to transport and urban planning strategies, considering how impacts of some transport and land use policies could be diversified considering the short and the long term and controversial if some reciprocal and secondary effects are underestimate during the planning phase.

Results presented in this article confirm LUTI modeling as a proper tool to study complex and articulated territorial dynamics, allowing, as illustrated later, to read and decode different factors that influence inverse relationship between generalized transport cost and demand distribution.

Moreover we are conscious that use of LUTI is still limited and many criticisms are addressed to this modeling technique, especially about its complexity, its low theoretical progress and its character of black box (Timmermans, 2003). Further limitations are related to the need of a multidisciplinary approach, to the large amount of data required and also to the difficulty in defining automated and standardized calibration and validation methods.

Different authors like Lee (1974) and later Waddel (2011) have described and analyzed main critical elements of LUTI models, as well as their greatest potentialities, as for instance: *transparency, understanding, flexibility* and *uncertainty*.

This complexity explains how rare are examples of LUTI models applied to support real decision processes (Gayda, 2011). Otherwise the research project Cities[1], founded by the French ANR (*Agence Nationale de la Recherche*), is indeed an example of integration between research, planning and decisional actors, to work on implementation of an operative LUTI model and on development of solid and consistent calibration methods (Bonnel *et al.*, 2014; Capelle, Sturm et Vidard, 2014; Prados *et al.*, 2014)).

LUTI models generally require the definition of population, employment and transport demand categories, of activity sectors and also of land use and housing types. It is also necessary to accurately divide study area in discrete zones, define physical (infrastructure) and operative (services) transport supply and time intervals of simulation.

The scientific literature has a wide number of documents that analyze different LUTI modeling approaches (Wilson, 1997; Wegener, 2004), reviewing their main potentialities, weaknesses and operational characteristics (Clement, Peytron, et Frenois, 1996; DETR, 1999; NCHRP, 2002; Timmermans, 2003; DT, 2005; Hunt *et al.*, 2005; Zhao and Chung, 2006; Wegener, 2010).

Among them in a report of the British Department of the Environment, Transport and the Regions (DETR, 1999), Simmonds and others proposed a classification of LUTI models in two macros categories: *static* models (referred to a single point in the time) and *quasi-dynamic* models (referred to a series of time horizons). This last category is then divided in: Entropy-Based models (in which relations between activities are based on the analogy with Newton's gravitational theory); Spatial-Economics models (based on description of spatial distribution of people and activities) and Activity-Based Models (based on representation of interactions between activities). Following Simmonds classification, the Tranus model, used for this research, belongs to Spatial-Economics models. This type of models articulate micro-economic theories with spatial interaction models and random utility based multi-region input-output models.

Micro-economic theories (Von Thunen, 1826; Wingo, 1961; Alonso 1964) describe land use market with a disaggregated approach, considering a competition between households and firms to consume space, that reaches an equilibrium when land and transport costs maximize utilities for consumers (and benefits for suppliers).

Spatial interaction models (Lowry, 1964; Echenique, 1968; Wilson, 1974) describe location of activities in space and interaction flows, using aggregated discrete categories and assuming similar behaviors and characteristics for members belonging to a same group. Interactions between activities produce flows (of

1. Calibrage et valIdation de modèles Transport – usagE des Sols.

passengers or freights) and are proportional to number of activities in a particular zone and inversely proportional to transport network constraints.

Random utility theories (Mc Fadden, 1973) and discrete choice models describe the decision chain of demand groups in function of multiple possible interdependent choices (as typically happens in urban and regional systems). Users make their choices influenced by variable costs, supply constraints and elastic demand functions (that describe relationship between demand and supply).

Econometric input-output models are then used to reproduce interaction and relations between activities and the urban and regional territorial structure (de la Barra, 1989). In the input/output model (Leontief, 1941) regional economy is divided in activity sectors and transport demand is obtained in function of economic relations that occur between activities. Products of an economic sector (outputs) can be used as inputs for another productive sector (induced) or consumed by final demand (which may include population, exports, investments, etc.) (Wilson, 1974). Inputs are divided in produced inputs and primary inputs, while outputs are divided in intermediate and final demand (de la Barra, 1989). Industrial inputs coming from outside the regional economic system represent exogenous inputs (raw material, financial capital, public subsidies, etc.) (Wilson, 1974), while intermediate demand is characterized in a matrix, where each element represents the amount of output from a production sector, demanded by another activity sector. Once completed the iterative calculation and once convergence is achieved, the input/output model provides the amount of regional production required to meet the total consumption demand (de la Barra, 1989).

2. The integrated simulation software Tranus

Tranus presents an approach based on the overall equilibrium between supply and demand (of transport, of land and/or housing). It is an aggregated spatial input/output model, based on equilibrium in function of price and time and on a nested logit multinomial model (de la Barra, 1989).

This model has been select mainly because of its multi-scale potentiality of representation (regional, suburban and urban) of the study area and because it is an open source software, with a direct on-line support by its creators. Other reasons were the Tranus integrated conformation, that doesn't implicate the use of external transport models, as in the case of many others LUTI models, and the presence in the research environment of the author, of researchers with precedent experiences in Tranus modeling.[2]

Tranus stands out in particular by its ability to include several theoretical approaches into a single integrated structure, which represents both transport and

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2. This work is part of a joint PhD research program in urban and transport planning, which took place at the University of the Sciences and Technologies of Lille 1, in the Laboratory city mobility and transport (LVMT), research unit of the French institute of sciences and technologies for transport, development and networks (IFSTTAR) and in the Department of Territorial Planning of University of Calabria (Italy).

land use phenomena. Among the theoretical basis of Tranus we have: the economic based theory of Lowry (1964), which considers that a territorial system develops around a main attractive economic center; the input/output model (Leontief, 1941) to define relations between consumption and production; microeconomic theory of random utility of McFadden (1973) to define user behaviors (path choice, modal choice, location choice, etc.) depending on the utility attributed to all available options.

Tranus includes, in fact, a transport sub-model (which simulates generation and distribution of transport demand, modal share and congestion levels), an activity sub-model (which simulates economic interactions between activities and households and location dynamics) and an interface module that allows transforming economic interactions between activities in transport flows.

The activity and land use sub-model is a discrete-economic spatial model and consists in the calculation of total demand, through an input-output matrix, which is then distributed in space according to the principle of utility maximization (considering localization and transport costs). Demand functions define consumption of each economic sector in function of prices and can be elastic for commodities that could be consumed only in their production zone (basically land and housing types) or completely inelastic for other economic sectors. Each activity sector and population category can choose within a range of different location types (Johnston et de la Barra, 1998) and consume production of several productive sectors, previously reported as substitutes (with corresponding preferences and penalties by demand category). The model is therefore able to reproduce the own competition mechanism of real estate market, where, for example, if housing demand increases in a specific area, without available surface for new urbanization, housing and land prices will also increase.

Tranus also represents in detail the transport system, taking into account capacity constraints, congestion and multimodality. Transport demand is distributed over transport network in function of disutilities, which include monetary (price, toll, energy costs, cost of transfer between modes of transport, etc.) and non-monetary factors (value of waiting time, penalties related to each transport category) and travel time is calculated according to a *capacities restrictions* process (de la Barra, 2013) (where if assigned demand exceeds capacity, then there will be an increase of congestion and thus of travel time). This process is therefore a fundamental characteristic with reference to the substitution and communicating vessels effect observed in the model and described later in this article.

In particular the process of *capacity restriction* allows to adjust travel times and waiting times as a function of demand/capacity ratio (Modelistica, 2013). At the end of each iteration demand is assigned to supply and then speed of vehicles is reduced in function of congestion levels, while in accord with queue theory, waiting times for public transport modes are increased as number of boarding units match or exceeds capacity. That is a crucial step that occurs at the end of the decision chain that defines in Tranus land use and transport integration.

The decision chain process starts calculating the cost of travel at a route level, then aggregating it from route level to model level and after to origin-destination level, generating the generalized composite cost of travel (de la Barra, 1989).

Activity location model is then executed as a function of this generalized composite cost and then potential travel demand is estimated by an elastic trip generation model. Modal choice is then defined as a function of composite costs by mode and assignment probabilities are calculated in function of travel cost at a route level (de la Barra, 1989). Finally *Capacity restriction* step allows to compare demand with supply, adjusting if necessary travel and waiting time that will be considered in next iteration.

The definition of a time lag beetween the location/interaction of activity and the transport chain allows to adapt activity location choices to changes in accessibility, giving an integrated and dynamic structure to the model (de la Barra, 1989).

For each zone of the model and for each sector, values of production and demand, induced and exogenous, are defined. Exogenous sectors consume only inputs coming from outside the study area, while induced sectors are both consumers and producers and represent sectors induced by the production of exogenous activities.

The mechanism of distribution of households and jobs in space, follows the principle of minimization of generalized cost and thus of maximizing the utility function. The utility function therefore includes both generalized transport costs and location costs. This modeling structure has the ability to reproduce some typical urban cause and effects mechanisms as for example the fact that living in areas with high employment density implies a reduction in transport costs (related to home-work trips), while living in low density area implies reduced localization costs but increased transportation costs.

The interface model is finally represented by an input/output matrix, which has the function to manage the interaction between the two sub-models (transport and activity sub-models) and which essentially transforms economic interactions between activities in transport interactions, that is economic flows in transport flows. Then it calculates costs and transport disutilities which will influence the interactions of activity in next simulations, reproducing the feedback loop between transport and land use (Wegener, 2010).

3. The Tranus model for the French region of Nord-Pas-de-Calais

The Tranus model for the French region of Nord-Pas-de-Calais was designed mainly to simulate, analyze and evaluate interaction between transport, activities and residential systems with a multi-scale approach, which includes urban, suburban and regional scales, in different time horizons (Lo Feudo, 2014).

In particular, the main objective of this modeling research was to test the application of a regional plan of Transit Oriented Development (TOD) (Calthorpe, 1993, Cervero, 1998, Bertolini & Split, 1998), with the aim of concentrating future urban development as much as possible near main regional railway corridors and nodes.

TOD is in fact a model of urban and territorial development which favours mixing and compact urban densification near transit corridors and nodes, giving priority to active modes and public transport. Basically TOD consists in concentrating quality urban development around rail stations or interchange nodes, to encourage use of public transport (Bertolini, and al., on 2009) and with the aim of reducing natural land consumption, urban sprawl and car dependence.

Most important theoretical references of TOD could be found in previous concepts of *Garden City* (Howard, 1898) and of *Linear City* (Soria y Mata, 1926), with the intent to adapt these principles to complexity of contemporary cities and to create an alternative to *automobility* (Urry, 2003), which strongly characterized transport and urban planning in the last decades (F. Lo Feudo, 2014).

The fundamental interest of the model is the analysis of effects of these integrated policies with the aim of resolving some territorial priority issues found in the main regional strategic planning documents (Conseil Régional NPDC, 2013), such as urban sprawl, excessive consumption of natural land and car dependence.

North-Pas-de-Calais is a region well equipped in transports infrastructures and located in a strategic geographical position, between Brussels and Paris. Despite significant regional investments in last years to improve railway network and public transport services, car still results largely predominant in mobility practices (see *Figure 1*).

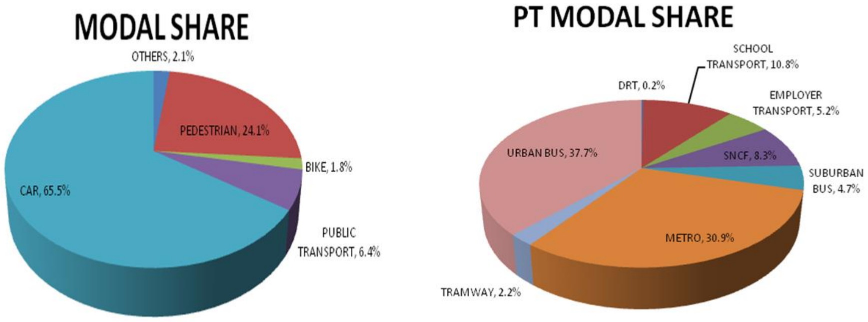

Figure 1. Modal share and public transport modal share in the study area in the base scenario (2010). (Conseil Régional NPDC, 2010).

Most important transport flows are in direction of the metropolitan area of Lille, main regional economic pole, originated mainly from the central urban area and from the urban agglomerations of Valenciennes and Dunkerque. Smaller but not negligible flows occur also among medium urban agglomerations located along the ideal arc, placed at south of Lille (see *Figure 2*) defined "*Arc sud*". In that context is evident a greater dynamism of the north part of the region, concerning economic activities and mobility, also influenced by its cross-border nature.

In regional strategic planning documents railway is considered as the element on which to found and build future development, following principles of environmental and energy sustainability, economic growth and quality of life. In this regard, some regional rail corridors have been identified as potentially capable of hosting TOD interventions. Then, on these areas, were simulated, in a time horizon of 16 years (2009-2025), hypothesis of progressive urban densification, improvement of public transport supply quality, as well as the application of policies of integrated public transport ticketing and of discouraging car use.

The main objective was to evaluate effects of these policies on residential and activities location and modal share evolution.

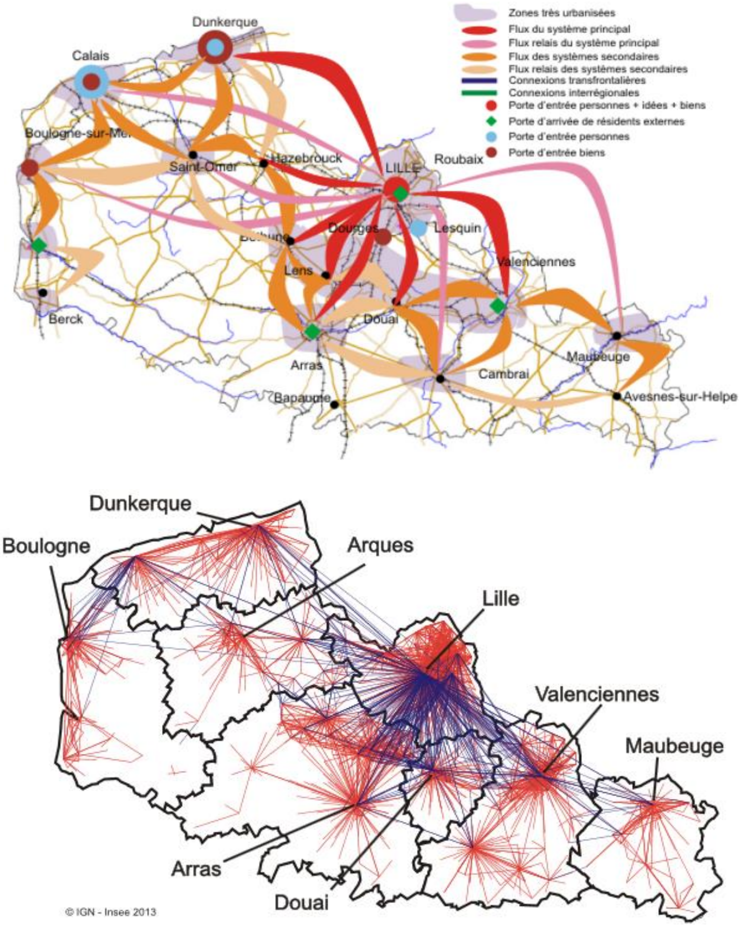

Figure 2. Structuration et interconnexions en Nord-Pas-de-Calais (Fabre, 2012).

4. Structure of the model

For zoning characterization of the Tranus model 16 urban zones were defined, representing main regional cities of Nord-Pas-de-Calais. The agglomeration effect was also considered, grouping each main regional city with most important adjacent peripheral municipalities, following building and morphological continuity.

Metropolitan agglomeration of Lille (*Lille Metropole Communauté Urbaine*) was instead divided in 21 different zones, related to most representative municipalities. Furthermore 15 zones corresponding to the rest of regional territory were considered, according to institutional limits of main regional employ areas (*Zones d'Emplois*). Finally were also identified 14 "*TOD zones*", corresponding to groups of two or more municipalities containing rail stations sufficiently integrated with the surrounding urban fabric (F. Lo Feudo, 2014). To take account of the cross-border nature of the regional territory of Nord-Pas-de-Calais, 7 external zones were also defined.

The model considers three household categories in function of income levels (high, medium and low income) and two transport categories related to home-work and home-service trips. The whole operative and physical transport supply was loaded in the model and several parameters were defined, characterizing mobility behaviors of each transport demand category. In particular the transport sub-model considers the morning rush hour period (7:00 – 9:00 a.m.) and only motorized inter-zonal trips (internal zonal trips and no-motorized trips are not considered)[3].

Furthermore two exogenous activity sectors (industry and construction; agriculture) and two induced activity sectors (public tertiary and service tertiary) were defined, with correspondent number of employs for each zone of the model.

Land use sectors are exclusively related to urbanized land and to empty land for new urbanization, without considering natural land. Seven land use types were considered: residential land; continuous urban dense land or mixed land; collective residential land; isolated residential land; activity land; empty land; *TOD land* (introduced in the model to represent land with housing density levels of 10% - 15% higher than existing residential and mixed land). For each type of land available surfaces were calculated and rental prices par unit of surface were estimated.

Three alternative scenarios have been implemented on a time horizon of 16 years, from 2009 (base scenario) until 2025. A *trend scenario* (scenario A) was implemented assuming any change in transport and land use policies. A *TOD scenario* (scenario B) was implemented referred to the application of a *TOD Regional Plan* that provides, in some specific areas (TOD zones), interventions of

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[3] Internal zonal trips cannot be simulated in Tranus, therefore in the model are simulated only inter-zonal trips and bike and pedestrian trips related to transfers between transport modes and connections to zone centroids. That is actually an unfavourable condition to evaluate and verify expected effects of TOD hypothesis; because normally the most important positive impacts of TOD mixed densification interventions are related to proximity and not motorized mobility.

progressive mixed and multifunctional urban densification and of improving public transport frequencies of service. From this second scenario was also developed a third scenario *TOD + scenario* (scenario C), which provides in addition to scenario B, some supplementary interventions to discourage car use, such as the introduction of motorway tolls and of an integrated ticketing system between regional rail services and urban and suburban bus services.

Hypothesis of densification applied in scenario B and C, consist specifically of interventions of urban renewal and regeneration (without consuming natural or agricultural areas), transforming progressively part of existing empty and residential land, in mixed, multifunctional and dense land and thus in *TOD land*.

According to TOD principle, *TOD land* is in fact characterized by high quality of urban design and high public transport connectivity and accessibility. This quality attributes of TOD urban space were reproduced in Tranus using some parameters called attractors, assuming a gain of attractiveness for areas affected by TOD interventions.

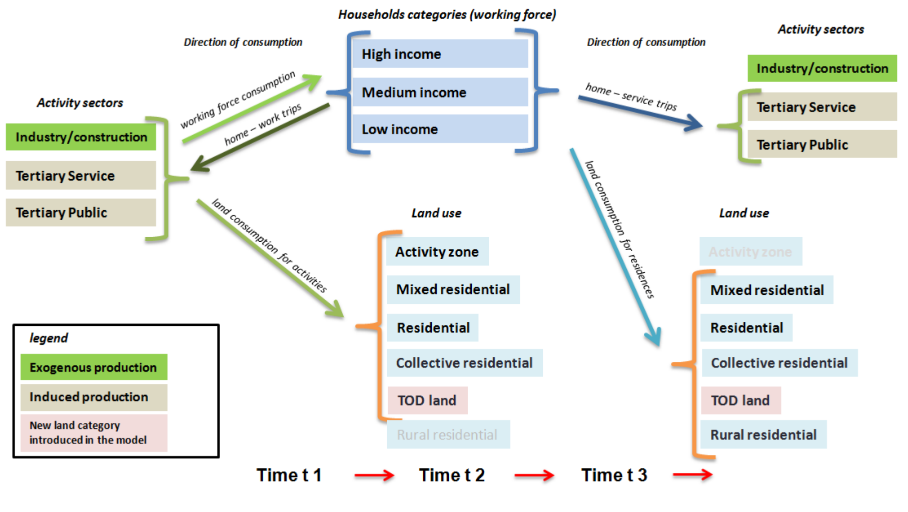

Figure 3. Interactions between sectors in the Tranus model for North-Pas-de-Calais.

5. Model results and evidences of the communicating vessels principle

Results of the model, as exposed in detailed in (Lo Feudo, 2014), show that without specific actions, an intensification of urban sprawl would be observed, especially in Lille metropolitan area and in urban central area of the region.

In scenario A at 2025 (the last simulation period) most of growth is in fact located in rural zones, perceived more attractive than urban and TOD zones, consequently indicating an intensification of urban sprawl.

Interventions of multifunctional and mixed urban densification following TOD principles, simulated in scenario B, show a reversed trend. Residences and activities, hence households and jobs are mainly located nearby urban and TOD zones, even more distinctly in scenario C, demonstrating an increase of attractiveness of mixed, dense and public transport well-connected areas (see Figure 4). After the introduction of TOD hypothesis, rural and detached land consumption remains almost constant, even decreasing for high income households, in contrast with urban mixed land consumption, that generally increase for all demand sectors. Results related to land prices evolution also show how TOD interventions applied in scenario B and C contribute to improve land values in TOD zones.

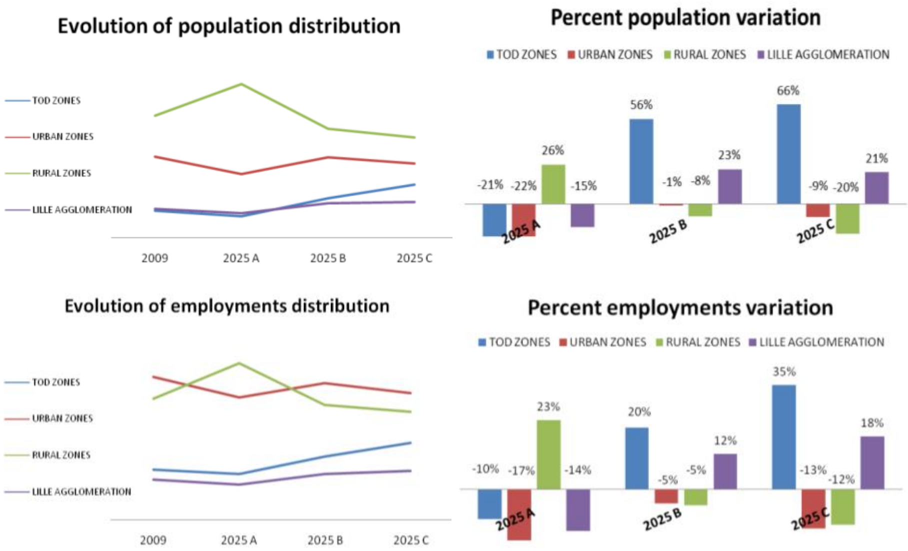

Figure 4. Evolution of population and employment in the study area.

Transport results also show a positive effect of *TOD Regional Plan* in increasing modal share for public transport (see Figure 5). In particular results (considering motorized and inter-zonal trips only) show how public transport rates of frequentation redouble in the last time of simulation of scenario C. We also observe that at 2025, the strategic objective, considered in regional transport planning documents (Conseil Régional NPDC, 2013), of doubling number of passengers for regional rail services is reached in scenario B and even exceeded in Scenario C (see Figure 6).

In particular we observe that rail corridors that link Lille metropolitan area to the central urban area of the region (Lens, Douai, Bethune) and to the TOD zone located in the south of Valenciennes (including municipalities of Denain, Somain and Bouchain), give a positive response to TOD interventions.

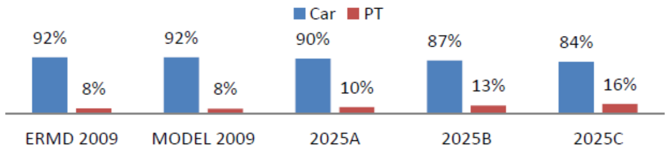

Figure 5. Evolution of transport demand modal share between car and public transport. (F. Lo Feudo, 2014)

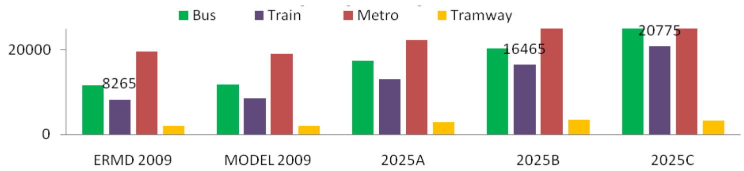

Figure 6. Total trips evolution by transport mode. (F. Lo Feudo, 2014)

We can argue that the strategic position of these rail corridors, located on the axis Brussels-Lille-Paris, in a large and attractive jobs and residences regional polarity, and affected by important and growing transport flows directed to Lille, promotes a positive response to TOD interventions (see Figure 7).

More attractive and more efficient public transport services, seems to generally increase attractiveness for areas on which were activated TOD interventions.

Analyzing modal share for each single TOD zone, results give a trend that essentially reproduce the total modal share data, with some more favorable effects in zones closeness to rail corridors previously described.

However we observe in two TOD zones (TOD zone of Armentières and TOD zone of Denain, Somain, Bouchain, in the south of Valenciennes), a different trend, with public transport modal share that decreases in the last scenario (the most favorable to public transport) (see Figure 8).

Figure 7. Evolution of railway services rate of frequentation. (F. Lo Feudo, 2014)

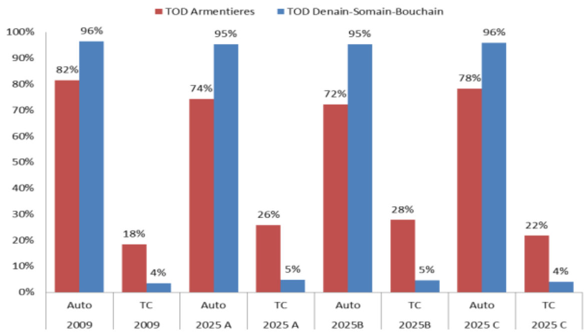

Figure 8. Evolution of transport demand modal share in TOD zones of Armentieres and Denain-Somain-Bouchain (in the south of Valenciennes). (F. Lo Feudo, 2014)

Moreover these transport results are associated with a general increase of transport demand in these two zones, due to the significant growth of population and employees (especially for tertiary activity sectors) in the last simulation scenario (effects of TOD densification hypothesis) (see Figure 9 *and* Figure 10).

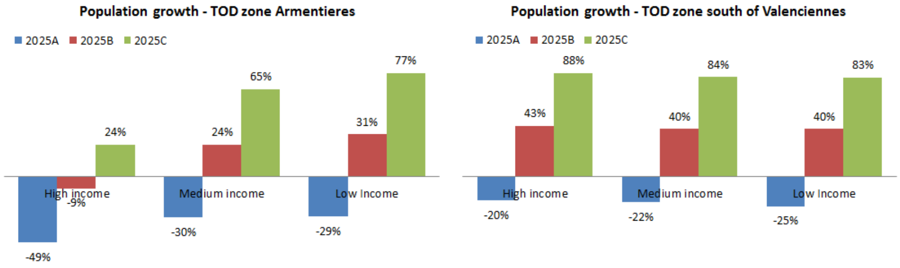

Figure 9. Population growth in two TOD zones at 2025, by simulation scenario.

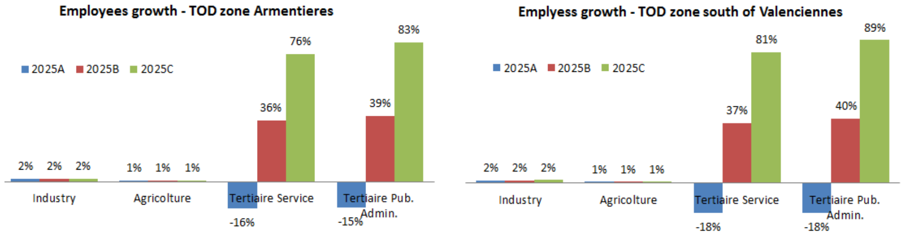

Figure 10. Employment growth in two TOD zones at 2025, by simulation scenario.

To understand the reason of these unexpected results was analyzed the Tranus output related to evolution of road level of service[4]. Results about road network level of service show in fact that in last simulation period of scenario C there is a significant reduction of highway congestion levels and therefore an increase in average speed.

If we consider the specific case of the TOD zone of Armentières, we can say that the gradual reduction of road congestion of highway A25 (consequently to increased public transport rate of frequentation), added to the high level of road accessibility and connectivity of this zone (that represents a strategic access point to Lille agglomeration), induced on this specific highway section, in scenario C, an initial increase of public transport rate of frequentation (simulation periods 2013, 2017, 2021) and then a return of attractiveness for private car (simulation period of 2025).

[4] Level of service (LOS) is a qualitative measure used to analyse the quality of traffic service. LOS standards are defined in the Highway Capacity Manual (HCM), published by the Transportation Research Board (TRB) and in the Geometric Design of Highways and Streets, published by AASHTO (American Association of State Highway and Transportation Officials), using letters A through F, with A being the best and F being the worst.

The same mechanism can be found in correspondence of the TOD zone located in the south of Valenciennes, where in scenario C the A2 highway section that connects Valenciennes to Cambrai, becomes completely decongested and characterized by the maximum level of service (level A). Also in this TOD zone private car became more attractive in the simulation scenario C, the most favorable to public transport (see Figure 11 and Figure 12).

Basically TOD hypothesis applied to our study area, leading gradually to a significant reduction of traffic congestion, bring cars in the last simulation time to regain attractiveness (especially in two TOD zones particularly well-connected to highway network), hence to the activation of an initial substitution effect between private car and public transport demand (generalized in the entire study area), followed by a re-equilibration, that we define as a communicating vessels effect, in favor of private car.

This situation is however quite limited, because in all other zones of the model public transport modal share generally grows in TOD scenarios, even if there is a general improvement of traffic conditions and road levels of service. TOD zones of Armentières and in the south of Valenciennes are very well road-connected, with high level of commuter flows directed to Lille agglomeration and dramatically affected by road congestion in the base time period (2009), in particular during rush hours. These two zones seem therefore incorporate many of different conditions that influence the activation of substitution and communicating vessels effects, applied to mobility and transport dynamics (Bovy et al., 1991).

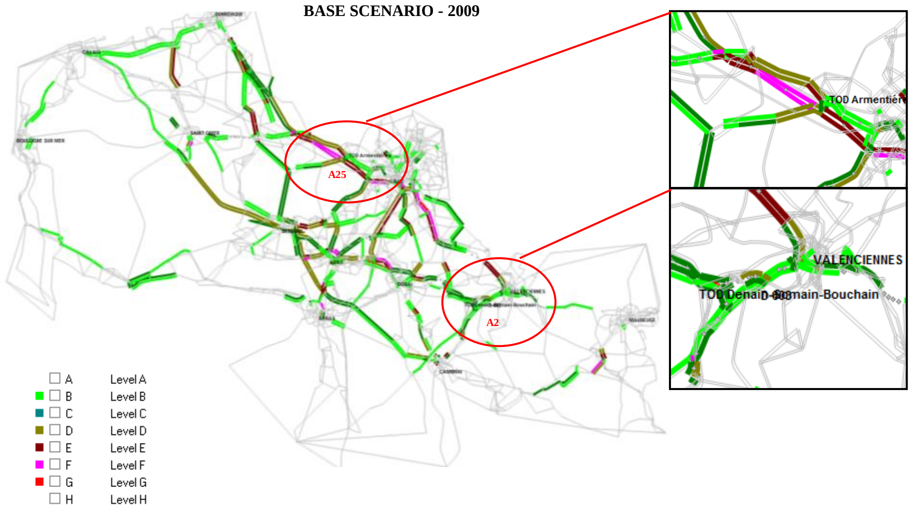

Figure 11. Evolution of road network level of services at 2009 in the base scenari..
(F. Lo Feudo, 2014)

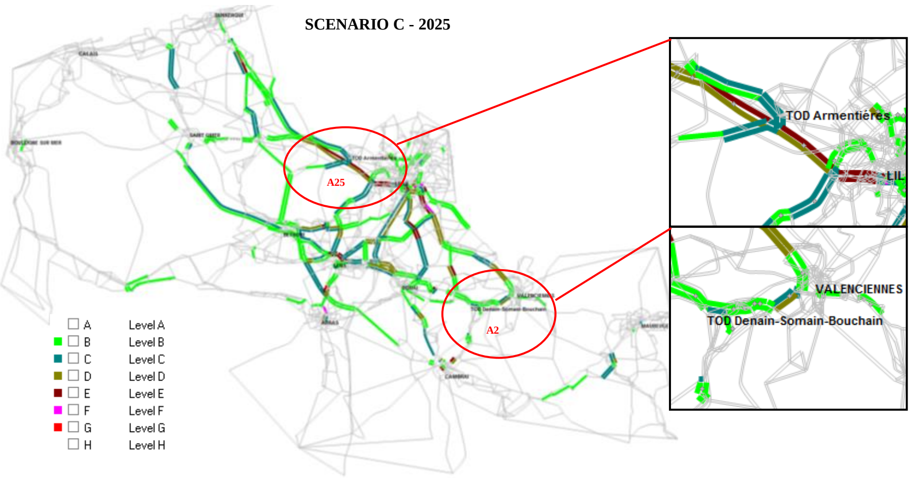

Figure 12. Evolution of road network level of services at 2025 in Scenario C. (F. Lo Feudo, 2014)

6. Further considerations about the sequence of substitution and communicating vessels effects

In accord with theory of demand, a change in price or in transport costs (in Tranus generalized transport costs include monetary costs and perceived travel and waiting time (Modelistica, 2103)), keeping constant utility, will cause an increase of consumption, therefore there is an inverse relationship between transport cost and demand.

This inverse relationship produces an income and a substitution effect. Income effect means that lower prices allow users to have the same consumption level with less expenditure (Button, Vega et Nijkamp 2010). Moreover if consumption of two goods (or services) increases as income rises, these are normal goods, while if consumption of one within two goods decreases as income rises, hence this is an inferior good.

Furthermore according to cross elasticity of demand, if ratio between changes in demanded quantity of a good (or service) B and changes in price of a good (or service) A is positive, goods are substitutes, otherwise are complementary. Furthermore cross elasticity is zero when two goods or services are not related and the substitution effect increases proportionally in function of number of available substitutes (choice options) for consumers (Fouquet 2012).

Results of the model show the activation of a substitution effect related to distribution of transport demand between private car and public transport.

Substitution effect favors private car or public transport, depending on modeling assumptions and on different simulation scenarios, demonstrating a greater sensitivity to some specific factors: households and activities location trends, levels of congestion, speed and travel time, frequencies of public transport services.

In two particular zones, according to theory of demand, was observed that during the first three simulation periods (2013, 2017, 2021), generalized transport costs for private car increased, due to strong road congestion, while demand for public transport increased, thanks also to TOD interventions (population and activity densification; improvement of public transport frequencies), hence activating a substitution effect.

In the last simulation period (2025), highway congestion levels resulted significantly reduced, while despite an increasing demand for public transport, generalized transport costs for private car decreased, hence public transport and private car became complementary.

Following the substitution effect, reduction in traffic congestion levels restores a comparative advantage for cars versus public transport, leading to the activation of a communicating vessels effect. This trend indicates how transport demand progressively level off, following a temporary and instable equilibrium, influenced among others by demand behaviors and by physical and operative constraints of infrastructure and transport services.

The model essentially provides an empirical confirmation of the existence of a substitution effect between private cars and public transport and of a communicating vessels effect that attenuates this substitution effect. This sequence of substitution and communicating vessels effects, takes place in particular time intervals and conditions and the same factors that determine the activation of substitution effect also influence timing of activation of communicating vessels effect.

Therefore results show the existence of a permanent state of tension in modal share that in the short term induces to consider private car and public transport as substitutes, while in the long term as complementary. In the short term high levels of road congestion (high private car transport costs) associated with increased public transport frequencies, induce to lower private car demand and higher public transport demand (behaving as substitutes). In the long term high rates of public transport use induce lower road congestion levels (lower private car transport costs), thus higher private car demand (behaving as complementary).

Other authors affirm that the substitution effect between private car and public transport occurs only in some specific situations, depending on trip purpose, traveled distance and segments of transport demand.

In particular Baanderr *et al*. (2011) affirms that, as confirmed by results of the Tranus model, substitution effects happen only in presence of severe congestion, in areas close to large urban centers and in reference to more *stable* transport demand segments, as *house - school* and *home - work* trips.

Bovy *et al.* (1991) also affirms that some particular transport demand segments related to public transport and private car cannot overlap and therefore cannot be included in the substitution effect and thus in the communicating vessels effect.

Some examples of these limitations are the fact that private car is available 24 hours a day while public transport services are available only in service hours, and the fact that public transport services are more accessible in urban areas instead of rural areas (Bovy et al., 1991).

These considerations are a further confirmation of the validity of Tranus model results, which mainly considers *home - work* trips during morning rush hours. Bovy *et al.* (1991) in fact also affirms that other trip purposes, so-called chains of displacements (which includes various types of activities before reaching final destination), are not included in the substitution and communicating vessels effects between public transport and private car.

Baanderr *et al.* (2011) also sustains that activation of communicating vessels effect can be observed only in situations where car and public transport are strongly competitive, providing a further explanation of why return of attractiveness for private car has not occurred in other zones of the model, affected by low congestion and more distant from urban areas. Anyway these considerations cannot prevent to suppose that communicating vessels effect could also happens in other zones of the model, but with different temporalities, that go beyond the simulation period.

A this regard is important to precise that if we can observe a sort of "temporal dynamics" in the context of the modeling exercise presented in this article, that is essentially related to the succession of multiple states of equilibrium, temporary (because they relate to specific time intervals) and interdependent (because each is influenced by the previous equilibrium generated by the model). Anyway the controversy over differences in potentiality, consistency and reliability between *static* and *dynamic* LUTI models goes beyond the intentions of this article.

The model for the French region of Nord-Pas-de-Calais considers five times of simulation, with intervals of four years (from 2009 to 2025); in line therefore with Tranus characteristics identified by N. Coulombel (2006), which makes it particularly suitable to simulate long-term process. The succession of several equilibrium states, relating to different time simulations, gives the appearance of a temporal evolution in model results. A level of evolution that is enough to read a temporal cause and effect dynamic in the process of interaction between supply and demand of transport.

The five times of simulation allow comparing short and long term effects (24 years can be considered as long term compared to phenomena analyzed in that model), in terms of evolution of transport demand modal share. On the other hand it is clear that other more specific events, such as for example rate of frequentation of a specific bus stop, would be more difficult to analyze considering given zoning and model structure.

It is also clear that, as explained in paragraph 2 of this article, the calculation process of Tranus related to capacity restrictions, have a considerable impact on the nature and evolution of obtained results.

Analyzing these results from a point of view more oriented to strategic and operative planning, we can also observe that factors and conditions necessary to the activation of the sequence of substitution and communicating vessels effects, can alternatively favors private car or public transport and in some situations cancel or notably downsize effects of policies and actions encouraging public transport use (Baanders *et al.* 2011).

This is also the case of this model where return of attractiveness for private car occurs exactly in the simulation period where most favorable policies to public transport use are applied. Therefore observed communicating vessels effect, invites to consider public transport as not necessarily competitive and alternative to private car, but rather as complementary, in particular in the case of long term TOD plans.

This necessarily implies the need to consider, in the phase of strategic planning, all possible unexpected reciprocal effects that some transport and land use planning policies can arise. In the phase of operative planning the main need is instead of providing a continuous action of observation, control and adaptation of implemented policies, to well manage modal share evolution.

In particular planners have to consider the tendency of transport demand to be distributed following multiple temporary and instable equilibriums, which in turn are influenced by transport costs, user's perceptions and behaviors and by planning actions.

7. Conclusions

Model results show the ability of a TOD intervention extended to the entire region of Nord-Pas-de-Calais, to limit or at least moderate urban sprawl, promote urban development along main corridors of the regional rail network and increase use of public transport. However were observed unexpected results, related to return of attractiveness of private cars as a result of highway congestion reduction in two TOD zones of the model, in the last simulation scenario (more favorable to public transport).

A phenomenon that should be explained through the activation of a substitution effect followed by a communicating vessels effect, which influenced transport demand distribution between private car and public transport, depending on travel costs and congestion levels, following a principle of succession between multiple temporary and instable states of equilibrium.

Furthermore the fact that these effects do not appear in other zones of the model, indicates that the sequence of substitution and communicating vessels effects occurs only in some specific contexts and time intervals, depending on particular conditions (stable demand segments; strong competition between car and public transport; high levels of congestion; proximity to attractive urban agglomerations).

In particular results show the existence of a permanent and instable state of tension in modal share that induces to consider private car and public transport as substitutes in the short term and as complementary in the long term.

Referring to strategic and operative planning, possible activation of substitution and communicating vessels effects, demonstrates that the application of policies encouraging use of public transport (interventions of TOD in the case of this model), may have controversial long-term effects and contrary to expectations. To answer and react to this trend planners have to develop the ability of constantly controlling and adapting policies and interventions, in function of their potential differentiated and reciprocal impacts and of equilibrium evolution between car and public transport costs.

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