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A MODEL TO EVALUATE THE HUBBING EFFECT ON TRANSPORTATION NETWORKS

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This Thesis was deemed appropriate to obtain the title of Doctor of Engineering and approved in its final version by the Post-graduate program in Industrial Systems Engineering.

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This thesis is dedicated to my family, who supported me throughout this journey of knowledge.

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An investment in knowledge [always] pays the best interest.
(Benjamin Franklin)

ABSTRACT

Logistics hubs are flow-concentrating structures that affect the success of transportation network design and supply chain management, influencing the distribution system as a whole. Although such terminals have been around for some time, it has been only recently that a concern about measuring their impact on goods distribution has emerged. In light of this, a network flow model that supports the evaluation of the hubbing effect on freight transportation networks has been developed. The first step was to devise a general framework that covers the most important aspect of logistics terminals, and guides the classification of these facilities. The framework is based on three aspects that permeate the development of this research: infrastructure availability, type of products handled, and market coverage, which consequently influence the function of each terminal. From that, we bring an updated perspective on the definition of logistics hubs. Having in mind the type of facility and the characteristics of real transportation networks, we verify that the evaluation of the hubbing effect is a result of two major decisions: hub location and flow allocation. Yet, while hub location is an established field of knowledge, the models available in the literature present limitations for flow allocation that are related to topology design, representation of supply-demand relationships, and implementation of economies of scale. Hence, a new flow model has been proposed, with a graph adaptable to different supply chains and freight networks, containing one or more hubs. The attributes of the network and the modeling approach allowed applying the mathematical formulation for the minimum-cost flow problem and Network Simplex proved to be the best algorithm for solving this problem, both in terms of speed and robustness. The proposed model was then tested using real data from the Brazilian poultry supply chain and the road network of the state of Santa Catarina. Results obtained ratified the importance of representing full networks, and of properly applying economies of scale. They further uncovered trade-offs between economies of scale and flow allocation, hub geographic coverage, demand fulfillment, and infrastructure availability – aspects influenced by logistics hubs. Results from this evaluation may be useful for business managers, which could gain insights on plant location, identification of supply routes, and visualization of changes in consumer markets. They may also support decision making when addressing logistics infrastructure challenges, especially those of developing economies, reducing processing costs and improving the quality of investment analyses.

Keywords: Logistics hub. Hubbing effect. Transportation. Network flow. Infrastructure.

RESUMO

Plataformas logísticas são hubs concentradores de fluxo que afetam o sucesso do design das redes de transportes e da gestão das cadeias de suprimentos, influenciando o sistema de distribuição como um todo. Embora esse tipo de terminal já seja conhecido há algum tempo, foi somente recentemente que surgiu uma preocupação em medir o seu impacto no transporte de produtos. Assim, esse trabalho apresenta um modelo de fluxo em redes que dá suporte à avaliação do efeito do hub na rede, conhecido como *hubbing effect*. Para alcançar este objetivo, o primeiro passo consistiu na elaboração de uma estrutura que abrangesse os principais aspectos dos terminais logísticos, servindo de guia para a classificação destas instalações. Tal estrutura se baseia em três aspectos, que permeiam o desenvolvimento da presente pesquisa como um todo: disponibilidade de infraestrutura, tipos de produtos manuseados e cobertura de mercado, os quais consequentemente determinam a função de cada terminal. A partir daí, construiu-se uma perspectiva atualizada sobre o conceito de plataforma logística. Tendo em vista o tipo de instalação e as características das redes de transporte na prática, verificou-se que a avaliação do *hubbing effect* é resultado de duas decisões principais: localização da plataforma e alocação de fluxo. Todavia, embora a localização de hubs seja uma área de conhecimento já estabelecida, os modelos disponíveis na literatura apresentam limitações para a alocação de fluxos que estão relacionados ao desenho da topologia da rede, à representação das relações de oferta e demanda, e à aplicação de economias de escala. Diante disso, foi proposto um novo modelo de rede, através de um grafo adaptável a diferentes cadeias de suprimentos e redes de transporte, contendo uma ou mais plataformas. Os atributos da rede e a abordagem de modelagem permitiram utilizar a formulação matemática para o problema de fluxo de custo mínimo e o algoritmo Network Simplex mostrou-se a melhor ferramenta para resolver o problema, tanto em termos de velocidade de solução quanto de robustez. O modelo proposto foi testado na prática utilizando dados da cadeia de produtos de proteína animal no Brasil e a rede de transportes do estado de Santa Catarina. Os resultados obtidos ratificaram a importância de representar topologias completas e de aplicar corretamente os descontos das economias de escala. Além disso, foi possível observar *trade-offs* entre as economias de escala e a alocação de fluxos, cobertura geográfica, atendimento de demanda e disponibilidade de infraestrutura – aspectos influenciados pelas plataformas logísticas. A avaliação do *hubbing effect* mostra-se útil para a indústria, que pode obter informações sobre a localização de plantas, identificação de rotas de transporte e mudanças nos mercados consumidores. Por outro lado, serve de apoio para enfrentar os desafios da infraestrutura de transporte e logística, especialmente em países em desenvolvimento, reduzindo custos e melhorando a qualidade das análises de investimento.

Palavras-chave: Plataforma logística. *Hubbing effect*. Fluxos em rede. Transporte. Infraestrutura.

RESUMO EXPANDIDO

Introdução

Plataformas logísticas são hubs concentradores de fluxo que afetam o sucesso do design das redes de transportes e da gestão das cadeias de suprimentos, influenciando o sistema de distribuição como um todo. Eles apoiam as operações da cadeia de abastecimento, tornando-se componentes importantes do uso do território e da coesão geográfica. Desse modo, a compreensão da alocação de fluxo torna-se indispensável para avaliar adequadamente as economias de escala que podem ser alcançadas com essas instalações. Há, no entanto, uma escassez de modelos na literatura que permitam avaliar a influência de um hub na rede de transportes, conhecido como *hubbing effect*. Os efeitos dessa ausência são ser observados através da variedade de redes de transporte com hubs ineficientes encontradas na prática. Isso se torna evidente em países em desenvolvimento, como o Brasil, onde as dificuldades no planejamento de infraestrutura de logística e transporte resultam em redes predominantemente rodoviárias e na falta de instalações tipo *buffer* além dos terminais portuários. Por outro lado, o desenvolvimento de estratégias para gerenciar a demanda por infraestrutura, como aquelas que incluem a análise do *hubbing effect*, melhora as opções de transporte, permite alcançar custos mais baixos e aumenta a acessibilidade local, levando a soluções ganha-ganha. Ao passo que o Banco Mundial aponta a logística como cada vez mais presente na formulação de planos de investimento e políticas públicas, alguns exemplos bem sucedidos da implementação de hubs logísticos já podem ser encontrados na Europa e na América do Norte. Como resultado, economias de escala são obtidas devido a um melhor projeto de rede.

Objetivo

Propor um modelo de fluxo em redes que dê suporte à avaliação do *hubbing effect*, considerando aspectos inerentes da distribuição de produtos através de redes de transporte que contenham um ou mais hubs logísticos.

Metodologia

A estrutura que dá suporte ao desenvolvimento desta tese está baseada na perspectiva de pesquisa operacional para a solução de problemas, e contempla quatro etapas: i) definição do problema; ii) construção do modelo; iii) solução do modelo; e, iv) validação do modelo. A primeira etapa foi realizada com o auxílio de três revisões de literatura. A primeira adotou uma abordagem estruturada para fazer uma análise terciária dos modelos de classificação de terminais logísticos. A segunda consistiu numa revisão tradicional, que teve como objetivo a caracterização dos hubs logísticos, que são o objeto de estudo desta tese. Tendo em vista este conceito, a terceira revisão de literatura objetivou a avaliação da aplicabilidade de modelos de localização de hubs para a alocação de fluxos em redes de transportes. Devido às características particulares das redes de transportes na prática, esta análise permitiu a identificação da melhor abordagem metodológica para a avaliação do *hubbing effect*. Uma vez que um modelo apropriado isto não estava disponível na literatura, um novo modelo conceitual de grafo que representa as redes de transporte com hubs foi elaborado. O principal conceito por trás desse modelo consiste na criação de uma topologia em dois níveis, através da qual as cargas podem trafegar para obter economias de escala quando o hub é utilizado. Em seguida, o problema de alocação de fluxos foi traduzido em um modelo matemático apropriado este tipo de rede, tendo como função objetivo a minimização dos custos de transporte. Para avaliar o *hubbing effect* e comparar seu impacto com redes de transporte tradicionais, o problema de alocação de fluxo foi solucionado para duas redes: uma rede básica e uma rede com hub. Nesse caso, o modelo de fluxo de custo mínimo foi o que melhor representou os objetivos e restrições da alocação de fluxos nos grafos desenhados. Graças aos aspectos lineares do modelo de fluxo de custo mínimo, foi possível solucionar o problema com o uso do Network Simplex, ferramenta mais apropriada para a alocação de fluxos neste cenário em termos de estabilidade para solucionar diferentes instâncias de problemas. Para validar se o modelo proposto descrevia corretamente o comportamento de hubs logísticos em redes de transporte, uma aplicação prática na rede rodoviária do estado de Santa Catarina foi realizada. A alocação de fluxos foi verificada para produtos de frango congelado da cadeia de suprimentos de proteína animal. Com estes resultados, foi possível então observar e avaliar o *hubbing effect*.

Resultados e discussão

O ponto de partida do desenvolvimento do modelo proposto consistiu no desenvolvimento de uma classificação para os terminais logísticos e do conceito de hubs logísticos. Tal estrutura está baseada em três aspectos: disponibilidade de infraestrutura, tipos de produtos manuseados e cobertura de mercado, os quais consequentemente determinam a função de cada terminal. Tendo em vista o tipo de instalação e as características das redes de transporte na prática, verificou-se que a avaliação do *hubbing effect* é resultado de duas decisões principais: localização da instalação e alocação de fluxo. Todavia, os modelos disponíveis na literatura apresentaram limitações para a alocação de fluxos que estão relacionados ao desenho da topologia da rede, à representação das relações de oferta-demanda e à aplicação de economias de escala. Enquanto estes modelos se encaixam para redes com hubs que possuem características do transporte aéreo e dos serviços postais, aquelas que exibem a capilaridade das redes rodoviárias necessitam de uma estrutura de grafo mais detalhada.

O modelo proposto foi implementado na prática e o efeito do hub observado através da análise da variação das economias de escala no grafo proposto. Foi possível verificar o efeito da inclusão dos hubs nas redes de transportes sob três perspectivas. A primeira delas consiste na concentração de fluxos no hub: observou-se uma tendência da roteirização de cargas, especialmente as de longa distância, através do hub. Essa consolidação de fluxos está relacionada com a disponibilização de melhores conexões entre os nós de origem e destino, traduzidas no modelo por custos de transportes mais baixos. Por outro lado, os resultados encontrados ratificam o fato de que o uso de instalações intermediárias leva a um aumento nas distâncias trafegadas e nos tempos de viagem. O segundo efeito está relacionado com a área de cobertura do hub e os mercados servidos. Isso significa que as economias de escala influenciam não somente a área de cobertura do hub através do número de fornecedores que utilizam a instalação, mas também impactam os padrões de atendimento de demanda, com a redefinição das relações de oferta-demanda na busca dos menores custos de transporte da rede. Por fim, a intensidade do uso da infraestrutura também é influenciada pelo hub. Foi possível observar mudanças consideráveis nas rotas de transporte em razão da variação das economias de escala – informação importante no planejamento da construção de infraestrutura. Todos estes resultados ratificam a importância de representar topologias completas e de aplicar corretamente as economias de escala.

Considerações finais

Embora o modelo proposto represente um ambiente complexo dos sistemas de transporte e logística, os atributos da rede e a abordagem de modelagem adotada permitiam a utilização de um modelo matemático

bem estabelecido de fácil aplicação prática. Uma variedade de análises pôde ser realizada, especialmente devido a duas características principais do design do grafo. A primeira diz respeito à topologia em dois níveis, a qual permite que sejam avaliados separadamente os fluxos que atravessam o hub daqueles que não utilizam este tipo de instalação. A identificação de diferentes tipos de produtos que podem ser manuseados no hub teve papel essencial nessa forma de dividir a rede. O segundo aspecto está relacionado com o nível de detalhe utilizado para desenhar as conexões da rede, que, junto à topologia de dois níveis, possibilita a aplicação de economias de escala específicas em qualquer seção da rede. Além disso, é possível também modelar os custos de utilizar os hubs logísticos e seus serviços especializados. Dessa forma, a topologia proposta traz benefícios importantes devido à facilidade de adaptar a sua estrutura a diferentes cenários de infraestrutura de transporte e cadeias de suprimentos. A análise da alocação de fluxos realizada por meio da aplicação prática revelou uma variedade de *trade-offs* entre economias de escala e alocação de fluxos, cobertura geográfica das instalações, atendimento de demanda e disponibilidade de infraestrutura. Uma análise mais aprofundada desses *trafe-offs* mostra que eles estão diretamente relacionados com a estrutura que guia a classificação de terminais logísticos, baseada no tipo de produto, cobertura de mercado e infraestrutura. Essa consistência entre os resultados obtidos e as características das redes de transportes com hubs confere confiabilidade ao modelo proposto, evidenciando a sua aplicabilidade na avaliação do *hubbing effect*.

A avaliação do *hubbing effect* mostra-se útil para a indústria, que pode obter informações sobre a localização de plantas, identificação de rotas de transporte e mudanças nos mercados consumidores. Por outro lado, serve de apoio para enfrentar os desafios da infraestrutura de transporte e logística, especialmente em países em desenvolvimento, reduzindo custos e melhorando a qualidade das análises de investimento.

Palavras-chave: Plataforma logística. *Hubbing effect*. Fluxos em rede. Transporte. Infraestrutura.

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LIST OF ABBREVIATIONS AND ACRONYMS

ABNT – Associação Brasileira de Normas Técnicas
AHP – Analytic Hierarchy Process
CAS – Capacity Scaling
COS – Cost Scaling
DN – Demand Nodes
GDP – Gross Domestic Product
GIS – Geographic Information System
HLP – Hub Location Problem
ICT – Information and Communication Technologies
LEMON – Library for Efficient Modeling and Optimization in Networks
LPI – Logistics Performance Index
LSP – Logistics Services Providers
MCDM – Multiple-criteria Decision Making
MCF – Minimum-cost flow
MILP – Mixed Integer Linear Programming
MIP – Mixed Integer Programming
NP – non-polynomial
NS – Network Simplex
PELT-SC – Logistics and Transportation Plan of Santa Catarina
PLAZA – Plataforma Logistica de Zaragoza
POMS – Production and Operations Management Society
SN – Supply Nodes
SSP – Successive Shortest Path
SWOT - Strengths, Weaknesses, Opportunities and Threats
TOPSIS – Technique for Order of Preference by Similarity to Ideal Solution
UCC – Urban Consolidation Centers
UNCTAD – United Nations Conference on Trade and Development
UNECE – United Nations Economic Commission for Europe
UNESCAP – United Nations Economic and Social Commission for Asia and the Pacific

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INTRODUCTION

Transportation networks have been expanded considerably in the last decades in order to increase regionalization, provide better logistics services, and add capacity to the existing infrastructure. This expansion is not only related to transportation ways, but also to a variety of logistics facilities, such as warehouses, distribution centers and seaports, being motivated by changes in consumer markets, globalization of production sites and pursuit of cost reduction. In this context, logistics hubs stand out as terminals where value-added operations are performed, product flows are consolidated, and information is made available across local, regional, and international borders. They support supply chain operations, becoming important components of territory use and geographic cohesion (RODRIGUE; COMTOIS; SLACK, 2017).

The growing importance of hubs for logistics operations can be associated to switching from an anticipatory supply chain scenario to a response-based logistics context (LEE; HUANG; TENG, 2009). This becomes possible because hubs function as buffers, i.e. they allow flow regulation for the coordination and integration of freight, as well as of information, enabling flexible management solutions with mutual support and cooperation between supply chain players (DING, 2013; FERNANDES; RODRIGUES, 2009; KABASHKIN, 2007; RODRIGUE; NOTTEBOOM, 2009). As buffers, hubs can also be used to reduce supply chain risks, aiding in the minimization of delays and other problems due to currency fluctuation, political uncertainties, strikes, trade barriers, government policies and natural disasters (MELO; NICKEL; SALDANHA-DA-GAMA, 2009). In turn, the polarization of logistics services at hubs accounts for improvements in operations, which can be achieved not only by sharing facilities and infrastructure, but also by the interaction between world-class logistics players (CAMBRA-FIERRO; RUIZ-BENITEZ, 2009; GRUNDEY; RIMIENĖ, 2007; HIGGINS; FERGUSON; KANAROGLOU, 2012; NOTTEBOOM; RODRIGUE, 2009).

The possibility of flow consolidation allows exploiting economies of scale, which are associated to the reduction of logistics costs incurred when linking origins and destinations through the connections available in hub networks (ALMEIDA; AMARAL; MORABITO, 2016; PEKER et al., 2016). While efficient and well-positioned hubs boost this scenario, they also compensate transportation lead-times, even though the speed of transportation modes has not significantly increased in the last decades (RODRIGUE; COMTOIS; SLACK, 2017). Thereby, the ability of a hub to provide scale economies is directly related to its location and connectivity to the transportation network. The movement of goods will be carried out throughout the available connections between the different elements of the infrastructure, taking advantage of the existing transportation ways and facilities. The infrastructure configuration will influence the nature, origin, destination, distance, and movement of goods, as well as the market coverage that can be achieved (RODRIGUE; COMTOIS; SLACK, 2017). The implementation of logistics hubs, in turn, influences the need for future infrastructure, fostering the development of more efficient ways and connections, which will probably impact future flow allocation. With this, it becomes evident the existence of a dual relationship between infrastructure and flow distribution, as also observed by Campbell and O'kelly (2012).

Based on the premise that logistics hubs have the ability to influence the efficiency of freight distribution, and impact the volume of trade, understanding flow allocation becomes indispensable to properly evaluate the economies of scale that can be achieved with such facilities (FARAHANI et al., 2013). Nonetheless, Farahani et al. (2013), Farahani, Seif and Asgari (2010), and Melo, Nickel and Saldanha-Da-Gama (2009) point out that there is a shortage of frameworks that allow the evaluation of the influence exerted by a hub in the network, known as *hubbing effect*. The authors highlight the need to investigate the implementation of logistics hubs under the perspectives of transportation systems design and supply chain management. Dablanc and Ross (2012) and Ding (2013) also point out that academic studies usually do not include logistics terminals in the context of freight infrastructure planning.

A couple of reasons could help to explain this gap, related to the network representation and the evaluation perspective adopted. The majority of network flow models that concern the addition of a hub to the network do not fully represent the flexible structures of real transportation networks. They consider more elementary topologies, such as pure or hybrid networks, identified by Guastaroba, Speranza and Vigo (2016), which have as goal to find the best hub location and allocate suppliers and customers to the facility. This seems inherent to the perspective of private warehouses and distribution centers. While these models abstract key features of such networks, they consequently neglect important aspects of the underlying freight distribution system, as noted by Campbell (2013), Campbell and O’kelly (2012), and Peker et al. (2016). Due to this, it becomes hard to draw conclusions about the hubbing effect, since there are no details about the paths of flow allocation. On the other hand, the few works that consider the available infrastructure and its accessibility take a focus on operational aspects of the hub without actually evaluating the entire transportation system, as seen in Kabashkin (2007) and Rahimi, Asef-Vaziri and Harrison (2008).

A myriad of incompatible and disconnected hub networks follow from the lack of tools to study and evaluate the hubbing effect. As observed by Rahimi, Asef-Vaziri and Harrison (2008), the number of logistics hubs have grown over the years based on decisions that disregard how the terminals will interact with supply chain players, available infrastructure and markets to be served. In some cases, planners will only consider or evaluate a facility and its potential to change flows and traffic after the project is already under execution. As a result, many terminals end up being served by only one mode of transportation, and distribution channels become more complex, expensive, and ineffective.

This becomes evident in developing countries like Brazil, where difficulties in transportation infrastructure planning arise, leading to the predominance of roadways and to a shortage of buffer facilities other than import/export terminals (DUBKE; PIZZOLATO, 2011; LI; LIU; CHEN, 2011). In these cases, the lack of flexibility and the limited capacity of the network actually lead to a situation where other infrastructure elements are not seen as effective alternatives for the improvement of the transportation system. This situation is corroborated by the low positions occupied by developing countries throughout the years in performance indexes that evaluate logistics and transportation infrastructure, such as the Logistics Performance Index, issued by The World Bank (2016).

On the other hand, some successful examples of the proper implementation of logistics hubs can be found, such as the logistics cluster of Zaragoza, in Spain (SHEFFI, 2012). The development of strategies to manage the demand for infrastructure, such as those that include the hubbing effect analysis, improves transportation options, allow achieving lower costs and increases local accessibility, leading to win-win solutions (LITMAN, 2013). A report by The World Bank (2014), points out that logistics has been increasingly present in the formulation of investment plans and public policies, with the collaboration of government, local, regional, and international organizations. This ultimately results in economies of scale being obtained due to a better network design (CAMPBELL; O'KELLY, 2012).

In light of this, a model that allows including logistics hubs as part of real transportation networks is proposed, which can be used as a decision support tool to evaluate the hubbing effect, both by the public and private sectors.

1 GOALS

1.1 RESEARCH QUESTION

How to evaluate the hubbing effect on transportation networks?

1.2 SPECIFIC GOALS

The specific goals of this research are:

a. Conceptualize logistics hubs;
b. Evaluate models and methods available in literature for logistics hub location and flow allocation;
c. Determine a network model to evaluate the hubbing effect on real transportation networks;

Identify a method and algorithm for flow allocation; and

d. Verify the practical applicability of the proposed model.

2 LIMITATIONS

The size and characteristics of real transportation networks and supply chains were determinant to the adoption of an analytical methodology to evaluate the hubbing effect. This approach allows treating separately the problems of hub location and flow allocation, differently from the traditional hub location models. Flow allocation will be performed considering predefined hub locations on the network. Thus, the problem of locating the hub will not be addressed in this thesis and the location will be treated as an input to the flow allocation problem. Yet, this decision allows testing different network configurations and using hubbing effect information to refine location decisions.

The costs incurred in the implementation of logistics hubs will not be considered since the goal of this research is to evaluate the effect of such intermediate facilities over flow allocation. Since we will not evaluate the location, size and number of hubs to be installed, this aspect can be, at first, disregarded. Besides, there is a greater interest in the possibilities of using hub, expansion of its coverage area and changes in market served than in the necessary investment costs per se (TURSKIS; ZAVADSKAS, 2010). Likewise, constructive, environmental and geologic aspects, such as land availability, will not be taken in account. Although we are aware that these factors could influence the hub location decision, they do not impact on the proposed model directly.

The proposed model allows the proper application of discount factors in all arcs of the network, as suggested in literature, which can be defined as constants or functions according to the activities performed at the hub. Yet, the definition of the function that represents economies of scale is not in the scope of this research. As commonly found in literature, constant discount factors between 0.5 and 0.9 are applied to the network, which enables the generation of a variety of hubbing effect scenarios. Likewise, decisions related to which logistics services will be performed at the hub will not be addressed, although they influence the extent of economies that can be obtained with the addition of hubs. Yet, the model allows modeling such costs per volume of goods with the use of a specific arc, called the interhub arc.

It is assumed that shippers will decide on whether or not to use the hub based on two criteria: i) transportation costs, set as parameters, and ii) need to fulfill demand, modeled as restrictions. There are other factors that, in practice, may influence this decision, such as the service level required by a customer or the type of product; yet, while the choice of service is hard to model in a macroeconomic analysis, it is possible to split flow allocation into a series of single commodity problem instances because arc capacities are loose.

Finally, although changes in transportation costs may impact on hub location and flow allocation decisions, the proposed model will be developed in the scope of a determinist scenario. However, this issue can be overcome through sensitivity analysis, which evidences the possible alterations to flow allocation when such parameters are changed (KLAPITA; ŠVECOVÁ, 2006). Yet, this type of analysis will not be performed in this thesis. For an example of a dynamic approach in hub location, the reader may refer to the paper of Taner and Kara (2016).

3 METHODOLOGICAL PROCEDURES

This section presents an overview of the methodological procedures employed to answer the research question posed in this thesis. Because of the choice to present the thesis content as a set of articles, details of the materials and methods applied were described accordingly within each paper.

To structure the development of this thesis, the perspective of operations research for problem solving was adopted, as proposed by Morabito, Neto and Pureza (2012). It comprises five stages: i) problem definition; ii) model construction; iii) model solution; iv) model validation; and v) solution implementation. We followed the first four stages; the last one was not in the scope of this thesis. Different methods were used to solve each stage of this approach. The combination of procedures enables a holistic comprehension of the phenomena studied, leading to highly productive results with less risks of being biased, especially in the field of operations and supply chain management (BAHRI, 2009; KAPLAN; DUCHON, 1988). Likewise, the application of multiple methods allows closing the gap between theoretical development and practical application, granting robustness to the final results.

The first stage, i.e. the problem definition, was performed with the aid of three literature reviews. They build the thesis foundations through the definition of concepts, determination of the scope of application, and evaluation of mathematical models available. The first review adopted a structured approach to perform a tertiary analysis of classification frameworks for logistics terminals. The second review consisted of a traditional literature review, which had the goal to characterize a special type of terminal – the logistics hub – that is the object of study in this thesis. Having in mind the logistics hub concept, the third literature review aimed at evaluating the applicability of hub location models to flow allocation in transportation networks. Due to the particular characteristics of such networks in practice, this analysis allowed to identify the best methodological approach for the evaluation of the hubbing effect.

Since an appropriate graph to evaluate the hubbing effect was not found in literature, a conceptual model of a graph that represents hub transportation networks was at first devised. The main idea behind this graph design lies on creating a two level topology, throughout which shipments can traverse in order to obtain economies of scale if the hub is used. The goal of this step was to ensure that there is a link between the reality of hub transportation networks and the elaborated graph model. Next, flow allocation problem was translated into a mathematical model that was appropriate to the hub network and to the objective of finding the lowest transportation cost overall. In order to evaluate the hubbing effect and compare its impact against regular transportation networks, the allocation problem needed to be solved for two networks: a base network and a hub network. Thanks to the topology adopted in the graph, the same mathematical model could be used for both networks. In this case, the minimum-cost flow (MCF) problem was the one that best represented the objectives and restriction of flow allocation throughout the graph designed. Because hubs are structures that handle a large variety of products, MCF problems commonly take the shape of a multi-commodity network flow problem in this context. Nonetheless, due to specific characteristics that allowed relaxing some problem restrictions, we were able to split the MCF problem in instances of single-commodity problems, one for each product.

Thanks to the linear aspects of the mathematical model, it was possible to solve the MCF problem with mathematical programming tools. Four different algorithms were tested in order to identify the most suitable one in terms of speed and robustness in terms of stability to solve different problem instances. A total of 212 test instances were solved over the Brazilian road network, considering goods distribution in 12 different supply chains. Results from the evaluation indicated that the Network Simplex was the most appropriate tool for flow allocation throughout hub transportation networks. The algorithms implementation is available with full source code as part of the LEMON optimization library, an open source C++ library dedicated to solving graphs and networks combinatorial optimization problems (KIRÁLY; KOVÁCS, 2012). Codes were compiled using Visual Studio 2015 and experiments were conducted on an Intel® Core™ i7-2620M CPU @ 2.70GHz machine, with 8GB RAM memory, using Windows 7 operating system.

In order to validate if the proposed model properly described the behavior of logistics hubs in transportation networks, a practical application on the transportation network of the state of Santa Catarina was performed. Flow allocation was solved for frozen poultry goods from the animal products supply chain. All data and network parameters were available from the PELT-SC project, including the location of the hub, developed by the Supply Networks Group, which defined a logistics and transportation plan for infrastructure investment in Santa

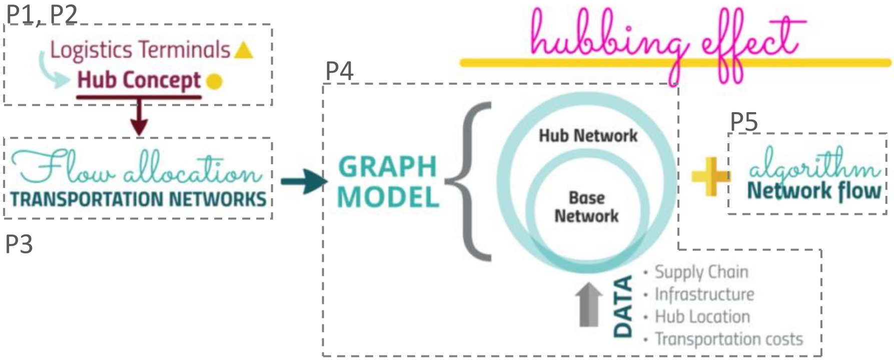
Catarina. From that, it was then possible to observe and evaluate the hubbing effect.

Due to the multi-method approach adopted, this thesis takes on different classification perspectives, according to each stage accomplished while devising the model to evaluate the hubbing effect on transportation networks. Regarding its main goal, it is an empirical research, because it concerns the development of a model that comprises aspects existent and observable in practice when a hub is added to a real transportation network. Secondly, it is quantitative because it explores the implementation of mathematical methods to solve the problem of flow allocation throughout the network. Finally, it takes on a descriptive role since the results obtained from the model validation enable evaluating the impact of hubs on supply-demand relationships and transportation infrastructure.

4 THESIS STRUCTURE

The structure of this thesis is organized as depicted in Figure 1, which translates the four stages of the operations research approach used in this research. The content is organized as a collection of five manuscripts P1-5, indicated in Figure 1, which have been accepted in conferences, published in peer-reviewed journals, or are under review.

Figure 1 - Thesis structure.



The first two papers, P1 and P2, bring forward the conceptual definitions. Grounded on the structured review, the first article presents a framework to support the classification of logistics terminals, based on the aspects that influence the function of logistics hubs in supply chains and transportation networks. Entitled “A framework to guide the classification of logistics terminals”, it is under review at the journal *Transport Reviews*. On the other hand, the concept and characteristics of logistics hubs, devised from the second literature review, can be found in the paper entitled “A new perspective on the concept of logistics hubs”, which has been presented at the *27th POMS conference*, in May 2016.

The boundaries of the network model and the methodological approach used to solve the flow allocation problem in hub transportation networks resulted from the third literature review (P3). It comprises an evaluation of hub location models and their applicability to transportation networks. Results from this analysis, included in the paper “Models and methods for logistics hub location: a review towards transportation networks design”, have been published in the journal *Pesquisa Operacional*.

The network flow model that enables the evaluation of the hubbing effect in real transportation networks is presented in paper P4. Entitled “A model to evaluate the hubbing effect on transportation networks”, this manuscript describes the graph model that depicts the two-level topology for such hub networks, as well as the mathematical model adopted. In order to increase the reliability of the proposed model, a practical application was also included, which was solved for frozen poultry products over the road network of the State of Santa Catarina.

The analysis that grounds the choice of the most efficient algorithm for solving the single-commodity MCF problem is described in the paper “Minimum-cost flow algorithms: a performance evaluation using the Brazilian road network” (P5). Although logistics hubs are not included in this analysis, results are also applicable to the graph model designed because of the topology used for such transportation networks. This paper has been accepted for presentation at the *21st Conference of the International Federation of Operational Research Societies*, which will take place in July 2017. Since the analysis of flow algorithms is used in the practical application, the article “Minimum-cost flow algorithms: a performance evaluation using the Brazilian road network” is presented in this thesis before the paper entitled “A model to evaluate the hubbing effect on transportation networks”.

A final section ties together the findings of all papers, brings general conclusions and suggests avenues of future research. To avoid duplicity of content, the references of all papers have been condensed in a single bibliography section at the end of this document. To conform to the ABNT rules and keep a consistent layout throughout this document, the content of the published articles and their references were formatted to follow the ABNT standards.

A FRAMEWORK TO GUIDE THE CLASSIFICATION OF LOGISTICS TERMINALS

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Abstract

The functionality of logistics terminals has evolved over time from traditional services, offered individually, to sophisticated and highly automated value-added services. Due to the diversity of facilities and terminologies used to identify them, a variety of classification systems has emerged in the literature with the goal of defining a proper categorization for such structures. These frameworks are based on terminal evolution, their context of application, or even attributes of the infrastructure available, and can be found in the form of hierarchic or feature-differentiation structures. Although authors seem to agree on the main criteria that drive the development of typologies and taxonomies for such facilities, there is still a lack of consensus in the literature about the classification and definition of logistics terminals. In light of this, we performed a structured tertiary review that summarizes and evaluates the results of multiple literature review studies, which address the classification of logistics terminals. Using a novel approach that dissociates from the usual perspectives, we devise a general framework that underlays the conceptuality of terminals categories and considers the basic characteristics needed to distinguish between facilities. The structure is based on three aspects: infrastructure, market coverage and type of products handled, which can be combined to determine the function and role of a terminal in supply chains. It supports the classification of logistics terminals as it pieces these aspects together so that facilities can be categorized using a single framework. It is flexible enough to fit plain or hierarchic structures, and to devise typologies or taxonomies for both generic and specialized facilities.

Keywords: logistics terminal, classification, literature review

1 INTRODUCTION

Roadways, waterways, railways, airways, pipelines, and terminals are parts of the transportation infrastructure of a region that have the power to influence considerably the efficiency of a logistics network. Over time, the characteristics of transportation ways have changed very little, but the same cannot be claimed about terminals. As time goes by, new generations of facilities emerge in response to changes in production, logistics costs and market location due to globalization, boosted by reduced trade barriers and requirements of more complex and value-added logistics services (GRUNDEY; RIMIENĖ, 2007; HIGGINS; FERGUSON; KANAROGLOU, 2012; MEIDUTĖ, 2005; NOTTEBOOM et al., 2016). Following this evolutionary trend, facilities changed and became fundamental elements of local, regional and international transportation systems (HIGGINS; FERGUSON; KANAROGLOU, 2012).

The expansion of facilities functionality from traditional individually offered services, such as storage and shipping, to sophisticated and highly automated value-added services, ranging from consolidation, specialized storage and customs clearance, to final assembly, maintenance and financial services has been followed by a myriad of terms to differentiate the variety of logistics facilities (GRUNDEY; RIMIENĖ, 2007). Logistics hub, logistics center, freight village, logistics platform, transport terminal and dry port are expressions widely used, to name a few.

In view of the diversity of facilities and terminologies, many authors suggest classification systems for logistics terminals with the goal of defining a proper categorization of such structures. According to Lambert (2006), the classification of objects within a research domain is indeed an important step towards new investigations on the field since as “theory cannot explain much if it based on an inadequate system of classification” (LAMBERT, 2006). Hence, an appropriate classification scheme can support the theory development, giving order and sense to the research (MEYER; TSUI; HININGS, 1993). Despite the several frameworks presented in the literature, these have a variety of limitations, as highlighted by the authors themselves, which hinder their adoption as a tool to assist the classification of logistics terminals in practice. There is a constant report of a lack of standardization and consensus on the classification and definition of logistics terminals, as pointed out by Cambra-Fierro and Ruiz-Benitez (2009), Grundey and Rimienė (2007), Higgins, Ferguson and Kanaroglou (2012), and Meidutė (2005). This is revealed by the difficulty to fit each facility in a single category (HIGGINS; FERGUSON; KANAROGLOU, 2012) and by the use of a single term to designate different facilities (JARŽEMSKIS; VASILIAUSKAS, 2007). Moreover, terminology and classification are usually place-dependent, as similar facilities are named differently according to the region where they have been developed (MEIDUTĖ, 2005; NOTTEBOOM et al., 2016).

In light of this, our work proposes a comprehensive framework to support the classification of logistics terminals. We focus our analysis on literature reviews due to the variety of such works that have been published so far, which condense and organize classification frameworks devised up to 2016. The majority of reviews have the goal of finding a common classification structure for the classification of logistics terminals as they build on previously developed schemes, yet with no consensus so far about a unique framework. Using a novel approach, we took one-step back from classifications schemes presented by several authors and analyzed the criteria that guided their proposals. Then, we devised a general framework that covers the most important aspects of logistics terminals.

Following from this introduction, section 2 brings forward the diversity of concepts found for logistics terminals, and of classification schemes. Section 3 describes the materials and methods employed to perform a structured tertiary review. The analysis of literature review works is performed in section 4, showing their characteristics, similarities and shortcomings. A new framework to guide the classification of logistics terminals is presented in section 5, and section 6 concludes this paper with some final thoughts about our proposal, including avenues of future research.

2 CONCEPTS OF LOGISTICS TERMINALS

Logistics terminals have been around for some time – according to Grundey and Rimienė (2007), the first logistics facilities of this kind appeared in the 60s. Over time, a great variety of terms has been used to define logistics terminals in literature and practice. Higgins, Ferguson and Kanaroglou (2012) found more than 34 different terms in their research. The most usual expression is logistics center, but other common terminologies include logistics village, logistics park, freight village and dry ports. Logistics terminals are also coined specifically in different countries: in Germany, they are known as *guterverkehrszentrum*, in Italy as *interporti*, in the United Kingdom as *freight village*, in France as *plateforme logistique*, in Spain as *plataforma logística* and in Brazil as *centro integrado de logística* (CAMBRA-FIERRO; RUIZ-BENITEZ, 2009; CATAPAN, 2016;

MEIDUTĖ, 2005). An extensive list of terms and the corresponding authors that mention them can be found in Appendix A.

Still, with so many terms found, there is not yet a single concept that is widely adopted to designate logistics terminals. The definitions found in literature are centered in a variety of aspects and terminology seems to be directly related to the focus of each concept, which range from the availability of transportation modes to the portfolio of logistics services offered, including the ability to integrate supply chain flows. In light of this, we adopt in this paper the generic term *logistics terminal* to designate all sorts of facilities. The word terminal is related to the idea of a convergence point in transportation systems, provided that such facilities tend to consolidate supply chain flows and are more than just warehouses, which usually have a private perspective.

The most common aspect of the logistics terminal concept is related to a facility that allows the integration of transportation modes, as highlighted by Afandizadeh and Moayedfar (2008), Konings (1996), Šulgan (2006), Tsamboulas and Dimitropoulos (1999), and Tsamboulas and Kapros (2003). Cassone and Gattuso (2010) point out that, more than integrating transportation, the terminal should also integrate the different players that operate in the facility, who organize the service structure so that goods can flow smoothly between different modes of transportation.

The agglomeration of different players and services at a delimited geographic area is the basis for a well-accepted concept in the literature, which has been proposed by Europlatforms (2004). Eryuruk, Kalaoglu and Baskak (2011), Jaržemskis (2007), Meidutė (2007), and Silva et al. (2014) agree that a logistics terminal is a hub, established in specific area, where all activities related to transportation, logistics and distribution of goods are carried out on a commercial basis, by various operators. Functioning for both the national and international transits, these facilities should encourage multimodal handling of products, being served by a variety of transportation modes (EUROPLATFORMS, 2004). Savy (2005) and Tambi et al. (2013) use a similar concept to define a logistics village. They consider that these facilities are a center where several companies participate in activities related to transportation and logistics. This idea is expanded by Grundey and Rimienė (2007), Savy (2005), and Sheffi (2012), for whom this consolidation of logistics activities and service providers follows the principles of territorial occupation dynamics, being planned to have a determined geographic market coverage according to the services offered and transportation infrastructure available.

The fact that logistics terminals should have the function of integrating supply chain flows is highlighted by Meidutė (2005). Other authors that adopt this perspective argue that, beyond integrating flows, logistics terminals actually operate as supply chain elements, integrating players throughout different tiers, with different distribution goals (CAMBRA-FIERRO; RUIZ-BENITEZ, 2009; FERNANDES; RODRIGUES, 2009). According to Silva et al. (2014), this integration has a broader aim to allow more efficient and flexible logistics operations to be performed at the terminal. Recent studies ratify that the supply chain coordination aspect is indeed relevant, being used together with the other abovementioned characteristics to define logistics terminals, as observed in Notteboom et al. (2016).

As a result of this diversity of concepts and terminologies, different classification systems arise in the literature in an attempt to find common aspects and categorize logistics terminals. A variety of leading works, which are usually cited in literature, attempt to organize the facilities according to their complexity based on the available infrastructure, concentration of services, scope of activities, function in the transportation network, and/or geographic coverage. One of the first classification frameworks is proposed by Wiegmans, Masurel and Nijkamp (1999) which present a hierarchy of four facilities based on size, geographic coverage, volume of products handled and type of cargo. Leitner and Harrison (2001), in turn, consider transportation modes, demand, location, activities performed for trade facilitation and management strategy. Function and scope of logistics activities are the main criteria considered by Notteboom and Rodrigue (2009) and UNESCAP (2010) to devise their typologies, which will vary according to the specific needs of the consumer market and the respective supply chain (RODRIGUE; NOTTEBOOM, 2009). Savy (2005) proposed a taxonomy based on the geographic concentration of logistics facilities.

While each one of these works tries to find the most appropriate scheme for the categorization of logistics terminals, considering even similar classification aspects, there is also no consensus about a unique framework that could fit all types of facilities. This is corroborated by a variety of literature reviews available in literature, e.g. Grundey and Rimienė (2007), Higgins, Ferguson and Kanaroglou (2012), and Notteboom et al. (2016), that constantly evaluate a wide range of classifications in order to develop a common structure for logistics terminals.

3 MATERIALS AND METHODS

Classification is a procedure that still receives little methodological exposition, as observed throughout this research, although it is basic to social sciences, according to Bailey (1994). The existence of different configurations of things allows people to give order and sense to their worlds (MEYER; TSUI; HININGS, 1993). Such things can be classified in discrete and relatively homogeneous groups that distinguish themselves by similarities and contrasts identified between the objects analyzed (SILVA; ROCHA, 2010). The systematic classification of things into ordered categories through the study of types is commonly broken down into two essential approaches, which have as basic requirement the existence of an underlying theory: typology and taxonomy (BAILEY, 1994).

Typologies are classification systems derived from a theoretical framework and drawn from the differences between objects belonging to a given population (SILVA; ROCHA, 2010). This approach provides the means to sort and compare such objects, as well as to group them into categories, without losing sight of the fundamental diversity and substantiality that exists in each one of the objects (RICH, 1992). According to Lambert (2006), typologies are a product of deductive theory. They are usually devised from qualitative analysis and establish a reasonable foundation for both theoretical and empirical research (BAILEY, 1994). Due to this, a typology may not faithfully represent reality, since it consists of a personal attempt to make sense of non-quantifiable observations, and may have limited explanatory or predictive power (HAMBRICK, 1984). Nonetheless, typologies serve well for descriptive purposes – because they are specific classifications, a great variety of typologies may be developed over time, each one serving a specific purpose (HAMBRICK, 1984). Taxonomies, in turn, are developed from empirical analysis, i.e. from the observation of events in nature, and should be therefore employed only for empirical hierarchic classification systems (RICH, 1992). In line, Baden-Fuller and Morgan (2010) point out that taxonomies comprise classes observed in the world, from an empirical work, and in a bottom-up approach, while for typologies, classes are decided conceptually by the scientist from top to bottom.

A variety of typologies and taxonomies has emerged throughout the years and offer an explanatory potential to the classification of logistics terminals. Yet, if such works are to stand the tests of reason, time and place, their findings must be accumulated and synthesized. This research is structured as a tertiary review to summarize and evaluate the results of multiple literature review studies that address classification schemes of logistics terminals. Through an overarching analysis of multiple analyses, we seek to derive a common structure behind the conceptuality of the classes of logistics terminals, and the characteristics that enable the differentiation between them, either by a typological or taxonomic classification.

The first step carried out to achieve this goal consisted of a systematic review focused on papers that addressed classification schemes for logistics terminals. Using the Scopus database, we started out by searching for terms commonly adopted in the literature to describe logistics terminals, such as *logistics center, logistics hub, logistics platform, transport terminal, mainport terminal, freight village, distripark, logistics node, transport center, transportation hub,* and *distribution hub*. At this stage, our aim was to explore the literature and have an idea of what kind of studies were available regarding the classification of terminals. Results from the database were refined according to the subject area, type of document, title relevance and abstract content, as suggested by Vieira (2012). From the study of the content of these works, we observed that a greater variety of terms was actually employed in the literature to designate logistics terminals. They included: *bulk terminal, distribution terminal, dry port, hinterland terminal, inland clearance depot, inland customs depot, freight terminal, inland port, inland terminal, intermodal and multimodal industrial park, intermodal freight center, intermodal railroad terminal, intermodal terminal, load center, nodal centers for goods, satellite terminal, trade and transportation center inland port, transfer terminal, transmodal terminal, urban consolidation center, urban distribution center, inland freight facility,inland hub,* and *logistics zone*.

One may find a couple of reasons to explain this diversity of terms. On one hand, this is mainly related to expressions describing facilities with similar logistics purposes, e.g. inland terminals or hinterland terminals connected to ports, or that connect different modes of transportation, such as intermodal terminals. On the other hand, some terms result from differentiating between the logistics activities performed at each facility, such as urban consolidation centers and urban distribution centers. Beyond that, there are also the idiomatic variations according to the country where the logistics terminal is installed. In light of this, we extended our search query to include a wider variety of terms that could be used as logistics terminal synonyms, except from those of idiomatic forms due to language barriers.

Next, we built a second group of keywords related to classification and definition of categories in order to narrow down the search results to encompass only the works that had some sort of relation the classification of logistics terminals. The choice of words was based on the definition of typology, classification, framework and their synonyms. Hence, this search group was composed of the following terms: *classification, definition, conceptualization, role, hierarchy, taxonomy, organization, configuration, framework, structure, category, function, typology,* and *rank*.

The results of the search using the two keywords groups were again filtered according to the subject area, type of document, title and abstract concerning to the purpose of this research. Here, we focused on works that performed a review of classification frameworks for logistics terminals. Such papers could have as goal to integrate classification concepts, criticize them, solve conflicts, identify central issues or present the state-of-the-art of this subject. Eleven papers were selected and analyzed in order to characterize the type of research and approach adopted. We distinguished the type of classification framework adopted in each paper between: i) typologies, which are based on theoretical grounds; and ii) taxonomies, which comprise classes observed from empirical works – in accordance with the definitions presented by Baden-Fuller and Morgan (2010), Bailey (1994), Hambrick (1984), and Lambert (2006).

The criteria on which each framework was underpinned were identified, as well as other aspects considered relevant by each author but not included in their original proposal where also identified. We organized these criteria into four groups according to their common and contrasting aspects. Each group included similar criteria and exhibited an internal homogeneity with respect to the group theme; extra care has been taken to avoid overlapping or redundancy among groups. A further analysis of each group allowed us to identify the relationships between them, which resulted in the proposal of a general structure to support the classification of logistics terminals.

4 CLASSIFICATION OF LOGISTICS TERMINALS

The classification of logistics terminals has been a constant theme of interest in the last decade. A variety of papers have tried to overcome the conceptual ambiguity through literature reviews, either by describing the facilities categories available or by proposing new classification schemes based on previous works. The diversity of classification proposals found in the literature increases with the variety of logistics facilities. One can observe that, in an effort to specify the possible types of terminals, authors tended to consider more and more classification criteria and types of facilities throughout the years.

It is interesting to notice that the effort to organize the knowledge about the classification of logistics terminals emerged in places where this kind of facility is extensively used as an element to improve transportation systems and supply chain performance. The first three reviews that shed light into this matter have been developed in Eastern Europe, especially by Lithuanian researches such as Meidutė (2005) and Grundey and Rimienė (2007). The development of logistics terminals in this region is related to the lower construction costs, when compared to other East European regions, as well as to the fact that Lithuania is considered an important connecting point in the context of European trade and logistics (GRUNDEY; RIMIENĖ, 2007). Hence, there is a need to understand the type of terminals that can be implemented and how they will function to stimulate the collaboration between different business players. The importance of these first works is confirmed by other authors that built their analysis based on previous findings, e.g. Higgins, Ferguson and Kanaroglou (2012), Nam and Song (2011), Notteboom et al. (2016), and Rožić, Rogić and Bajor (2016).

These works usually adopt a neutral representation perspective for the content, in most cases presenting arguments for new frameworks based on an attempt to summarize prior classifications found in literature. Although the extent of literature coverage of such works is not explicit, one may verify that their reference lists are representative, especially because authors commonly use the same references. In fact, recent works tend to cite all previous reviews.

4.1 CLASSIFICATION REVIEWS

In general, the classification reviews propose frameworks to categorize logistics terminals based on previous works found in literature. While some papers deliberately organize content in order to devise a standardized hierarchy, such as Higgins, Ferguson and Kanaroglou (2012), others end up bringing definitions for different categories as a result of an investigation about the concept of such facilities, e.g. Grundey and Rimienė (2007). The majority of works used previous literature review works to support the proposal of a new classification scheme of logistics terminals, while others were built upon frameworks devised both in theory and in cases studies or real-world examples. Although some authors stated the type of classification framework proposed, we differentiate them between typologies or taxonomies mainly based on the methodological approach adopted: theoretical or empirical, respectively. A summary of the classification reviews identified can be found in Table 1.

The first review identified is presented by Meidutė (2005), which proposes a structure to differentiate logistics centers based on the facility purpose. Through a comparative analysis of different concepts of logistics centers, the author concludes that there is no clear viewpoint on a single definition for such facilities. Although this is not a systematic review, the paper seems to be the first to summarize the concepts proposed in the literature, examining them based on an epistemological analysis of the terms logistics and center. As a result, Meidutė (2005) devises a twofold typology, where logistics centers are defined: i) based on the role of the facility as part of the transportation infrastructure, especially designed to develop transportation activities; or ii) as a generator of business, being perceived as a facility to create secure and beneficial business conditions. The author also finds some regional preference for one type or the other. While the first is favored in Europe and Central Asia, the second is preferred by American and Asian scientists.

A couple of years later, Grundey and Rimienė (2007) also attempted to build a typology grounded on the concept of logistics centers. Their classification approach is supported by a hierarchic structure based on the evolution of the logistics center concept and, consequently, on the scope of the logistics activities performed at such facilities. Through a non-systematic comprehensive review, Grundey and Rimienė (2007) organize the types of logistics centers found in their review in three classes. The levels range from the smallest scope of activities, where the operational focus lies on collection and delivery of goods, to the highest, where a variety of transportation modes are connected in order to concentrate high volumes with lowers costs, high capacity utilization and IT-intensive operations for international transactions. This classification also implies that facility size grows accordingly.

Because of the great variety of terms found in the literature to define the facilities present in each hierarchic level, Grundey and

Rimienė (2007) highlight that their proposal should be used with care and that “the model can be applied only if citing the [respective] authors”. They recognize that each center may differ according to the emphasis that is given, and a distribution center, for example, may be classified in more than one level. They finally propose a single concept of logistics center that takes into account aspects of intermodality, network connectivity, service providing, variety of logistics facilities and geographic coverage, which should be applicable to a variety of logistics centers.

Differently from the abovementioned reviews, which take a broad perspective on logistics terminals, Roso, Woxenius and Lumsden (2009) propose a hierarchic classification for a specific type of facility: dry ports. The authors start by synthesizing the literature and determine three types of dry ports, i.e. distant, midrange and close, taking into account their function and location in the hinterland. The infrastructure availability is also an aspect to be considered, as observed by Roso, Woxenius and Lumsden (2009), especially due to the intense use of railways to connect facilities. According to the authors, the three types of facilities can also work integrated in transportation networks, allowing to increase connectivity and coordinate seaport flows, offering value-added logistics services and saving port physical space.

Besides the theoretical review, Roso, Woxenius and Lumsden (2009) verify the applicability of their classification scheme in practice with examples of dry ports in the United States, Tanzania, Australia. It thus characterizes their proposal as a taxonomy. With this, they expand the conventional concept of dry ports as facilities that merely connect a seaport with its hinterland to an understanding where dry ports are used as an element to secure markets in the hinterland, offer better services and reduce congestion at seaport cities.

Table 1- Classification frameworks proposed from literature reviews.

AUTHOR	COUNTRY	CLASSIFICATION TYPE	CLASSIFICATION CATEGORIES	CLASSIFICATION CRITERIA
Meidutė (2005)	Lithuania	Typology	Objectives of logistics centers: i. a part of the transportation infrastructure ii. a generator of business	Location Available infrastructure Business environment
Grundey and Rimienė (2007)	Lithuania	Typology	Hierarchic levels of logistics centers: i. warehouse and distribution center ii. transport terminal, logistics center and freight village iii. logistics node	Scope of logistics activities Facility size
Roso, Woxenius and Lumsden (2009)	Sweden	Taxonomy	Dry port proximity to maritime port: i. close ii. mid- range iii. distant	Function Location Infrastructure available Volume of flow
Nam and Song (2011)	United Kingdom	Typology	Perspectives of logistics center: i. traditional or logistics and supply chain, that includes warehouses and distribution centers ii. transport or freight perspective, with freight village/logistics nodes and freight terminals iii. international facility location perspective, including international logistics zones	Function Infrastructure Services offered Geographic coverage
Higgins, Ferguson and Kanaroglou (2012)	Canada	Typology	Hierarchic levels of logistics centers: i. warehouses, distribution center; container yard and inland container depot ii. intermodal terminal, inland port and freight village iii. gateways	Terminal size Influence in regional transport Function in regional transport Value-added services Volume of products

Allen et al. (2014)	United Kingdom	Taxonomy	Objectives of urban consolidation centers service: i. all or part of an urban area ii. large sites with a single landlord such as a shopping center, airport, or hospital iii. major construction sites	Product type Location Services offered Terms of use (compulsory or voluntary) Type of urban area served
Notteboom et al. (2016)	Italy, China, Belgium	Typology	Function of the logistics facilities and infrastructure: i. storage, deposit and warehousing ii. cargo transloading and rapid transit iii. Value-added-services and soft/light manufacturing	Functional criteria Infrastructural size Geographical market scope Position in transport and commodity chains Strategy Organization and technology Governance settings

In an effort to differentiate maritime logistics hubs from the variety of existing terminals, Nam and Song (2011) organize the concepts of logistics centers available in literature according to three perspectives. While the first has a more traditional focus, which encompasses facilities for logistics and supply chain activities of warehousing and distribution, the second is related to freight transportation, with the purpose of expanding geographic coverage and functioning as intermodal extensions of other facilities. The third perspective adopts an international terminal focus, especially regarding free trade zones and customs clearance facilities for import/export trade.

Nam and Song (2011) also highlight the evolutionary aspect of the logistics center concept, similarly to Grundey and Rimienė (2007) and Meidutė (2005). Thereby, the three perspectives proposed by Nam and Song (2011) are further used to classify logistics centers into a hierarchy of five levels, pointing out each level's key characteristics. In fact, the terminals identified and the typology described resembles the proposal of Grundey and Rimienė (2007), with the addition of dry ports, based on a work by Roso, who also devises a taxonomy for such facilities in Roso, Woxenius and Lumsden (2009). Although the review procedures are not explicitly structured, the reference list is extensive and considers most of the papers regarding logistics center classification up to the date of its publication. Based on these works, Nam and Song (2011) expand the previous typologies with the addition of geographic coverage and infrastructure availability as important classification criteria.

Higgins, Ferguson and Kanaroglou (2012) seem to be the first authors to present a clear and well-organized literature review regarding typologies of logistics centers. They consider previous classification papers identified in our study, as well as technical reports, and other established works related to the conceptualization of such facilities. In order to integrate logistics centers in a hierarchic typology, Higgins, Ferguson and Kanaroglou (2012) identify eight different logistics centers: warehouses, distribution centers, containers yards, inland container depots, intermodal terminals, inland ports, freight villages, and mainport terminals. Following the same methodological procedure of Grundey and Rimienė (2007) and Nam and Song (2011), these logistics centers are classified into three levels, which are related to the complexity of each facility. This complexity is translated into functionally, scope of value-added services, and geographic influence. Thereby, the framework devised by Higgins, Ferguson and Kanaroglou

(2012) shows a strong influence from works that consider the facility function in transportation networks as links to connect the hinterland at different levels, as well as terminal scale, as seen in Notteboom and Rodrigue (2009) and Wiegmans, Masurel and Nijkamp (1999).

In the same way as Roso, Woxenius and Lumsden (2009), Allen et al. (2014) focus on a specific type of logistics terminal; the authors consider only those facilities destined to urban logistics operations. Allen et al. (2014) use the same methodological approach and perform a literature review, followed by the evaluation case studies, in order to devise a classification of urban consolidation centers (UCC). Three types of UCCs are defined, namely: i) those that serve urban areas with spatial features of narrow street, historic layouts, and limited unloading spaces; ii) those that serve large sites with a single landlord, such as shopping centers, airports and hospitals; and iii) those that serve major construction sites. Six case studies in the United Kingdom, Sweden and Monaco are used to establish the attributes of UCCs and ratify the taxonomy applicability.

It is interesting to notice that the proposal of categories by Allen et al. (2014) is based primarily on the type of urban area served, their spatial characteristics, and the type of products processed in the UCC. Each one of the centers may offer "from basic consolidation and delivery services to a wide range of value-added activities" (ALLEN et al., 2014). In the same way as dry ports, these UCC facilities also have a goal of reducing traffic and congestion in cities.

Due to the attributes chosen by Allen et al. (2014), and differently from the other approaches found in literature, their taxonomy does not exhibit a hierarchic structure. Actually, depending on the criteria used to classify logistics terminals, a framework might not embed a hierarchic structure. While the majority of authors adopt a wide perspective of logistics terminals to elaborate a hierarchic structure, Allen et al. (2014) show that the characterization of specialized terminals does not necessarily require such framework.

The most recent review seeks to overcome the much-discussed conceptual ambiguity of logistics centers. After an extensive literature review, Notteboom et al. (2016) used a structured methodology based on temporal and spatial evolution of the concept of logistics center to propose a typology – an approach similar to the one adopted by Grundey and Rimienė (2007), Meidutė (2005), and Nam and Song (2011). The primary function of logistics centers is taken as a key criterion for clustering facilities, besides other dimensions related to infrastructure size, geographic market scope, position in transportation/commodity chains, strategy, organization and technology, and governance settings. This broad range of criteria is a summary of those considered by other authors since the 50s, and creates the possibility of having 18 different classes of logistics centers.

Taking into account the primary function of logistics centers, the three groups of facility are focused on either storage, deposit and warehousing; cargo transloading and rapid transit; or value-added-services and soft/light manufacturing (NOTTEBOOM et al., 2016). In this approach, facilities rise in the typology based on the complexity of logistics services and their ability to add value to the operations. The other criteria are used to describe the characteristics of each logistics terminal rather than defining their ranked position. In each one of the categories proposed, Notteboom et al. (2016) also fit a variety of logistics terminals terms, as commonly found in the literature.

4.2 DESCRIPTIVE REVIEWS

Some authors adopt a more neutral position and simply provide a description of the types of logistics terminals found in the literature. Cassone and Gattuso (2010) perform an exhaustive review about the representation of intermodal terminals, having as goal to devise functional and topological models for container ports and freight villages. With respect to the functional representation, the authors present six models of intermodal nodes, which are employed to draw two generic block diagrams (for ports and freight villages) that show the typical utilities of each terminal and the connections within. The topological representations, in turn, are based on eight models that guide the design of two graphs that depict the various phases of goods handling in such facilities. Through the analysis of both the functional and topological models proposed, Cassone and Gattuso (2010) stress the role of intermodal nodes to the efficiency of supply chains. They further propose an analytical model to represent cost functions that allow evaluating the costs of handling products at ports and freight villages.

Silva et al. (2014), on the other hand, present a systematic and extensive review about the concept of logistics platforms, which aims to describe the typologies and characteristics of such facilities. Yet, the authors reveal no effort to propose a classification framework or to integrate the concepts found in literature. Silva et al. (2014) limit themselves to describing the main characteristics of platforms highlighted in 21 references and bring forward the concepts of the following facilities: distriparks, freight consolidation center, freight village, intermodal distribution center, logistics zone, logistics center, logistics part, logistics platform, nodal center for goods and transshipment, storage and distribution centers. While the authors recognize that a single definition of logistics terminal is not available, they point out that size, location, function, governance, infrastructure and value-added services are important attributes that could be employed to characterize such facilities.

In a recent study originated in Eastern Europe, Rožić, Rogić and Bajor (2016) address the research trends of inland terminals by summarizing the literature related to the development, classification, technological processes performed and location determination of such facilities. They perform an exhaustive review, covering 68 papers published between 1980 and 2015. Regarding the classification of inland terminals, Rožić, Rogić and Bajor (2016) highlight that location, ownership structure, position in the relation to business centers, terminal capacity and cargo variety are features that define the function of these facilities in transportation networks. They take an impartial approach and describe the achievements of a variety of authors, including the ones present in this paper, which contribute to the definition of concepts, typologies and taxonomies for the variety of inland terminals found in literature, as well as in practice. Although Rožić, Rogić and Bajor (2016) verify that this field of knowledge has been widely explored and analyzed, the authors agree that an intelligible definition of the function and classification of inland terminals is still unclear and needs further development.

4.3 SHORTCOMINGS OF CLASSIFICATION PROPOSALS

Although the researched authors try to establish a solid foundation for the analysis of logistics centers, typology proposals also have classification limitations, which are inherent to the use exclusively of theoretical grounds (HAMBRICK, 1984). Higgins, Ferguson and Kanaroglou (2012), for example, observe that their hierarchy fails to cover all variations of logistics terminals seen in practice in an unambiguous way, and the categories devised are not exclusive. Some facilities found in literature take on characteristics of two or more terminal types due to their function, operations performed, location, geographic coverage and even semantic (HIGGINS; FERGUSON; KANAROGLOU, 2012). For instance, the term logistics center itself is used in a general way to name the classification structure and, at the same time, shows up among the terminology found in the literature.

This difficulty in clarifying the conceptual ambiguity of logistics terminals that still exists, as pointed out by Notteboom et al. (2016) and Rožić, Rogić and Bajor (2016), may be related to the fact that the majority of the proposed frameworks are developed based on an evolutionary perspective of the concept and function of logistics terminals, as well as spatial characteristics. Thereby, if concepts carry intrinsic aspects of the context to which they were developed, then the analysis and determination of classes will most likely hinder fitting all types of facilities in a particular framework. Another aspect that interferes with the definition of a unique scheme is the fact that logistics terminals are constantly reinventing themselves due to the need of fitting to new market requirements and exploring time-window opportunities (NOTTEBOOM et al., 2016). So the specific classifications schemes could become inappropriate in some cases.

While designing their frameworks, some authors also identify other criteria that were not taken into consideration but could be useful in future classification proposals. For Grundey and Rimienė (2007), who define the types of logistics centers based mainly on their function, this functionality could actually be influenced by the purpose of the facility and its location. The location decision, in turn, should take into consideration, market trends, proximity to current and potential customers, access to suppliers and sellers, transportation services and costs. Moreover, Grundey and Rimienė (2007) point out that this process should take into account the products for which the facility is designed; other criteria that may guide the classification of logistics centers include telecom infrastructure, labor availability, labor cost, training facilities and regulatory factors. Nam and Song (2011), in turn, suggest that the volume of products throughput should also be considered, which may be tied to the facility size or to its operational efficiency.

As time goes by, more and more criteria are being considered to classify logistics terminals. Yet, up to the most recent review, authors keep finding the same challenges of disentangling the ambiguity found in the conceptualization and classification of logistics terminals. Although a wide range of criteria is taken into account, it was interesting to notice that classification frameworks tend to have three main classes, where authors attempt to fit a variety of facilities. While this might be an influence of previous works, especially of Grundey and Rimienė

(2007), we could not find a particular reason to why this happens. The persistence of this challenge could actually be related to the fact that authors who devise hierarchic frameworks from literature reviews ground their developments in the same set of references, except from Roso, Woxenius and Lumsden (2009).

5 A FRAMEWORK TO GUIDE LOGISTICS TERMINAL CLASSIFICATION

In spite of the several classification frameworks found in literature, the criteria used by authors to elaborate their proposals are recurrent. While this can be partially explained by the use of the same references to ground the majority of proposals, it also reveals that the list of criteria collected from literature is exhaustive and seems to represent all aspects that could differentiate logistics terminals. All those criteria were synthesized under 17 main criteria, which were then organized into four groups that hold common aspects, namely: market coverage, infrastructure, product and services offered, as shown in Table 2. It includes both the criteria considered in the classification frameworks and those the authors felt that should also be taken into account.

Table 2 - Criteria for the classification of logistics terminals.

MARKET COVERAGE	**INFRASTRUCTURE**	**PRODUCT**	**SERVICES OFFERED**
· Business environment · Geographic coverage · Location · Market served	· Available infrastructure · Influence in regional transport Information technology · Labor availability	· Type of product · Throughput volume	· Governance · Legal, financial and administrative services · Value-added services · Strategy · Terminal function

The first group of criteria includes those related to market coverage, which are determinant to guide the decision of locating logistics terminal. The location will determine the capability of a facility to serve specific market areas due to its proximity or connectivity to suppliers, consumers and other logistics facilities. Hence, logistics terminals may be designed, for example, to serve large cities, seaports, industrial area, or commodity production sites, and can be classified according to kind of spatial connectivity allowed. As highlight by Notteboom and Rodrigue (2009) and Rodrigue, Comtois and Slack (2017), the degree of terminal connectivity is established by its geographic coverage, which grants a terminal the ability to reach a desired market area and expand its scope of action through the regionalization of flows, taking advantage of commercial opportunities.

A second set of criteria used to classify logistics terminals is related to the infrastructure available, either of transportation or of terminal structure per se, which includes not only physical facilities but also information technology infrastructure and workforce. The accessibility to different modes of transportation is a criterion that often appears in literature, most likely because traditional activities performed at logistics terminals are associated to cargo consolidation and freight transfer between modes of transportation. Due to this, facilities have been classified according to the transportation modes available in each terminal area, e.g. multimodal terminal, and maritime terminal.

The product category concerns the goods handled at the terminal. While the type of product refers to the nature of cargo and its unitization method, the throughput volume is related to the amount of goods handled and the capacity of processing freight. These two criteria allow classifying logistics terminals in the sense that products influence the structural capacity of a logistics terminal, determining the need of space, equipment required to receive, store and ship goods. That is, the type of product and the volumes processed determine the characteristics of each terminal. For example, terminals that handle a large flow of products, such as commodities, may embed large capacity storage, while urban consolidation centers are likely equipped to handle small packages.

The category “services offered” concentrates the attributes related to the type and complexity of the activities performed at the terminal, as well as their capacity to add value to logistics operation. This group of criteria is present in all classification frameworks evaluated in this research, and defines the function of a terminal. In papers that devise a hierarchic typology, the function is actually the key feature that guides the definition of complexity for each class, since it reveals itself in the development of the logistics center concept throughout the years, as noted by Notteboom et al. (2016). Likewise, Higgins, Ferguson and Kanaroglou (2012) connect the function of the terminal to the activities developed at the facility. The authors argue that the function of a terminal in the transportation network is related to the scope of activities performed, which can go from simple storage to complex consolidation operations. Meidutė (2005), for example, distinguishes between logistics terminals according to their strategic function, i.e. the primary function to which the facilities have been conceived. The function of dry ports, on the other hand, are associated to their geographic coverage, as highlighted by Roso, Woxenius and Lumsden (2009), and urban consolidation centers have their function defined mainly by the type of product, as pointed out by Allen et al. (2014).

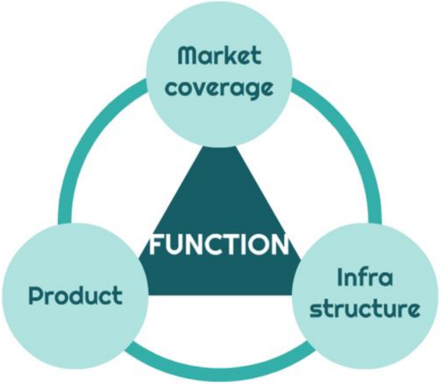
It should be noted that the services offered in a terminal are outlined by products characteristics, markets served and infrastructure available. For instance, customs clearance services for export and import are offered in maritime terminals, airports or inland borders, where, in general, long-distance transportation modes are available. On the other hand, typical service in urban terminals includes deliveries of small shipments, freight consolidation, transshipment, and even business-to-consumer solutions to serve a restricted area. The governance and the strategy adopted at the terminal are also criteria that influence the activities performed in a terminal. While public terminals usually offer legal services, private terminals adopt differentiation strategies and offer administrative/fiscal services, value-added services, and IT solutions.

Market coverage, infrastructure and product are also interrelated. The market served by a logistics terminal clearly gives an idea of the products that would be handled at the facility, as pointed out by Rodrigue and Notteboom (2009). On the other hand, distribution strategies will be impacted by geographic and economic characteristics specific to each production site and consumer market. The same happens when we evaluate the transportation modes available, which have a direct relation with the products shipped and the market served. For example, low value products processed in bulk terminals, such as commodities, will likely go through terminals that offer efficient transportation modes for this type of cargo, e.g. railway and waterway. This interdependence between groups is depicted in Figure 1.

This relationship between criteria has been highlighted by Catapan and Luna (2016) while characterizing logistics terminals in the Brazilian context. The authors identified the importance of the market served, the infrastructure available, and the products processed to differentiate logistics zones in three Brazilian states. In Catapan (2016), these attributes also supported a taxonomy proposal of logistics terminals, which includes the following classes: commodities terminal, maritime port, industrial platform, distribution platform and reverse logistics platform.

The terminology presented in the literature related to logistics terminals also corroborate with the groups of criteria presented in Table 2, since they seem to guide the designation of such facilities. For example, the terms *railroad terminal* and *seaport terminal* indicates that the framework adopted to categorize facilities is based on infrastructure attributes. On the other hand, market coverage becomes clear in *hinterland terminal*, *satellite terminal* and *urban consolidation center*, indicating the location and geographic coverage of the terminal. The type of product handled can be differentiated according to the unitization of cargo, e.g. *bulk terminal*, *container yard* and *inland container depot*. Finally, the services offered can also be specified in the terminology, such as *inland customs depot*, *inland clearance depots* and *transfer terminal*.

Figure 1 - Criteria that guide the classification of logistics terminals. Adapted from Catapan (2016).



Thereby, our model functions as a foundation to support the classification of logistics terminals. It is also flexible enough to fit plain or hierarchic structures, and to devise typologies or taxonomies for both generic and specific facilities. One may notice that all classification frameworks found in this structured review can be fit in the model depicted in Figure 1, although different classification perspectives are taken by each author, corroborating with its applicability.

6 FINAL THOUGHTS

Based on a structured literature review, we reason that there is no consensus on the logistics terminal concept, neither on a general classification framework for this type of facility. On the other hand, authors seem to agree about the main criteria that drive the definition of typologies and taxonomies. Perhaps the best avenue for the classification of logistics terminals is not to find a single classification to all types of facilities, but to recognize that their function and role in supply chains are tied to the infrastructure, market coverage and products handled. These aspects constitute homogeneous groups that summarize the criteria elected by several authors as most appropriate to distinguish logistics terminals between themselves.

The function of a terminal, in turn, can be seen as resulting from infrastructure, market coverage and product characteristics since logistics activities are determined by each one of these criteria. Consequently, the differentiation between facilities is naturally determined by a combination of these three factors. Logistics terminals also grow in complexity as more comprehensive multimodal structures are built, a greater variety of products is handled, with higher value addition, and markets are expanded through globalization. This evolutionary idea of the logistics activities performed is what guides the formulation of different classification frameworks available in literature, being inherent to the function of each facility.

One should notice, however, that the evolution of logistics services leads to the development of new functions that may not have been observed in classification frameworks developed so far, which may then become obsolete as time goes by. The development of activities related to reverse logistics is an example of a new transportation context, which is becoming more and more relevant as sustainability issues are perceived in different tiers of supply chains. Nonetheless, infrastructure, market coverage and product are criteria that tend prevail in the categorization of logistics terminals, as also observed in the literature analyzed. The structure proposed in this paper supports the classification of logistics terminals as it pieces all these aspects together so that facilities can be categorized regardless of the methodological approach chosen and context of operation.

Future work could apply this framework in practice to devise new classification schemes of logistics terminals. Since typologies are usually found in literature, a new research avenue lies in focusing on the development of taxonomies. One could also evaluate which class of criteria is more relevant according to the characteristics of the region where terminals are implemented.

APPENDIX A – Terminology adopted in the literature to denominate logistics terminals.

EXPRESSION	AUTHOR
Air cargo port	Leitner and Harrison (2001)
Bulk terminal	Wiegmans, Masurel and Nijkamp (1999)
Container Yard	UNESCAP (2009)
Distribution center	Grundey and Rimienè (2007); Hesse (2004); Notteboom and Rodrigue (2009)
Distribution terminal	Wiegmans, Masurel and Nijkamp (1999)
Dry port	Beresford and Dube (1991), Ng and Gujar (2009), Roso, Woxenius and Lumsden (2009), and UNESCAP (2010)
Freight village	Boile, Theofanis and Strauss-Wieder (2008), Grundey and Rimienè (2007), Tsamboulas and Kapros (2003), and UNESCAP (2009)
Gateway	Notteboom and Rodrigue (2009)
Hinterland terminal	Wiegmans, Masurel and Nijkamp (1999)
Industrial park	Boile, Theofanis and Strauss-Wieder (2008)
Inland clearance depot	UNECE (1998)
Inland container depot	Jaremskis and Vasiliauskas (2007) and UNESCAP (2009)
Inland customs depot	Beresford and Dubey (1991)
Inland freight terminal	UNECE (1998)
Inland port	Rodrigue *et al.* (2010) and UNECE (2001)
Inland terminal	UNCTAD (1982)
Intermodal and multimodal industrial park	Boile, Theofanis and Strauss-Wieder (2008)
Intermodal freight center	Cardebring and Warnecke (1995)
Intermodal railroad terminal	Roso and Lumsden (2009)
Intermodal terminal	UNESCAP (2009)
Load center	Notteboom and Rodrigue (2009)
Logistics center	Europlatforms (2004), Grundey and Rimienè (2007), and Meidutė (2005)
Logistics node	Grundey and Rimienè (2007)
Maritime feeder inland port	Leitner and Harrison (2001)
Nodal centers for goods	Tsamboulas and Dimitropoulos (1999)
Satellite terminal	Notteboom and Rodrigue (2009) and Slack (1999)
Seaport	Dooms and Macharis (2003)
Trade and transportation center inland port	Leitner and Harrison (2001)
Transfer terminal	Wiegmans, Masurel and Nijkamp (1999)
Transmodal terminal	Notteboom and Rodrigue (2009)
Transport terminal	Grundey and Rimienè (2007)
Urban consolidation center	Allen et al. (2014)
Urban distribution center	De Cerreño *et al.* (2008)
Warehouse	Grundey and Rimienè (2007)

Adapted from Catapan (2016) and Higgins, Ferguson and Kanaroglou (2012).

AN UPDATED PERSPECTIVE ON THE CONCEPT OF LOGISTICS HUBS

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Abstract

The concept of logistics hubs is still far from reaching an agreement in literature. By evaluating different concepts and hierarchies of logistics facilities, we bring an updated perspective on the definition of logistics hubs. We also propose a classification based on the hub positioning, distribution network, and goods handled.

Keywords: logistics hub, concept, review

1 INTRODUCTION

A transport infrastructure is an essential requirement for the movements of products, whether commodities or consumer goods. It comprises not only roads, railroads, or waterways, but also a variety of logistics facilities that support industrial and commercial operations, promoting the flow of goods and information across local, regional, national and international borders. These facilities allow increasing the logistics service level, particularly through the reduction of lead-times and transport costs. Among the available facilities, logistics hubs have gained prominence in the recent years in academia, business, and government.

Although the concept of logistics hubs has been around for some time, it is still far for reaching an agreement in literature. While several studies point out classification criteria or present hierarchy proposals for logistics facilities, in an attempt to differentiate among them, there seems not to be a consensus on a general framework for ranking facilities. In addition, a wide range of terms is associated with this type of facility, which seems to vary according to the region where the hub is located, the services offered, and its integration with the available infrastructure. Due to this, the main features and function of such hubs as part of transport networks are also not yet properly defined.

This paper reviews the literature in order to propose a suitable and comprehensive concept for logistics hubs, distinguishing it from other facilities. It also presents a typology and discusses the vocation of different types of hubs, taking into consideration their role as supply chain players and the types of products handled.

2 LOGISTICS FACILITIES HIERARCHY IN THE LITERATURE

The classification of logistics facilities is the first step in determining the concept of logistics hub. This aids in identifying basic features, goals, and operational boundaries of each type of facility, differentiating them against other existing structures. Regarding this aspect, Savy (2005) formerly distinguish the different forms of logistics facilities agglomeration. The author presents a structured hierarchy of four levels. In the first level we find single establishments such as depots, warehouses, and sorting centers. The second level comprises specialized facilities in a logistics zone, also called platform if it is a formal organization. Logistics hubs encompass several zones or platforms in a given area and are situated in the third level. Lastly the author defines the logistics area, which corresponds to a large scale agglomeration in a metropolitan/regional scope.

Grundey and Rimienė (2007) review the literature and identify the terms most commonly used to define logistics centers. A three-level hierarchy is proposed, based on the facility performance and activities performed. Thereby, in the first level we find less sophisticated structures, such as warehouses and distribution centers, which increase in complexity as we go higher in the hierarchy; third level structures comprise so-called logistics nodes. The authors also indicate the possible conceptual interconnections among facilities at the same level and at different levels. They point out, however, that the use of the hierarchy is highly dependent on the surveyed authors and on the definitions they adopted, since each one of them ends up devising a particular description and characterization for each facility.

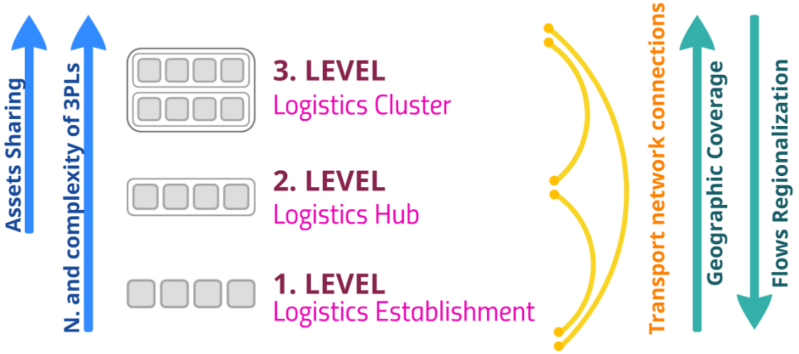
On the other hand, Notteboom and Rodrigue (2009) classify freight terminals regarding the added value of services offered, the size, and the scope of facilities. The suggested classification structure is divided into four levels, where one can identify the possible transport connections between terminals at different levels. According to the authors, the assortment of logistics facilities is related precisely to the possibilities of connections between sites, which directly affect the geographical coverage of each facility and the range of transport systems.

Based on the ideas of Grundey and Rimienė (2007) and Notteboom and Rodrigue (2009), among others, Higgins, Ferguson and Kanaroglou (2012) propose a more complex classification, identifying eight types of logistics facilities which were categorized into three hierarchical levels. For this, the authors took into account information on facility size, functionality, scope of activities, and terminology used. However, Higgins, Ferguson and Kanaroglou (2012) point out that the categories are not exclusive, and that a facility can be classified in one or another category depending on the characteristics presented. The authors hold true the considerations of Grundey and Rimienė (2007) regarding the need of care when using particular terminologies, since they tend to change over time and over regions as freight transport and logistics services evolve.

There is a consensus among the abovementioned authors that, much more than the size of the facility itself, it is the complexity of logistics activities and the number of logistics services providers (LSP) what distinguishes among levels of a hierarchy. According to the authors, while at lower levels more generic service providers are found, intermediate levels usually comprise logistics operators. In turn, fourth-party-logistics tend to function in higher level structures. Hence, the higher the position in the hierarchy, the more features/services are offered and the more should the services contribute to obtaining scale and scope economies (GRUNDEY; RIMIENĖ, 2007; HIGGINS; FERGUSON; KANAROGLOU, 2012; NOTTEBOOM; RODRIGUE, 2009).

A synthesis of the available hierarchies in literature is presented in Figure . The proposed hierarchy helps in understanding the function, scale, and scope of facilities, moving forward in developing a comprehensive classification for logistics facilities. Our goal here is to identify and classify logistics facilities, distinguishing especially the logistics hubs, based not only on abovementioned criteria, but also on their role as part of transport networks. We also try to use more generic terms, avoiding specific definitions by particular authors – leaving, thus, the traditional facilities terminology aside.

Figure 1 - Synthesis of the logistics facilities hierarchies available in literature.



First level facilities are called here logistics establishments, especially because they tend to act in a standalone manner. For second level facilities, the term logistics hub seemed more appropriate. Hubs serve as a platform for the cooperation among LSPs and other supply chain players, provision of more complex services, and coordination of related logistics flows. Finally, third-level structures are defined as clusters, given their capacity of broad agglomeration of various facilities and diversity of services. The next session will explore in more depth the differences among these facilities, with the aim of devising a concept for logistics hubs.

3 STRUCTURING A CONCEPT FOR LOGISTICS HUBS

A wide range of criteria may be related to the characterization of logistics facilities. Although we do not make a discrete delimitation of all features in each level of the proposed hierarchy, there are some key factors that can be used to distinguish between two or more types of facilities. While some of these criteria can be analyzed in isolation, most of them are not enough to, alone, differentiate each one of the categories. A combination of criteria seems more suitable for the task of classifying logistics facilities.

3.1 DISTINGUISHING AMONG HIERARCHICAL LEVELS

Issues related to the availability of logistics activities and number of LSPs, their form of organization and their capability of sharing assets, when evaluated together, clearly denote the heterogeneity among facilities. These actually seem to be the key-points that account for leveling up in a hierarchical structure. In addition, there is a tendency of facilities to organize themselves together in a specific area as they level up in a hierarchy. Having common goals, LSPs operating in such facilities also tend to increase assets sharing among themselves, seeking to improve service performance and add value to logistics flows (SHEFFI, 2012).

In general, one can say that the first level includes standalone facilities such as warehouses, distribution centers, and container yards, which can operate in two different ways: i) as private structures, owned by an industry or LSP, serving only one client; or ii) as a public structure, managed by an LSP but serving many clients. Second level facilities consist of are more complex facilities, with a well-defined structure, which comprises several LSPs, including logistics operators. They serve various clients through asset sharing, in an organized manner. Facilities such as freight villages, *interporti*, logistics centers, and *Guterverkehrszentrum*, among others, may be characterized as logistics hubs. Third level facilities, in turn, have much broader structures, such logistics areas (SAVY; LIU, 2009) or clusters (SHEFFI, 2012), where fourth-party logistics operate. Clusters are geographically more disperse and are not necessarily in a well-defined area (SHEFFI, 2012).

A second set of aspects that allow us to characterize logistics facilities is related to transport geography. Regarding geographical coverage, the higher the level of the facility in the hierarchy, the greater is its ability to embrace markets. While logistics cluster allow access to international transport corridors, logistics hubs cover areas that are not so spread out. Logistics establishments, in turn, usually function in more local or regional areas. These characteristics reveal the possibilities of transport connections between facilities, which allow reaching both distant and local markets. This enables and further increases the regionalization of flows through the use of different network topologies and of freight consolidation/deconsolidation operations.

We can also observe a difference in the transport modes adopted for the network connections between supply chain players. Logistics establishments, because of the type of market they serve, tend to use road transport. Logistics hubs, in turn, can be unimodal or multimodal. Clusters usually resort on multimodal networks, especially those that include rail or maritime transport. This also implies that the volume of freight handled and type of cargo unitization tend to increase as one ascends in the hierarchy, substantiating the use of larger scale transport modes.

While many hierarchies are based on the functionality and ability of facilities to add value, service providing in primary levels can also be highly sophisticated and specialized, i.e. either because LSPs act in specific market niches, carry out product finishing operations or perform postponement activities. Following the same line of reasoning, the diversity of products handled in each facility is also a weak predictor of classification. On the other hand, the use of information and communication technologies (ICT), although it can also be extensively applied in logistics establishments, is a determining factor for the existence of hubs and clusters. Therefore, increased coordination among LSPs through the use of ICT is a feature that becomes especially noticeable from the second hierarchical level upwards.

3.2 MAIN FEATURES OF A LOGISTICS HUB

The proposed hierarchy and the characteristics for logistics hubs found in literature guide the construction of a concept for second-level structures. This concept is based on a tripod of components, which are interrelated: i) assets' sharing among LSPs; ii) a collaborative framework of operation; and iii) provision of valued-added logistics services.

Sharing assets for performing logistics and transport services is the most discussed topic in literature; according to Eryuruk, Kalaoglu and Baskak (2013) and Higgins, Ferguson and Kanaroglou (2012), it is a basic feature of logistics hubs. Other authors such as Afandizadeh and Moayedfar (2008), Eryuruk, Kalaoglu and Baskak (2013), Jaržemskis (2007), Jurásková and Macurová (2013), Li (2011), Meidutė (2005, 2007), and Tambi et al. (2013) also highlight the importance of assets sharing for obtaining economies of scale. Actually, the assets shared go beyond those needed to carry out traditional logistics activities, but also include services provided by shipping agents, brokers, shippers, and packing companies Rodrigue and Notteboom (2009), as well as those related to support activities, e.g. foodservice, hospitality, and banking. Kabashkin (2007) and Li (2011) also emphasize the importance of sharing information through the use of ICTs, which are indispensable for the existence of a cooperative system that enables the efficient use of available assets.

If assets' sharing exists, then naturally more than two LSPs operate together in a collaborative framework. While authors such as Eryuruk, Kalaoglu and Baskak (2013), Krzyzaniak, Hajdul and Fechner (2012) and Tambi et al. (2013) generally suggest that in a logistics hub there must be a grouping of independent companies, others point out that these companies should be LSPs (CASSONE; GATTUSO, 2010; FERNANDES; RODRIGUES, 2009; MEIDUTĖ, 2005). These LSPs can also take shape as logistics operators, who increase the synergy of collaboration by providing more complex and complementary logistics services (AFANDIZADEH; MOAYEDFAR, 2008; JARŽEMSKIS, 2007; JURÁSKOVÁ; MACUROVÁ, 2013; MEIDUTĖ, 2007). Such collaborative framework drives horizontal "coopetion", allowing LSPs to benefit from synergy and value adding while still competing against each other.

For this reason, Jaržemskis (2007) asserts that a logistics hub must include LSPs that provide different and complementary services, which are integrated through sharing information, infrastructure, facilities, and/or equipment. Although this might imply a sort of coordinated management, discussion on this topic is generally aimed at defining the type of management that should exist (whether private, public or in the form of public-private partnerships), as showed in the paper of Eryuruk, Kalaoglu and Baskak (2013), and not yet at how to implement it.

Value-added services in logistics and transportation may seem quite obvious as a criterion for defining logistics hubs. Although increasing the value of goods through logistics should be inherent of using any kind of logistics facility, some benefits are accentuated by the use of hubs when compared to standalone establishments. Krzyzaniak, Hajdul and Fechner (2012) suggest that logistics hubs are key network nodes in which transport modes and logistics solutions fully show their potential and advantages. Even if they cause a rupture in the flow of goods, hubs enable the development of more efficient transport networks, adding value as an element of coordination and articulation of larger distribution systems (RODRIGUE; NOTTEBOOM, 2009).

Indeed, the added value obtained in logistics hubs is related to both geographical and functional aspects of such facilities. According to Rodrigue (2004) the increased efficiency in transport is due to the establishment of strategic interfaces between networks of different dimensions, whether they are local, regional, and/or global. These interfaces are implemented through transport connections and corridors, which consequently increase geographic coverage and enhance flow regionalization. On the other hand, the polarization of logistics services in hubs leads to greater economies of scale and scope (CAMBRA-FIERRO; RUIZ-BENITEZ, 2009). The authors point out that a logistics hub should act to reduce transport lead-time, improve customer service, and gain competitive advantages.

4 TYPOLOGY OF LOGISTICS HUBS

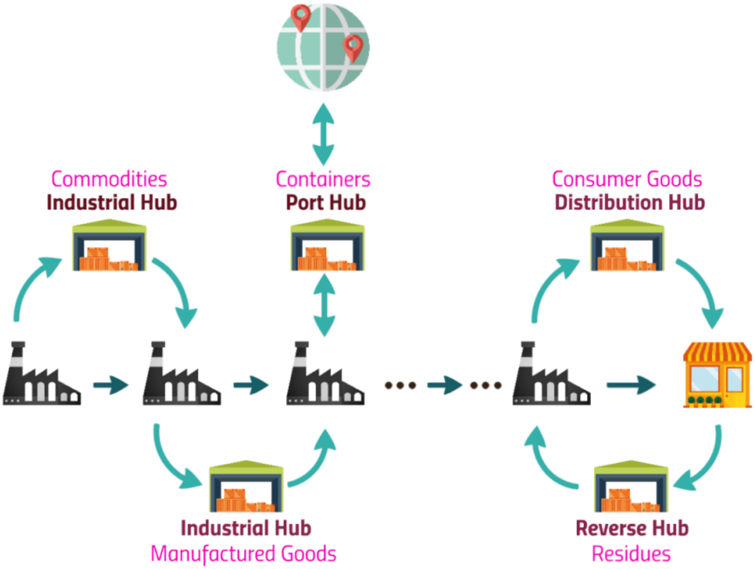
The structure of a logistics hub is dependent of the market served and products handled (GRUNDEY; RIMIENĖ, 2007; MEIDUTĖ, 2005; RODRIGUE, 2004), which restrict the use of transport modes and logistics services. Indeed, many products may require specialized services and handling, as is the case of e.g. electronics, commodities, chemicals or food. An example of product/market oriented facility is found in the case studies of Eryuruk, Kalaoglu and Baskak (2011, 2013), where the authors describe the planning and implementation of a logistics hub aimed at the textile industry in Turkey.

On the other hand, a logistics hub structure is also associated to the cargo type and packaging. There are service-specific processes and equipment according to the type of goods, whether they are dry, refrigerated, hazardous or perishable, as well as the type packaging, such as bulk, containers, full load or less-than-truck load. The served market, e.g. international or domestic, may also require specific services, such as customs clearance. Port hubs are good examples where one can find some particular conditions: they handle containers, in which a great variety of products of same nature may be stored, for which maritime transport is required, and where customs services may be found (DADVAR; GANJI; TANZIFI, 2011; RODRIGUE, 2008).

A great variety of products may be suited for logistics hubs. According to Šulgan (2006) these can be related to the auto, electronics, chemical, and textile industries, as well as consumer goods and supermarket chains. Besides these, Krzyzaniak, Hajdul and Fechner (2012) mention that products from the agribusiness and mining industry, machinery, equipment, furniture, and recyclable materials may also flow through logistics hubs. As a matter of fact, Afandizadeh and Moayedfar (2008) point out that logistics hubs can handle any type of product, whether bulk cargo or manufactured goods, as long as they can take advantage of the available services and infrastructure. This is the case of the Spanish hub PLAZA, where one can find from clothes to seafood goods (SHEFFI, 2012): although at a first glance they may seem quite different, both products take advantage of the hub structure by sharing the same transport mode and being destined to the retail market.

Setting up a logistics hub and defining its value-adding potential are directly related to specific attributes of the supply chain(s) it services (RODRIGUE; NOTTEBOOM, 2009), volume of goods handled, and flows that go through such facility (KONINGS, 1996). According to Rodrigue and Notteboom (2009), each supply chain may involve several different markets, which result in different ways of using the hub and of performing hinterland operations. With this in mind, it seems reasonable to distinguish logistics hubs according to their type. The analysis of literature and observation of existing hubs shows that the classification could be related to the point of the supply chain where the hub is positioned, the characteristics of products´ flows and the served market. The proposed typology, in which the different logistics hubs may be interrelated, is showed in Figure 2. It consists of four elements: industrial hub, port hub, distribution hub, and reverse hub.

Figure 2 - Typology and vocation of logistics hubs.



Industrial hubs are facilities dedicated to the articulation of products flows between different levels of manufacturing, including agribusiness and mining commodities; i.e. before the goods leave for distribution to end customers. Such hubs may offer multimodal transport, depending on the available infrastructure. In many cases, industrial plants can be found next to the hub, or even integrated to its own structure (SHEFFI, 2012). Cargo flowing through the hub can be unitized as full-load or less-than-truckload, according to the type of product and vocation of the facility. An example of industrial hub that serves the textile industry can be found in the papers of Eryuruk, Kalaoglu and Baskak (2011, 2013).

Operating usually as part of logistics clusters, such as ports or border points, port hubs handle bulk cargo or containers. This type of hub is generally related to international trade, although it can also handle cargo from domestic trade to be transported by coastal shipping or railways, for example. While providing customs services, it takes shape as a dry port. Due to its characteristics, it often comprises multimodal transport. Authors such as Dadvar, Ganji and Tanzifi (2011), Fernandes and Rodrigues (2009), and Rodrigue and Notteboom (2009) address this type of logistics hub.

Distribution hubs, in turn, handle the movement of goods to meet end-customers of supply chains, either through wholesalers or retailers. Therefore, it adopts as transport mode the road network. In this category we also include urban hubs, which concentrate logistics activities outside large cities or metropolitan areas in an attempt to improve traffic and distribution as a break-bull structure (AFANDIZADEH; MOAYEDFAR, 2008). This can be done, for example, through consolidation/deconsolidation of cargo or transfer between large trucks and smaller vehicles. Distribution hubs are among the most cited in literature and can be found in the papers of Jaržemskis (2007), Li (2011), Rodrigue (2008), and Tambi et al. (2013).

Finally, reverse hubs follow the current trend of changing from the traditional paradigm of producing and consuming goods to that of a circular economy. In this latest economic model, beyond the traditional flow of goods, we find a reverse flow of materials after their consumption, which could be destined to maintenance, reuse, redistribution, remanufacturing or recycling, setting up closed loop supply chains (ELLEN MCARTHUR FOUNDATION, 2013). Yet, while direct distribution channels are already well defined, reverse paths are still scattered, making it difficult to implement this newer idea.

Reverse hubs can be used as elements for organizing and articulating reverse flows, aiding in the set-up of pools of materials. In this sense, reverse hubs can also be integrated to other types of hubs, e.g. distribution or industrial hubs, taking advantage of economies of scope and of the use of transport connections and corridors. Although we have not identified papers that deal with the application of circular economy concepts to logistics hubs, Krzyzaniak, Hajdul and Fechner (2012) point out that recyclable materials can indeed be handled in logistics hubs.

5 FINAL THOUGHTS

The growing interest in logistics hubs observed in literature since 2005, as more and more papers are published, foments the need for a reflection of the logistics hub concept and properties. Based on the classification and hierarchy of logistics facilities, it is possible to eliminate ambiguities in the definition of hubs. For this, one must take into account a variety of criteria that allow distinguishing not only among different types of facilities, but also among hubs.

Indeed, the analysis of the existing facilities and structures shows that the heart of this issue is related in greater deal to the profile of the facilities than to the specific definitions adopted by each author. Hubs have, in essence, a conceptual tripod: collaborative framework, assets sharing, and value-added services, which can be expanded and absorbed by the existing facility terminology despite of their original nomenclature. Although greater economies of scale and scope are the main targets of a hub, each one of them is unique according to the proposed typology. The design of a hub can take into account the amount of LSPs operating, the transport infrastructure, the nature of goods handled, and markets served, among others.

The differentiation between logistics hubs and other facilities, and also among hubs, may be explained in an uncomplicated manner by means of analogies between shops and facilities, shopping malls and logistics hubs, and shopping areas and clusters.

Logistics establishments, such as warehouses, behave as regular shops spread around cities. We may even find large department stores, which resemble shopping malls. Indeed, this type of shop can have greater market coverage, or be highly specialized, e.g. those targeted to the construction market, but they are still individual units and usually do not show signs of collaboration with other stores in the area.

Secondly, there is also a correlation between logistics hubs and shopping malls. The configuration and operation of these facilities are similar, especially in the case of distribution hubs due to the disaggregated form of products unitization. In a shopping mall, we find individual shops, but with a common goal: offering consumer goods and other services related to the shopping experience to its customers. Different shops inside a mall may be compared to the different LSPs operating in a hub. A mall is installed in a delimited area, where stores share infrastructure and administrative services and may benefit from consolidated transport through the use of urban hubs. Shopping malls also perform, from time to time, collaborative actions that benefit the entire group while still competing, such as seasonal sales and advertising. Moreover, in the same way as distinct logistics hubs, different malls may be targeted to different markets, either local or disperse, can be focused on customers with different purchasing power, or even driven to a particular type of product, like furniture and home decor.

Finally, greater shopping areas may encompass different malls, department stores, and smaller shops, while serving geographically disperse markets. The area is not so well defined, and is usually installed outside great metropolitan areas. Nonetheless, the facilities still benefit from the agglomeration in different ways. In this sense, they resemble logistics clusters.

MODELS AND METHODS FOR LOGISTICS HUB LOCATION: A REVIEW TOWARDS TRANSPORTATION NETWORKS DESIGN

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Abstract

Logistics hubs affect the distribution patterns in transportation networks since they are flow-concentrating structures. Indeed, the efficient moving of goods throughout supply chains depends on the design of such networks. This paper presents a literature review on the logistics hub location problem, providing an outline of modeling approaches, solving techniques, and their applicability to such context. Two categories of models were identified. While multi-criteria models may seem best suited to find optimal locations, they do not allow an assessment of the impact of new hubs on goods flow and on the transportation network. On the other hand, single-criterion models, which provide location and flow allocation information, adopt network simplifications that hinder an accurate representation of the relationship between origins, destinations, and hubs. In view of these limitations we propose future research directions for addressing real challenges of logistics hubs location regarding transportation networks design.

Key-words: logistics hub; location; literature review; transportation network

1 INTRODUCTION

Logistics hubs are large-scale structures within which different logistics service providers collaborate in order to offer value-added services by sharing assets. Such hubs impact on the efficiency of transportation systems, since they directly affect the flow of goods. In order to achieve an increased efficiency, it is necessary to correctly position these hubs on a network. According to Li, Liu and Chen (2011), the purpose of adequate location of a logistics hub is to make products available to different markets through the best possible connections, allowing for a better use of the logistics and transportation infrastructure available.

The process of locating a logistics hub tends to be somewhat more complex than for industrial facilities or distribution centers, since the hub is not intended to be used exclusively by one supply chain, but by a broader network of distribution. In these cases, hub-and-spoke topologies are usually adopted, serving a wide variety of industries and products. Such configuration is common in the transportation of large volumes (CAMPBELL; O'KELLY, 2012; LIUM; CRAINIC; WALLACE, 2009), where goods are concentrated in a few nodes, i.e. hubs, which act as connection points, instead of being sent directly from a supplier to their destinations (AMBROSINO; SCIOMACHEN, 2012). This means that two major functions can be provided by hubs: i) consolidation/deconsolidation, and ii) switching, sorting or connecting (CAMPBELL; O'KELLY, 2012). Therefore, the decision on location should not be restricted by the definition of the number, site, and capacity of facilities (SIMCHI-LEVI; KAMINSKY; SIMCHI-LEVI, 2003), but must also take into account the allocation of products' flows and the network design itself (CAMPBELL; O'KELLY, 2012).

The location of logistics hubs is also considered to be a strategic and long-term decision, especially due to the amount of capital invested and the length of time that facilities will be available. Already in 1994, Izquierdo (1994 apud DUBKE; PIZZOLATO (2011) pointed out that among the criteria which impact logistics hubs design, the location seemed to be a crucial decision element. The choice of site affects the success not only of operational activities itself (TU et al., 2010), but also of supply chain management and of transportation network planning, ultimately influencing the distribution systems as a whole (MELO; NICKEL; SALDANHA-DA-GAMA, 2009; ŠKRINJAR; ROGIĆ; STANKOVIĆ, 2012). Consequently, the design of a transportation network becomes also strategically important for businesses, as it impacts on how the goods will flow throughout the distribution channels available (OKTAL; OZGER, 2013).

As a result, the optimal location of logistics hub may lead to reduced transportation costs, promote synchronization between production and consumption, ensure a balanced development of transportation systems, and achieve better overall benefits (GAO; DONG, 2012; LIUM; CRAINIC; WALLACE, 2009). A best location will effectively assist in the expansion of economies of scale, as well as increase competitive advantage, achieving higher customer satisfaction through more efficient transportation (DING, 2013). Given the importance of these issues, this paper analyzes the existing literature on location of logistics hubs, presenting an overview of the modelling approaches taken, the solution techniques implemented, and their applicability to the context of such structures. Differently from other reviews on hub location, here we bring together the developments regarding the logistics hub framework, instead of focusing on the development of a particular model or solution approach.

This paper is organized as follows. Section 2 presents the review papers that have dealt with hub location so far. Section 3 describes the methodological procedures and some particularities encountered while performing this research. Context and perspectives of logistics hub location are provided in Section 4. The types of models used, general aspects of their formulation, and their corresponding solution methods are displayed in Section 5. Section 6 discusses the applicability of models and solution techniques in the context of the logistics hubs, especially regarding their role as part of transportation networks. Finally, Section 7 comprises the final considerations, including future research directions.

2 LITERATURE REVIEW

Hub location is a well-established research field in operational research. This is ratified not only by the existence of journals dedicated to location science itself, but also by several review papers offering an overview of research progress over time. Although developments in the hub location area are mainly connected to the need to move people or products, this kind of problem formulation is also adopted in telecommunications, where data is distributed via hubs throughout information networks (ALUMUR; KARA, 2008). In fact, one of the first reviews on hub location was dedicated to the context of communication network architecture, by Klincewicz (1998).

Yet, it was only after a period of ten years that Alumur and Kara (2008) presented a new survey, fairly comprehensive, reviewing more than 100 articles related to hub location in general. The authors described mathematical models, solution techniques adopted, and benefits arising from the choice of one technique or another. They also identified the classic data sets available for the models' evaluation. A special section was dedicated on issues related to economies of scale, and how to include this feature on the models. The survey presented by Alumur and Kara (2008) indicate that, since 2000, the focus of works has shifted from the definition and formulation of new problems to the investigation of new solution methodologies. In general, time and cost were the main criteria to be minimized, especially in freight transportation. The authors also pointed out the need to address multiple criteria decisions, especially with conflicting objectives, as well as to represent the transportation networks more adequately.

Aiming to extend the research of Alumur and Kara (2008), Farahani et al. (2013) reviewed the literature on hub location from 2007 onwards. Besides presenting discrete problems, which were emphasized by Alumur and Kara (2008), Farahani et al., (2013) also included continuous approaches. The classification of the literature followed the proposition of Alumur and Kara (2008), although now with larger subdivisions to accommodate further modeling features, such as capacity limitation, multiple objectives, and network coverage. To Farahani et al. (2013), the consideration of multiple criteria and real world aspects are issues that still require improvement. Current logistics matters related to risk, sustainability, environmental impact, and globalization of supply chains are becoming increasingly more important in decision making. Furthermore, the influence of a hub on products' flows and the effects of traffic on a network also lack investigation.

Another study that surveys the literature on hub location was presented by Campbell and O'Kelly (2012). Here the authors took a slightly different approach, evaluating the origins of the hub location problem (HLP), its evolution over time, and how it presents itself nowadays. The current state of the art is discussed with respect to large-scale problems, network topology, integration between costs and services, dynamic modelling, competition situations, stochasticity, and reliability. Campbell and O'Kelly (2012) also described the relationship between the location of hubs and network design, which adds some special challenges to problem modelling and solving. Future research is in line with that indicated by Alumur and Kara (2008) and Farahani et al. (2013). In particular, Campbell and O'Kelly (2012) pointed out that the models available are still limited in representing real transportation networks, and do not emphasize results related to spatial organization and allocation of flows throughout the arcs of the network.

Although the majority of models available in the literature consider just one decision criteria, multiple-criteria decision making (MCDM) models have been increasingly adopted, allowing for a better representation of location issues. In light of this, Farahani, Seifi and Asgari (2010) compiled a set of papers on the application of MCDM for facilities location in general. In these cases, in addition to classic criteria such as cost or coverage, at least one other criterion was considered, generally a conflicting one, such as environmental risk or service level. Works were classified according to the number of objectives and attributes considered, and solution methods were described. Future research directions highlighted the need to consider aspects related to reliability against flow disruption, data uncertainty, sustainability, and network design.

Finally, Melo, Nickel and Saldanha-da-Gama (2009) reviewed the literature from the perspective of an application context: supply chain management. Here, facilities include not only hubs, but also industrial plants. The authors pointed out the criteria that should be taken into account when locating facilities within the scope of supply chain planning, as well as solution techniques adopted and some applications. Network structure, financial issues, risk management, and the incorporation of reverse logistics were also among the issues discussed in this paper. In addition to typical location and allocation decisions, the models presented evaluated capacity, inventory levels, procurement, production activities, vehicle routing, and/or modes of transportation. Still, the networks analyzed are considerably simplified, especially regarding the number of chain levels represented and the diversification of products handled. Regarding future research directions, Melo, Nickel and Saldanha-da-Gama (2009) highlighted the need to improve the orientation of the models, since they mainly focus on economic factors, as well as to take into account uncertainties inherent in the supply chain scenario. The integration between operational and tactical and strategic decisions also requires further elaboration, as do reverse logistics activities.

In general, the review papers above survey the literature with regard to a specific type of problem, such as the HLP, or a modelling approach, such as MCDM. However, this segmentation makes it difficult to identify the available (or more adequate) approaches to deal with a specific situation, such as logistics hubs; in fact, the applicability of location models is a matter at constant debate. We found the work of Melo, Nickel and Saldanha-da-Gama (2009) to go in this direction, extending the knowledge of a model's suitability for the supply chain management perspective, and allowing for better problem solving.

3 RESEARCH METHODOLOGY

For this survey, we adopted a content analysis approach, which aims for a systematic, quantitative, and qualitative description of the selected literature. Two databases were used in this research: Scopus and Emerald Insight. There, we initially identified the works that dealt with logistics hubs in general, instead of searching directly for facility location. This allowed us to limit the universe of papers to the logistics hub area, because the literature on location is quite extensive. Next, we searched for the papers that dealt with location, regardless of the approach adopted. Referenced papers or relevant literature reviews were added to complement the pool of articles.

One major obstacle faced during this process relates to which terms should be used to define a logistics hub. Since there is no stated consensus in the literature on the logistics hub terminology, and since this research aimed to identify the models and methods that could be used to locate logistics hubs, we have considered a broader array of expressions: logistics hub, logistics center, freight village, or logistics platform. Among these, logistics center seems to be the one mostly used by authors.

A total of 20 papers were selected for analysis, in which we sought to identify: overall characteristics, such as context and modelling perspective; modes of transportation, connections and infrastructure available; objectives and criteria used for decision making; solution techniques and/or algorithms adopted; and, suggestions for future research. The content analysis of the above allowed us to observe and evaluate the properties and goals of the location models available, the situations where they were implemented, their applicability and limitations to the context of logistics hubs.

4 CONTEXT, PERSPECTIVES, AND NETWORKS

Although facility location problems have been studied in the early 20th century (ŠKRINJAR; ROGIĆ; STANKOVIĆ, 2012), it was not until the 1950s that more elaborate approaches started to emerge for the location of interconnection points (CAMPBELL; O'KELLY, 2012). Goldman (1969) can be regarded as one of the first authors who modelled the transportation hub location problem. His paper pointed postal operations as an important application; in fact, the advent of express delivery firms in the late 1970s has also proved to be a practical motivation for further developments in this area (CAMPBELL; O'KELLY, 2012). Nevertheless, it was the seminal work of O'Kelly (1986) that set off the HLP as a new research agenda, which took into account the spatial interactions between location and transportation decisions (KARA; TANER, 2011). O'Kelly studied the interactions between hubs for the United States inter-city air passengers' streams; it was the starting point for a large spectrum of applications based on the concept that location had an effect on the design of its associated networks (KARA; TANER, 2011). These developments were further supported by the application of mathematical programming and heuristics techniques, and the increase in computational power. Subsequently, the need to consider a greater variety of decision criteria, both quantitative and qualitative, led to the consideration of other fields of investigation, such as MCDM, and formulations based on fuzzy logic.

Yet, despite the research interest in hub location, not many authors have applied their proposed approaches to solving problems in practice. The majority of works still evaluate applications with numerical data. This might be related, however, to the fact that their focus lies on the development or improvement of a given solution technique. On the other hand, the employment of primary data arise in two main situations: i) when new criteria are included in a model, in order to represent particular aspects of the problem, such as seen in Gao and Dong (2012), Klapita and Švecová (2006), Oktal and Ozger (2013), and Tu et al. (2010); and ii) for the analysis of results and implications of facility location for a supply chain or the transportation network, e.g. Alumur, Kara and Karasan (2012), Ambrosino, Sciomachen (2012), Dubke and Pizzolato (2011), Lee, Huang and Teng (2009), and Rahimi, Asef-Vaziri and Harrison (2008).

4.1 LOCATION PERSPECTIVES

Finding the best location for a logistics hub can be done using two different perspectives, which are related to the scope of the problem to be solved and the results obtained. While the first perspective is associated with a business or supply chain point of view, the second is broader and strives to improve the freight network and foster a better use of infrastructure through the planning of transportation systems. Both perspectives can be found in the literature as depicted in Table 1.

Table 1 - Perspectives of benefits obtained from the location of logistics hubs.

PERSPECTIVES	AUTHORS
BUSINESS AND SUPPLY CHAIN	Alumur, Kara and Karasan (2012), Dubke and Pizzolato (2011), Feng, Li and Zhang (2013), Klapita and Švecová (2006), Li, Liu and Chen (2011), Liu, Guo and Zhao (2012), Oktal and Ozger (2013), Ren et al. (2010), Škrinjar, Rogić and Stanković (2012), Tu et al. (2010), Wang and He (2009), Xiao and Zhang (2009), Zhi et al. (2010), Zhi and Li (2012)
TRANSPORT SYSTEMS PLANNING	Ambrosino and Sciomachen (2012), Rahimi, Asef-Vaziri and Harrison (2008), Turskis and Zavadskas (2010)

In papers focused on the first perspective, the choice of location has a direct impact on economic aspects related to the implementation and fulfillment of operational activities within a supply chain (WANG; HE, 2009). In such cases, reductions in transportation costs and lead-time or increase in revenues are issues that prevail in decision making; i.e. the authors adopt a microeconomic point of view. According to Škrinjar, Rogić and Stanković (2012), these benefits usually result from a better use of vehicle space and/or exploitation of transport capacities. This perspective is widely adopted in the literature and was found in 15 of the 20 papers analyzed.

On the other hand, the works of Ambrosino and Sciomachen (2012), Rahimi, Asef-Vaziri and Harrison (2008), and Turskis and Zavadskas (2010) address location from a transport system perspective, dealing with infrastructure planning on a regional level. For these authors, a transport system that includes logistics hubs could contribute to the establishment of a network that allows for a region to compete economically and efficiently in both local and regional markets. Some papers show a predominantly public goal, where there is a concern with obtaining benefits for the society. Maximizing the support provided by the transport systems in this perspective would also imply on the reduction of adverse factors, mainly caused by an inadequate use of the network, which results in damage to the environment and public health, such as air and noise pollution (AMBROSINO; SCIOMACHEN, 2012; RAHIMI; ASEF-VAZIRI; HARRISON, 2008).

While the focus of research is the location and construction of new facilities, the type of investment required for the implementation of hubs is generally not discussed. Although construction costs are taken into consideration when there is a choice between different location sites, they seem to be related only to the new facilities, and not to the network design. Kampf, Průša and Savage (2011) and Zhi and Li (2012) claim that there should be a public-private partnership when locating logistics hubs, ensuring both the provision of value-added services and a positive outcome for society. In these cases, public funding should be directed to the construction or maintenance of infrastructure, while private capital would be better employed for construction of facilities, acquisition of equipment, and implementation of information and communication technologies (KAMPF; PRŮŠA; SAVAGE, 2011).

4.2 TRANSPORTATION NETWORKS CONSIDERED

The flows of goods that could be handled in a logistics hub depend directly on the distribution channels and connections available in the network. The surveyed papers consider a variety of transportation modes, as outlined in Table 2. There is a predominance of works dealing with road transport, followed by analyses that include hubs connected to railways. Airways, considered only by five authors, are always integrated with a multimodal platform. Given that multimodality is considered by many authors to be a basic feature of a logistics hub, it is understandable that the majority of papers that discuss the network consider more than one mode of transportation. On the other hand, there are several works, e.g. Li, Liu and Chen (2011), Liu, Guo and Zhao (2012), Škrinjar, Rogić and Stanković (2012), Turskis and Zavadskas (2010), Wang and He (2009), and Zhi and Li (2012) that do not mention the transportation mode used.

Liu, Guo and Zhao (2012) point out that a location model should always consider the transportation network as a system. Hence, the evaluation of location alternatives should also take into account possible connections and the accessibility to the transportation network (AMBROSINO; SCIOMACHEN, 2012). Railway, waterway and roadway links, which enable multimodal connections at transshipment points are regarded by Ambrosino and Sciomachen (2012), Feng, Li and Zhang (2013), Gao and Dong (2012), and Kampf, Průša and Savage (2011).

Table 2 - Transportation modes available in networks.

AUTHOR	TRANSPORTATION MODE					
	Roadway	Railway	Maritime	Waterway	Airway	Other aspects
Alumur, Kara and Karasan (2012)	✓				✓	✓
Ambrosino and Sciomachen (2012)	✓	✓				✓
Dubke and Pizzolato (2011)	✓	✓				✓
Feng, Li and Zhang (2013)	✓	✓			✓	✓
Gao and Dong (2012)	✓	✓		✓		✓
Kampf, Průša and Savage (2011)	✓	✓		✓	✓	✓
Klapita and Švecová (2006)	✓					
Lee, Huang and Teng (2009)	✓		✓			✓
Oktal and Ozger (2013)					✓	
Rahimi, Asef-Vaziri and Harrison (2008)	✓	✓				✓
Ren et al. (2010)	✓					✓
Tu et al. (2010)					✓	
Xiao and Zhang (2009)	✓					

The infrastructure conservation state and the use of its capacity are issues that impact the performance of a transport system. According to Zhi and Li (2012), these aspects are directly related to the service level achieved when using the infrastructure, which in turn directly affects the services offered in a logistics hub. The assessment of the infrastructure conditions further indicates whether or not it is possible to remodel existing facilities to be used as hubs, which could save money and time (FENG; LI; ZHANG, 2013; REN et al., 2010). On the other hand, observing traffic conditions and flow patterns not only assists in the identification of potential sites for a logistics hub, but aids in evaluating the flow changes and their environmental impacts due to more intense traffic or congestion (LIU; GUO; ZHAO, 2012; REN et al., 2010).

5 MODELS AND SOLUTION TECHNIQUES FOR THE LOCATION OF LOGISTICS HUBS

The location models available in the surveyed literature were sorted into two categories, based on the number of decision criteria considered: multi-criteria or single-criterion. This classification is related not only to the model itself and type of results obtained, but also to the solution techniques adopted.

Different aspects can be considered during modeling, which are used either as decision criteria or model restrictions. They comprise: i) transport, related to transportation costs, time or distance travelled; ii) hub functionality, regarding the activities carried out on the hub, capacity, skilled labor availability, operating costs, fees, etc.; iii) investment, concerning the required amount of capital for the construction of facilities; iv) supply and demand, which deals with the availability of products and volumes to be handled, including traffic; v) market, considering the proximity to customers and potential for coverage expansion; vi) policy, which includes the development of policies, current legislation, and benefits of tax incentives; and vii) environment, linked to terrain characteristics, geography, and environmental protection. Table 3 presents the types of models and features taken into account, per author.

Meanwhile, regardless of model's features, it is a consensus among authors that the decision on location begins with the pre-selection of a set of potential sites where the hub could be implemented, particularly if the network considered has a large number of possible locations (ZHI; LI, 2012). Indeed, to test all possible combinations becomes impracticable. Although most authors do not make clear how this pre-selection is made, several criteria could be identified which are related to product flow, supply and demand of products, and available infrastructure.

According to Dubke and Pizzolato (2011) and Gao and Dong (2012), logistics hubs should be located at the intersection of large streams of flow, or very close to major transport links, especially in order to take advantage of multimodality. In addition to ensuring the existence of a greater volume of cargo that could be handled in the hub, this would encourage a better use of the existing infrastructure. Rahimi, Asef-Vaziri and Harrison (2008), for example, rated potential location sites based on traffic distribution and total distances travelled by vehicles. On the other hand, Ambrosino and Sciomachen (2012) considered the possibilities of exchange between modes as a basis for the pre-selection.

Table 3 - Types of models and aspects taken into account.

AUTHOR	**ASPECT**						
	Transp.	Function.	S/D*	Invest.	Market	Policy	Environm.
Alumur, Kara and Karasan (2012)	✓	✓	✓				
Ambrosino and Sciomachen (2012)	✓	✓	✓				
Dubke and pizzolato (2011)	✓	✓	✓				
Feng, Li and Zhang (2013)	✓	✓	✓	✓			
Gao and Dong (2012)	✓						✓
Kampf, Průša and Savage (2011)	✓			✓			
Klapita and Švecová (2006)	✓	✓	✓				
Lee, Huang and Teng (2009)	✓	✓	✓	✓	✓	✓	
Li, Liu and Chen (2011)			✓	✓			✓
Liu, Guo and Zhao (2012)	✓		✓				
Oktal and Ozger (2013)	✓	✓	✓				
Rahimi, Asef-Vaziri and Harrison (2008)	✓	✓	✓	✓			
Ren et al. (2010)	✓	✓		✓	✓	✓	✓
Škrinjar, Rogić and Stanković (2012)	✓	✓	✓	✓	✓		✓
Tu et al. (2010)	✓	✓	✓	✓	✓	✓	✓
Turskis and Zavadskas (2010)				✓	✓		
Wang and He (2009)	✓	✓	✓	✓			
Xiao and Zhang (2009)	✓	✓	✓	✓			
Zhi and Li (2012)	✓	✓	✓				
Zhi et al. (2010)	✓		✓	✓			

*supply and demand

Defining the initial set of potential location sites could also be based on criteria related to the location of supply and demand of goods. Boudouin and Luna (2012) suggest that areas where product consumption is concentrated could be used as foundation to identify the need for a logistics hub, especially when urban transportation is at stake.

Ambrosino and Sciomachen (2012) go in the same direction, adopting a procedure that considers government data on supply and demand of products. Alumur, Kara and Karasan (2012), in turn, pre-select sites based on population and industrialization of cities and regions.

Identifying the existing infrastructure that could accommodate a logistics hub is the third criterion adopted in pre-selection. Oktal and Ozger (2013) and Tu et al. (2010) discuss the possibilities of installing hubs in airports that already have feasible features, such as size of landing runway and capacity to receive a greater number of aircrafts resulting from an increased volume of airflow. In line with this idea, Feng, Li and Zhang (2013) consider existing railroad stations and select those best suited to support a hub. The authors evaluate not only the physical conditions of the railroad station, but also the regional support, the traffic geography and environmental development. On the other hand, Lee, Huang and Teng (2009) verify the storage conditions of existing distribution centers that could develop into transshipment facilities for maritime shipping, as well as the distance between the hub and ports in the same region.

5.1 MULTI-CRITERIA MODELS

The location of logistics hubs is a complex problem, in which decision is affect by the context, the availability of information, and the importance given to the evaluation criteria (LEE; HUANG; TENG, 2009). Therefore, according to these authors, decision should be made based on multiple criteria, supported by quantitative and qualitative data. Multi-criteria models typically allow conflicting criteria to be taken into account, which would then be evaluated by decision makers in order to establish preferences among possible location sites. Among the papers surveyed, the ones that take in account the greater amount of criteria area proposed by Lee, Huang and Teng (2009), Ren et al. (2010) and Tu et al. (2010).

Formulating a multi-criteria model usually starts by identifying the most relevant decision criteria. Here the aspects described in Table 3 could be directly used as decision criteria. Next, the pre-selected sites would have their performance evaluated according to each criterion. The way in which the evaluation is carried out depends on the solving technique adopted, which can result in one optimal solution or a set of good alternatives. In this case, results could also be evaluated and ranked by means of sensitivity analysis.

Quantitative parameters are the most used, probably due to the ease of obtaining data and related information. Within this scope, all authors seem to agree that the investment required for construction should be considered in the models, as well as costs related to transportation activities. Functional aspects are less frequently used, such as issues related to product handling, and supply/demand information.

Qualitative criteria, on the other hand, require more complex analysis and are mainly grounded on expert knowledge. Nonetheless, the possibility of evaluating this type of criteria is highlighted as the major advantage of multi-criteria modeling. Therefore, they are found in larger quantities and practically in all modes in this category, except for Kampf, Průša and Savage (2011). The potential for facilities expansion, availability of skilled labor and proximity to marked are considered by Lee, Huang and Teng (2009), Ren et al. (2010), Tu et al. (2010) and Turskis and Zavadskas (2010), as well as the availability of support services, such as energy provision and waste management. Issues related to regional development policies, legislation, and tax incentives are taken into account by Lee, Huang and Teng (2009), Ren et al. (2010) and Tu et al. (2010). Lee, Huang and Teng (2009), Li, Liu and Chen (2011), and Tu et al. (2010) also point out the need to consider geographic, topographic, and hydrological aspects of the available land for the hub installation. Finally, environmental factors related to noise pollution and environment degradation are evaluated by Li, Liu and Chen (2011) and Ren et al. (2010).

More than selecting the best hub location, multi-criteria models expose some other interesting results. Turskis and Zavadskas (2010) show that the participation of stakeholders is crucial in the modelling process, since they allow for the assessment of qualitative criteria, such as expansion possibilities and market proximity. Lee, Huang and Teng (2009), in turn, give examples of strategies for the development of logistics hubs, pointing out the importance of cooperation between business and the public sector in strengthening the competitiveness of a region. Both sets of authors adopt a macroeconomic perspective, focusing on infrastructure planning.

5.2 SOLUTION TECHNIQUES FOR MULTI-CRITERIA MODELS

Multi-criteria models are usually solved by a specific set of tools, characteristic of MCDM. The combination of more than one solution technique seems common in the papers surveyed. Among the methods found, the most adopted ones are fuzzy sets and the analytic hierarchy process (AHP), followed by weighted sum, goal programming and technique for order of preference by similarity to ideal solution (TOPSIS). Other techniques, e.g. heuristics, are seldom applied, as can be seen in Table 4.

Table 4 - Solution techniques adopted for solving multi-criteria models.

	TYPICAL MCDM					**OTHERS**			
AUTHORS	AHP*	Fuzzy sets	Weighted sum	Goal programming	TOPSIS**	SWOT***	Genetic algorithm	Tabu search	Simulated annealing
Feng, Li and Zhang (2013)							✓	✓	✓
Kampf, Průša and Savage (2011)	✓		✓						
Lee, Huang and Teng (2009)	✓	✓				✓			
Li, Liu and Chen (2011)		✓			✓				
Ren et al. (2010)		✓							
Tu et al. (2010)	✓			✓					
Turskis and Zavadskas (2010)	✓	✓							

*analytical hierarchy process, **technique for order of preference by similarity to ideal solution, ***strengths, weaknesses, opportunities and threats

Due to the possibility of incorporating qualitative elements and uncertainty into the decision variables, Klapita and Švecová (2006) and Li, Liu and Chen (2011) indicate the fuzzy sets formulation as one of the most suitable tools for solving multi-criteria models. This approach allows decision makers to use inaccurate or incomplete data to find a solution (TURSKIS; ZAVADSKAS, 2010), without giving up the quantitative parameters. While the qualitative parameters are depicted in terms of fuzzy values, with the help of linguistic variables for their evaluation, the quantitative ones can be represented directly by numerical values and/or statistics. Furthermore, uncertainty can be represented by probability distributions (DING, 2013). Although the results obtained with this method are concrete outcomes, its credibility depends intrinsically on the skills of decision makers and their ability and experience in selecting the most appropriate level of preference when comparing decision criteria (KLAPITA; ŠVECOVÁ, 2006).

AHP is also a method that allows one or more decision makers to express their preferences by either numeric values or linguistic variables (KAMPF; PRŮŠA; SAVAGE, 2011). However, it appears to never be used alone, but in combination with another technique. When dealing with multiple criteria, the AHP is commonly applied as a first step of decision making, being employed to classify criteria in a scale of importance, such as done by Kampf, Průša and Savage (2011), Lee, Huang and Teng (2009), Tu et al. (2010), and Turskis and Zavadskas (2010).

Still in the MCDM field, we found the adoption of a weighted sums approach by Kampf, Průša and Savage (2011). One of the simplest methods of multi-criteria evaluation, it is applied only when all data can be expressed in the same unit, which makes its adoption quite limited. On the other hand, Tu et al. (2010) chose goal programming, which allows for detailed information to be incorporated into the problem's structure, aiding in the determination of the requirements that would maximize the customers' satisfaction based on limited resources. Finally, Li, Liu and Chen (2011) used the TOPSIS method, combined with axiomatic fuzzy sets in the initial stage of the decision process rather than with AHP.

Other non-traditional methods of multi-criteria decision making were also identified. Focused on the development of logistics hubs and transportation networks, Lee, Huang and Teng (2009) applied a SWOT matrix to evaluate the competitiveness of a number of possible sites for the hub installation. Feng, Li and Zhang (2013), in turn, propose a heuristic method which combines genetic algorithm, tabu search, and simulated annealing in order to minimize construction costs and customer costs.

5.3 SINGLE-CRITERION MODELS

Although real world logistics hub location problems have a multi-criteria nature, they are often reduced to simplify their solution (ALUMUR; KARA; KARASAN, 2012; ŠKRINJAR; ROGIĆ; STANKOVIĆ, 2012). The literature shows that there is an emphasis on the use of single-criterion decision models, especially in recent years.

Single-criterion models adopt a similar formulation to the hub location problem (HLP) in almost all cases surveyed, except for Gao and Dong (2012), Liu, Guo and Zhao (2012), and Zhi and Li (2012). This type of formulation deals with the location of facilities and the allocation of product flows between origins, hubs, and destinations, in order to distribute the goods through minimum cost paths (AMBROSINO; SCIOMACHEN, 2012). In these models, the transportation network is usually represented by a graph, composed of origin, destination and hub nodes, arcs connecting hubs with origins and destinations, and arcs linking hubs among themselves in case more than one hub should be installed. Transshipment nodes are not included in HLP models. Also, although the original formulation of the HLP allowed direct connections between origins and destinations, the absence of such connections has become a basic feature of HLP models, as defined by Campbell in 1994 (CAMPBELL; O'KELLY, 2012); i.e. origins and destinations can only be connected via one or more hubs.

An important feature that differentiates HLP models is the type of flow allocation allowed. Here, two different concepts could be identified: single allocation, where each source and each destination is allocated to only one hub, as show in Klapita and Švecová (2006), Škrinjar, Rogić and Stanković (2012), and Zhi et al. (2010), and multiple allocation, which allows non-hub nodes to be connected to more than one hub, as depicted by Ambrosino and Sciomachen (2012), Dubke and Pizzolato (2011), Oktal and Ozger (2013), and Rahimi, Asef-Vaziri and Harrison (2008). Škrinjar, Rogić and Stanković (2012) consider that multiple allocation provides the most complete allocation options, since they allow more flexibility in terms of connections available. In general, the benefits obtained with the location are inversely proportional to the amount of links required to connect the nodes in the network, and, consequently, to the transportation costs, which result from economies of scale achieved by a better network design (CAMPBELL; O'KELLY, 2012).

Flow allocation in a HLP model is linked to the adoption of a discount factor, with a value between 0 and 1, which indicates the range of economies of scale that can be achieved with the use of a hub. They are usually employed to lower the total transportation costs. This coefficient can be used in two different ways, depending on the connections available between the hubs. If the hubs to be opened are not connected, or if there is only one hub, the discount factor is applied to all arcs connected to that hub, leading to a reduction of the transportation costs on these arcs. If two or more hubs are connected, then the discount factor is applied to the inter-hub arcs (CAMPBELL; O'KELLY, 2012; GOLDMAN, 1969; O'KELLY, 1986). In this case, Škrinjar, Rogić and Stanković (2012) point out that the transportation costs between the hubs end up being lower than those of other arcs, resulting from a better use of the infrastructure available.

Nonetheless, defining the discount factor would require a specific and long study that, to the best of our knowledge, has not yet been carried out. The value of the discount factor has usually been defined based on interviews (ALUMUR; KARA; KARASAN, 2012), or taken from the literature (OKTAL; OZGER, 2013). According to Campbell and O'Kelly (2012), the discount factor could be related to the transportation mode used, ranging from 0.1 for rail to 1 for road. Although Kimms (2006) point out that this coefficient can be variable, depending on factors such as volume of flow in the arcs (CAMPBELL; O'KELLY, 2012), most authors still use a constant value due to the complexity that a variable factor could bring to the model. In order to work around this issue, Campbell and O'Kelly (2012) observed an increase in the use of sensitivity analysis for evaluating the model's behavior with a wide range of discount factors.

A further proposal for logistics hub location models deals with the representation of the network through geographic coordinates of origins and consumption points (LIU; GUO; ZHAO, 2012). Zhi and Li (2012), on the other hand, concentrate on the solution method and do not present a structure model for the problem.

As the network arcs are usually public roads, the addition of new arcs is not a concern in HLP models (CAMPBELL; O'KELLY, 2012). This, in fact, is a feature of a different category of models, called network design problems. However, when dealing with the location of more than one hub in the HLP, authors might consider new arc projects for inter-hub connections. Alumur, Kara and Karasan (2012) take this aspect into account, assessing not only the sites and number of hubs to be opened, but also how they will be connected between each other and the transportation modes used for that.

Single-criterion models seek to optimize different objective functions, often related to economic or financial matters, as shown in Table 5. Among these, the most common ones pursue costs minimization, either of transportation or total costs. Dubke and Pizzolato (2011), on the other hand, aim at maximizing the revenue. Other goals might also be related to minimizing the travelled distances, which could be indirectly related to financial results, as well as service level and market coverage. This idea is adopted by Zhi and Li (2012), who take a market perspective in order to reach the largest number of customers possible. In turn, Rahimi, Asef-Vaziri and Harrison (2008) point out that not only economic issues should be evaluated, but also social costs. Although they are usually not embedded in the prices payed by hub users, social costs have shown an increased importance as a critical element in sustainable transportation systems.

Table 5 - Objective functions adopted in single-criterion models.

AUTHOR	**OBJECTIVE FUNCTION**			
	Min. Transport costs	Min. Total costs	Max. Revenue	Max. Coverage
Alumur, Kara and Karasan (2012)	✓			
Ambrosino and Sciomachen (2012)	✓			
Dubke and Pizzolato (2011)			✓	
Gao and Dong (2012)	✓			
Klapita and Švecová (2006)		✓		
Liu, Guo and Zhao (2012)	✓			
Oktal and Ozger (2013)		✓		
Rahimi, Asef-Vaziri and Harrison (2008)	✓			
Škrinjar, Rogić and Stanković (2012)	✓			✓
Wang and He (2009)		✓		
Xiao and Zhang (2009)	✓			
Zhi and Li (2012)				✓
Zhi et al. (2010)		✓		

Quantitative aspects are thus predominant in decision making with single-criterion models. Except for Gao and Dong (2012), all models of this type consider data on transport and origin and destination of goods. Next, we found 15 of the 20 papers to adopt functional criteria. Data on the volume of investments is used in fewer cases, as can be seen in Table 3, and may be part of total cost minimizing object functions. Geographic characteristics of the terrain are also seldom applied.

Adding qualitative parameters is unusual in single-criterion models. Nonetheless, they could be found in the works of Gao and Dong (2012) and Škrinjar, Rogić and Stanković (2012). While the former believe that environmental protection issues are important, the latter add in the interaction of the logistics hubs with the market by evaluating the proximity between them.

Solving single-criterion models results not only in finding a hub location. The optimal amount of facilities required is obtained by Alumur, Kara and Karasan (2012), Oktal and Ozger (2013), Rahimi, Asef-Vaziri and Harrison (2008), and Xiao and Zhang (2009). In such cases, the pre-selected site set is tied to a restriction on the maximum number of hubs that could be installed. Results related to the allocation of origin and destination nodes are seldom found, highlighted only by Dubke and Pizzolato (2011) and Rahimi, Asef-Vaziri and Harrison (2008). In turn, the model proposed by Dubke and Pizzolato (2011) goes deeper into the functionality matter, identifying the logistics services to be performed in each new hub.

5.4 SOLVING TECHNIQUES FOR SINGLE-CRITERION MODELS

There is a mixed set of solution methods for single-criterion models, ranging between heuristic, exact, and stochastic ones. But, unlike for multi-criteria, we did not find a preferred set of techniques for solving single-criterion models. Nonetheless, heuristic approaches seem to be more frequently used to solve HLP models. An overview of the techniques adopted is shown in Table 6. After evaluating a variety of methods, Škrinjar, Rogić and Stanković (2012) considered the genetic algorithm to be the most suitable for logistics hub single-criterion location, although they do not present an implementation. We observed the application of this method in two instances. Zhi et al. (2010) adopted particle swarm optimization, which combines both evolutionary features of genetic algorithms and probabilistic search of simulated annealing. Also Xiao and Zhang (2009) worked with a combination of genetic algorithm, but in this case with an ant colony heuristic.

The ant colony heuristic by itself is adopted by Zhi and Li (2012). Ambrosino and Sciomachen (2012), in turn, combined traffic flow information obtained through a geographic information system (GIS) with a shortest path algorithm to find the best location in multimodal networks. Still in the field of heuristics, Alumur, Kara and Karasan (2012) proposed their own technique, based on set covering, for solving a problem that combined network design and allocation in the same model. This was justified due to the complexity of the proposed problem, which was quite difficult to solve with the techniques available in the literature. According to the authors, the results were considered to be of good quality and to have been achieved in reasonable computing time.

Table 6 - Solution techniques proposed for solving single-criterion models.

	HEURISTIC					**EXACT**				**STOCHASTIC**		
AUTHORS	Genetic algorithm	Ant colony	Particle swarm opt.	Shortest path	Specific heuristic	Spatial analysis	Gravity center	MIP	MILP	Fuzzy algorithm	Stochastic opt.	Robust optimization
Alumur, Kara and Karasan (2012)					✓							
Ambrosino and Sciomachen (2012)				✓								
Dubke and Pizzolato (2011)								✓				
Gao and Dong (2012)						✓						
Klapita and Švecová (2006)										✓		
Liu, Guo and Zhao (2012)							✓					
Oktal and Ozger (2013)									✓			
Rahimi, Asef-Vaziri and Harrison (2008)						✓			✓			
Škrinjar, Rogić and Stanković (2012)	✓											
Wang and He (2009)											✓	✓
Xiao and Zhang (2009)	✓	✓										
Zhi and Li (2012)		✓										
Zhi et al. (2010)			✓									

Traditional exact techniques of deterministic optimization also find their place in solving logistics hub location problems. This is the case for mixed integer programming (MIP) and mixed integer linear programming (MILP), which were applied by Oktal and Ozger (2013) and Dubke and Pizzolato (2011), respectively. Liu et al. (2012), although highlighting a variety of issues that influence this kind of decision, ended up using the gravity center method, a less elaborate tool based on geographic coordinates. In order to evaluate aspects related to network flows, Gao and Dong (2012) and Rahimi, Asef-Vaziri and Harrison (2008) solved their problem through spatial analysis with the aid of GIS. On the other hand, Rahimi, Asef-Vaziri and Harrison (2008) combined spatial analysis with partial weighted sum and with a procedure for constructing contour lines; however, when dealing with multiple hubs, the authors do not describe the method used.

Based on the premise that changes in input parameters may impact the decision on the number of hubs to be installed, their location, and flow allocation, Klapita and Švecová, (2006) and Wang and He (2009) claimed the adoption of measures to overcome uncertainty and variability to be necessary. Wang and He (2009) investigated these aspects by considering demand uncertainty in a variety of economic scenarios, while other model parameters were kept deterministic. In this case, robust optimization was compared against stochastic optimization: according to the authors, the first allowed for a better representation of uncertainties while effectively reducing the risks in decision making when compared to the second. Klapita and Švecová (2006) also performs comparisons between different solving tools that deal with the variability of parameters: sensibility analysis and fuzzy analysis. The authors propose an algorithm that employs principles of fuzzy logic, but does not depend on the skill of decision makers. According to them, the advantage of this proposal lies in identifying a best solution that, as pointed out by Wang and He (2009), is resistant to future changes in the model.

Authors such as Alumur, Kara and Karasan (2012) and Dubke and Pizzolato (2011) also shed light on sensitivity analysis. They evaluate the model's outcomes regarding the number of hubs to be installed and their impact on the volume of products handled, facilities capacities, transportation costs, and revenue. Ambrosino and Sciomachen (2012), also performs sensitivity analysis, but from a perspective of traffic reduction. Wang and He (2009), in turn, evaluate the model's behavior according to different economic scenarios; however, they do so by using different solving techniques instead of sensitivity analysis. Lastly, Rahimi, Asef-Vaziri and Harrison (2008) test the network sensitivity to the number of hubs that can be installed, evaluating the total travelled distances.

6 APPLICABILITY OF MODELS AND SOLUTION TECHNIQUES FOR TRANSPORTATION NETWORKS

In light of the concept of a logistics hub and its role in transportation networks, it is important to reflect on the adequacy and applicability of location models and solution techniques available to solve such problems in this context.

The type of model adopted seems to be directly related to the perspectives and goals of the papers surveyed. Models that seek to evaluate strategies, transportation network settings, or infrastructure planning and expansion, adopt predominantly a multi-criteria approach. This choice is mainly justified by the advantages of incorporating qualitative criteria, especially those related to policies, legal matters, and relationships with the market. They can be seen as models that encompass a macroeconomic view, which could be used to guide the improvement of a region's competitiveness. In turn, when the focus is on the benefits for those using the hub, it is evident that the choice is in favor of single-criterion models. They take a microeconomic view, evaluating aspects such as cost reduction and revenue increase. Although infrastructure investments, which depend mainly on the public sector, should be planned taking into consideration the goals of industries and logistics service providers and their customers, these two perspectives were not addressed together by one single model.

If we consider the variety of qualitative and quantitative aspects that influence decision making when locating logistics hubs, then multi-criteria models seem to be more adequate. They have the advantage of being quite flexible, encompassing not only conflicting criteria, but also aggregating views of different stakeholders. However, they do not provide the means to evaluate flow distribution and its impact on the transportation network; at least, none of the models available in the surveyed literature brought results in this matter. Yet this kind of information would be of great importance when dealing with strategic decisions, especially regarding infrastructure planning.

Bearing this in mind, HLP models may seem more comprehensive, since they allow both hub location and flow allocation to be performed throughout a network. Although they have been seen, over time, to be broadly applicable to many network topologies, the models' abstract nature, apparent simplicity, and generality limit their ability to accurately represent important features of logistics systems (CAMPBELL; O'KELLY, 2012). Three main issues hinder the application of HLP models in large-scale networks which include logistics hubs: i) the absence of direct connections between pairs of origins and destinations; ii) the requirement that all products should flow straight through hubs, and at least through one hub; and iii) the simplification of paths and connections between origins, destinations, hubs, and other network nodes.

The lack of direct connections between origins and destinations in HLP models is the first issue that calls for our attention. This absence is justified by Campbell and O'kelly (2012): the authors consider that such connections would be used only for large flows, especially full load trucks, which would naturally be transported straight from suppliers to customers. However, excluding these flows would prevent them from taking advantage of value added services that could be provided in the hub. This also implies that, for other flows, it would always be better to use routes that go through a hub. This does not correspond to reality, as it cuts out the use of other route options, which could end up being more profitable or guaranteeing a determined service level. This may even artificially overload the hub's usage, negatively impacting constructive aspects related to facilities' capacity and service dimensioning, leading ultimately to unnecessary investments.

Representing the routes through direct connections between origins and hubs, and between hubs and destinations makes it difficult to observe the real distribution of flows. This hinders the analysis from an infrastructure use perspective, as well as the evaluation of flow changes resulting from the implementation of a logistics hub. The use of HLP models itself actually leads us to believe that this may be a reason why the impact of a hub on networks and infrastructure planning is a subject that still requires further research.

The representation of other existing connections also would allow the use of different routes between origins and destination. In this case, the resulting graph would also include transit nodes, resembling transshipment models. This is actually the generic formulation for network flow problems, from which simplifications are made to reach HLP models (CAMPBELL; O'KELLY, 2012; RAGSDALE, 2014). Hence, an expanded representation would remain compatible to this class of problems. Yet it should be noted that the simplifications made are closely related to the complexity of solving HLP problems with larger graphs, once this is a NP-hard problem, as well as to the availability of models and solving techniques that would enable us to find a viable solution in a timely manner.

There are some applications where the classic HLP model would be well suited. Logistics hubs have been long dedicated to air transportation or postal services (ALLAZ, 2004). In these cases, transportation via hub is mandatory and direct connections do not make much sense, either with regards to the transportation mode used or to the characteristics of the service performed. The wide adoption of HLP models may also be related to the data sets mostly used to validate the proposed formulations, which are regarded to airport networks (such as the CAB dataset, introduced by O'Kelly in 1986) or postal operations (such as the AP dataset, introduced by Ernst and Krishnamoorthy in

1996). However, this might lead authors to disregard features that are common to other scenarios.

When locating a logistics hub, it may also be interesting to evaluate the available infrastructure and the need to build new links in order to improve the transportation performance. According to Campbell and O'Kelly (2012), there exists a direct relationship between location problems and network design. However, the design of large-scale networks with a variety of connections and logistics hubs is still a challenge, especially if we want to include this in the location model. Clearly, a free network design where many new links could be established would add great complexity to the model and be in conflict with the investment capacity of a region. Alumur, Kara and Karasan (2012) highlight these issues, proposing a framework that considers just a few possibilities of new arcs. In the same direction, sets of new projects could be formulated, simplifying the model to test pre-defined network topologies.

Since neither of the two types of models alone allows us to tackle all matters related to locating a logistics hub, an analytical modelling approach seems to be more suitable, combining features of both multi-criteria and single-criterion models. A multi-criteria model, taking into account strategic matters of hub positioning and regional competitiveness, could be adopted initially to define a location site, or a list of them. The results would then be used as an input for a more generic network flow model; i.e. a transshipment model. With this, a network could be represented in greater detail, allowing for the choice between different routes and assessment of the hubbing effect on the flow's distribution. This network flow model could take into account microeconomic perspectives for decision making, addressing transportation cost reduction and other issues related to the benefits that could obtained by hub users. Thus, we would be able to combine both perspectives in one approach for solving the problem.

Regarding the solutions techniques, we did not find a preference in the literature; nevertheless, we were able to identify some adoption patterns. There is a correlation between the models formulated and the solution techniques adopted: the degree of complexity used to represent the problem defines, in a certain way, the tools implemented. Quantitative methods, for example, are not traditionally the first choice when dealing with strategic location decisions, given the difficulty in obtaining information and processing the available data (MELO; NICKEL; SALDANHA-DA-GAMA, 2009). Besides, the fact that MCDM tools are able to handle many, and sometimes conflicting, variables may also explain the preference for this kind of method when solving multi-criteria models.

The choice of solution methods for single-criterion models, however, seems to be directly related to models' characteristics and the amount of time available to find a solution. A more detailed network and an increase in the volume and variety of product flows add computational challenges, due to the greater number of connections and constraints to be considered. Škrinjar, Rogić and Stanković (2012) point out that HLP models of small instances can be solved with exact methods, while larger problems require, in general, the use of heuristics. Accordingly, Ambrosino and Sciomachen (2012) assert that real world problems, usually characterized by a large volume of data, are also generally solved with heuristic tools. This is closely related to the combinatorial nature of these problems. The adoption of heuristics is related to the amount of time available to find a solution: they tend to achieve it in faster computational times. On the other hand, if we want to add uncertainty, stochastic or robust optimization could be good choices of tools.

Meanwhile, some evidence shows that new algorithmic and computational developments have enabled the use of exact methods for solving larger HLP models, with over 500 nodes of origin and destination (CAMPBELL; O'KELLY, 2012). In this direction, Škrinjar, Rogić and Stanković (2012) suggest that methods which adopt extensive search could benefit from aggregating Branch-and-Bound and Branch-and-Cut techniques in order to lower computing time by reducing the problems' dimensions.

7 CONCLUSIONS

The growing importance of logistics hubs as an element of transportation networks fosters the study and definition of their features, as well as the development of knowledge on how to deal with such structures. To shed light in this area, this paper presented a literature review on logistics hubs location. We surveyed models and solution techniques available, and assessed their applicability within this context. This work differs from others in the field of location science by evaluating an application area instead of a class of models or methods. It facilitates a better understanding of requirements and of how to solve this type of location problem.

We identified two categories of models which are used in logistics hubs location. Multi-criteria models enable the consideration of a broad range of criteria, both quantitative and qualitative, which makes them more suitable for representing such strategic decisions. However, they provide information only about location sites, and do not allow the assessing of the distribution of flows and their impact on the network infrastructure. Single-criterion models, on the other hand, tend be similar to the HLP and deliver results related not only to hub location, but also to flow allocation. Because of these features they might seem, at first glance, more suitable and complete. Yet they adopt network simplifications that do not correspond to a correct representation of the transport system and the connections between origins, hubs, and destinations.

It is also noteworthy that the papers surveyed adopt mainly two different research approaches, which are directly related to the type of models and solution techniques employed. While the multi-criterion category follows an empirical design approach, where the goal is to create models that better represent the existing relationships in real world problems, the single-criterion one has an axiomatic perspective, where the primary interest is to understand the modeling process, explain its characteristics, find an optimal solution, and compare the performance of different solution techniques. This contrast of approaches is emphasized by the different perspectives taken by each category: macroeconomic versus microeconomic.

Perhaps a better way to address logistics hub location would be by considering aspects of both categories – a two stage analytical approach through the combination of different features. First, a multi-criteria analysis could be used to define a location site or a ranked list of sites, taking into account political, legal, environmental, and market aspects, among others. Then, the implementation of a network flow model based on economic and/or business criteria would not only aid in defining the allocation of flow, but also allow the evaluation of changes in the use of infrastructure due to the installation of one or more hubs. This would furthermore enable the assessment of issues related to network design, by testing different sets of infrastructure projects and evaluating their impact on an integrated transportation networks considering logistics hubs. Solving tools could be chosen respectively.

There is, indeed, a stated need for a more refined representation of transportation networks. Alumur, Kara and Karasan (2012), Ambrosino and Sciomachen (2012), and Rahimi, Asef-Vaziri and Harrison (2008) are in agreement on the importance of considering different decision criteria, which are relevant and inherent to logistics hubs and their role in transportation networks. In this context, issues related to environmental impact, proximity to transportation modes, traffic, congestion, and volume of flow handled at the hub still require further investigation. On the other hand, Škrinjar, Rogić and Stanković (2012) point out the importance of studying network topologies where transportation can be done either via hub or by direct connections, which are scarce in the literature. According to Dubke and Pizzolato (2011), future research should also look at network design and infrastructure planning, comprising a variety of transportation modes such as road-, rail- and waterways. In addition, the impacts of a new hub on the network should be further explored (FARAHANI et al., 2013). Since all of this adds to the complexity of models, the search for new solution algorithms and improvements in computational power also find room in the logistics hub location context.

MINIMUM-COST FLOW ALGORITHMS: A PERFORMANCE EVALUATION USING THE BRAZILIAN ROAD NETWORK

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Abstract

Planning transportation infrastructure is a logical and technical process, which uses quantitative analysis to guide the definition of requirements and investments. In this paper, we evaluate the practical performance of four algorithms for solving the minimum-cost flow problem on road networks. Most computational testing has been based on artificially generated networks, which may differ from real road networks; for this study, we built 215 real-world test instances which were solved over the Brazilian road network. We verified that, differently from what was found in the literature, network simplex is the best performing algorithm in practice for this context, both in terms of speed and robustness. Features such as the number of supply and demand nodes influenced runtime, besides network topology and spatial syntax. On the other hand, the supplied volume and the ratio between supply/demand nodes were not good performance predictors. Our evaluation also showed that efficiency may be tied to algorithmic structure. These results should be particularly useful to support decision making when addressing logistics infrastructure challenges, especially those of developing economies, allowing to reduce the cost of processing analyses.

Keywords: transportation; minimum-cost flows; road networks; experimental study; Brazil

1 INTRODUCTION

Logistics and transportation infrastructure has an important role in spatial organization and economic development (STEADIESEIFI et al., 2014; YAMADA et al., 2009). It defines a transaction space where different supply chain players interact and products are distributed as a result of local, regional and global market relations (RODRIGUE, 2004). The movement of goods – and its efficiency – rely on the transportation system configuration (GUASTAROBA; SPERANZA; VIGO, 2016), which comprises production facilities, consumer markets, warehouses, and transshipment points, all interconnected by different routes and modes of transportation. Among the infrastructure available, roads are regarded as crucial elements of transportation networks, influencing not only logistics operations, but also traffic, urban sprawl, and structure of cities (BARTHÉLEMY, 2011). Roadways may help to increase transportation options, reduce logistics costs and expand accessibility to different locations (LITMAN, 2013). On the other hand, the costs of inadequate infrastructure investment are very high: $27 billion a year are spent by American businesses in extra freight transportation costs, reducing the level of logistics services and raising product prices (NATIONAL ECONOMIC COUNCIL, 2014).

Roads are the major transportation alternative for developing countries (YAMADA et al., 2009) such as Brazil. The Brazilian transportation network, similarly to others, has an unbalanced spatial distribution of roadways, railways and waterways, which are not explored to their full potentials (PORTAL BRASIL, 2014). The Logistics Performance Index (LPI) reported by the World Bank ratifies the drawbacks of underperformance, but also shows potential of growth. Although Brazil’s overall position increased from 65th to 55th in the 2016 LPI evaluation, the improvement on transportation infrastructure was still modest (THE WORLD BANK, 2016a). The definition of investment priorities in infrastructure should be supported by proper methods, which allow robust evaluations, considering the limited resources available in developing economies. Besides the fact that “network design costs greatly dominate routing costs” (SÁ et al., 2009), distribution-related costs significantly impact on the structure of economic activities and may account for up to 30% of product prices (FEDERAÇÃO DAS INDÚSTRIAS DO ESTADO DE SANTA CATARINA, 2014; MUSA; ARNAOUT; JUNG, 2010; RODRIGUE; COMTOIS; SLACK, 2017). Thus, as the world’s ninth economy (THE

WORLD BANK, 2016b) and an important international trade player, Brazil could benefit from better planning and investment on its network.

Planning road networks is a logical and technical process, which makes use of qualitative and quantitative analysis in order to define the best use and investment for existing and future infrastructure. Although there is a great variety of information that influences infrastructure planning, those related to the flow of goods play an important role in road network design (YAMADA et al., 2009). The flows determine the transportation network requirements since they reflect the nature of trade (DABLANC; ROSS, 2012; MEIDUTĖ, 2007), are related to the fundamental issues of geographic and spatial economics, and influence location and distribution of economic activities (BARTHÉLEMY, 2011).

The way information is used to evaluate projects and simulate the effects of transportation policies is also key in the process of planning transportation networks. The majority of logistics and transportation plans developed in Brazil, for example, use information gathered from vehicle count in scattered points of the network, or data aggregated by transportation mode, transportation corridor, market and/or geographic region (FARIA; HADDAD, 2014; HADDAD, 2009; LUNA et al., 2013). Although gathering data is sometimes a hard task, this type of aggregate analysis may lead to biased results, especially when dealing with lower level infrastructure such as those connecting cities, or cities and ports. Discrete analysis, on the other hand, takes into account the use of detailed network topology and location of supply/demand, leading to a more accurate flow distribution and future prognosis.

Determining the flow of goods in a discrete way can be done with the used of network flow models (STEADIESEIFI et al., 2014). Among the different models available, the minimum-cost flow (MCF) problem is regarded as the most generic formulation, with a wide range of applications (AHUJA; MAGNANTI; ORLIN, 1993; KIRÁLY; KOVÁCS, 2012). The special structure of the MCF problem and the use of graphs for modelling lead to the use of specialized and efficient network algorithms that take advantage of such aspects. Yet, because the majority of these tools do not run in polynomial time, both theoretical and practical expectations motivate research on the efficiency of solving the MCF problem – a variety of papers on the implementation efficiency of MCF algorithms can be found, e.g., Armstrong, Klingman and Whitman (1980); Becker, Fickert and Karrenbauer (2016); Bertsekas and Tseng (1988); Bland (1993); Bünnagel, Korte and Vygen (1998); Frangioni and Manca (2006); Grigoriadis (1986); Kovács (2015);

Portugal et al. (2008). These performance evaluations are important since they allow for better decision making when choosing the most appropriate tool for solving a given problem (ZHAN; NOON, 1998), both in terms of efficiency and robustness.

Nonetheless, practical performance of algorithms tends to be somewhat different when compared to theoretical runtimes, notably due to network topology (KOVÁCS, 2015; SIFALERAS, 2013). Road networks, for instance, differ from other types of networks especially in terms of topology and spatial syntax (BARTHÉLEMY, 2011; GASTNER; NEWMAN, 2006; ZHAN; NOON, 1998). Such characteristics grant a strong signature for road networks, with a graphic shape that is distinct from other nongeographic networks (GASTNER; NEWMAN, 2006). Performance may also be influenced by the use of computer generated networks, most commonly found in the literature. According to Király and Kovács (2012) and Zhan and Noon (1998), artificial networks can differ substantially from real-world ones, especially regarding roads. This is due to irregularities in either drawing arcs, establishing connectivity, or defining and locating supply/demand nodes.

In light of this, our paper presents a comprehensive study on the practical performance of four MCF algorithms for road networks: Successive Shortest Path (SSP), Capacity Scaling (CAS), Cost Scaling (COS) and Network Simplex (NS) as identified by Kovács (2015) as the fastest ones for this context. We used data from the Brazilian network and flow of goods, which evidence the applicability of tools for discrete analysis in a developing economy and account for scenario diversity. Full real-world test instances were built, comprising network topology, node-arc layout, supply/demand location, transportation costs, and volume of products to be transported. We also looked into road conditions, which affect transportation costs and choice of paths. Since it is already known that the number of nodes and arcs influence performance, we diversified test instances over the same network and evaluated the influence of the amount and location of supply/demand nodes, the relationship between them, and the supply volume over the algorithm runtimes.

The next sections are organized as follows. Section 2 presents the MCF problem, its formulation and the four abovementioned algorithms. Section 3 describes the experimental study design. Next, we present results and discuss the performance of the algorithms. Finally, conclusions are devised in order to provide guidelines for selecting an

MCF algorithm that is suitable for road networks when considering the freight transportation context.

2 DISTRIBUTING FLOWS THROUGHOUT ROAD NETWORKS

The MCF problem is a fundamental model for solving network flow problems with the purpose of moving an entity, e.g., product, person, vehicle or message, between different locations, having as goal of either providing service effectively or using the network efficiently (AHUJA; MAGNANTI; ORLIN, 1993; KHURANA, 2015; KOVÁCS, 2015). Its solution has been intensively studied for more than 50 years (AHUJA; MAGNANTI; ORLIN, 1993; KOVÁCS, 2015) and many algorithms are available in the literature, from linear programming to heuristics. An alternative modelling option is also to transform the original MCF problem into an equivalent transportation problem (KHURANA, 2015).

When solving the MCF problem, practical and theoretical performance of algorithms may differ, especially due to network topology and spatial syntax (KOVÁCS, 2015). In terms of topology, road networks display a hybrid structure. Zhan and Noon (1998) found that these networks often contain densely connected areas, surrounded by highly sub-networked areas, which are further surrounded by rural road structures, composing such a mixed pattern that is virtually impossible to simulate. On the other hand, spatial syntax of road networks is characterized by the presence of very short arcs, low degree of connectivity among network nodes, lack of hub-like nodes, and the presence of many loops (GASTNER; NEWMAN, 2006). In addition, capacity limitations on the arcs and the looseness of supplied volumes may hinder runtime; on the other hand, instances with loose capacity limits, or even infinite capacity, seem easier to solve (KOVÁCS, 2015).

2.1 THE MINIMUM-COST FLOW PROBLEM

The goal of the MCF problem to minimize some cost parameter so that the distribution of flows throughout the network is optimal, taking into account nodes and arcs restrictions (SIFALERAS, 2013). In the scope of freight transportation, it consists in finding the transportation alternative of less cost for a determined amount of products sent from a set of suppliers to a set of customers in order to meet supply/demand relationships. It can be useful not only for single-commodity problems, but also for multi-commodity ones in which road capacity can be disregarded. In this case, the problem is transformed in a combination of multiple single-commodity instances.

The MCF network can be best represented with the use of graphs, in which origins, destinations, and transshipment points are denoted by a set of nodes, and transportation connections between nodes are denoted by arcs. The graph is usually directed, with capacity restrictions and cost functions defined for each arc (KOVÁCS, 2015). Product flows can traverse between any sequence of nodes, not being restricted to direct connections (KHURANA, 2015), using one or more transportation modes (DÍAZ-PARRA et al., 2014). In such cases, the MCF problem is also known as the transshipment problem.

According to Díaz-Parra et al. (2014), three sets of information are necessary to represent the MCF problem for freight transportation. The first consists of data about the goods to be distributed, such as volume, weight, type, and transportation cost. The second concerns the location of supply, demand, and transshipment points: one should identify the function of each node in the network. Finally, the third set regards the transportation mode features, such as infrastructure availability, capacity, conservation state, and regulation, which can play an important role in defining the cost functions over arcs. Although a large amount of information may be used, the level of detail is related to the perspective and complexity of the analysis to be made Díaz-Parra et al. (2014).

Formally, the MCF problem can be modelled as a $G = (V, A)$ directed graph, connected, consisting of de $n = |V|$ nodes and $m = |A|$ arcs. To each arc $ij \in A$, there is an associated minimum capacity l_{ij}, a maximum capacity u_{ij}, and a cost c_{ij}. Each node $i \in V$ holds a supply or demand b_i. Supplies are represented by positive values, and demands by negative values. Transhipment nodes have $b_i = 0$. The variable x_{ij} represents the flow between nodes i and j. The MCF problem can be defined by equations 1, 2 and 3 (e.g., see Kovács 2015).

In this model, equation (1) represents the objective function, with the goal of minimizing the transport cost of each unit of flow x_{ij}. Equation (2) denotes the flow conservation restrictions, and equation (3) the capacity restrictions. We assume that all arc capacities are finite, that arc costs are non-negative and that there is a possible solution (AHUJA; MAGNANTI; ORLIN, 1993). Since the network is considered balanced, the total supply is equal to the total demand, which implies that $\sum_{i \in V} b_i = 0$. Although this is a common assumption in the literature, unbalanced networks with inequality restrictions can also be considered as seen in Khurana (2015).

$$Min \sum_{ij \in A} c_{ij} x_{ij} \qquad (1)$$

subject to

$$\sum_{j:\, ij \in A} x_{ij} - \sum_{j: ji \in A} x_{ji} = b_i \quad \forall\, i \in V \qquad (2)$$

$$l_{ij} \leq x_{ij} \leq u_{ij} \quad \forall\, ij \in A \qquad (3)$$

2.2 SOLUTION TOOLS FOR THE MCF PROBLEM

Due to the linear characteristics of the MCF model, the straight forward solution method is the simplex algorithm. Yet, due to the model particular network structure, other specialized and more efficient tools have been devised. A comprehensive list of MCF algorithms was studied by Kovács (2015), including the SSP, CAS, COS, and NS, which were identified as the fastest ones for road networks.

The SSP algorithm solves the MCF problem by computing a sequence of the shortest paths. It is a dual ascent algorithm that successively augments flow along the shortest paths of a residual network, in order to distribute the flow from supply to demand nodes (KOVÁCS, 2015). With the use of a residual network, the algorithm maintains an optimal pseudo-flow and node potentials as it attempts to achieve feasibility. The SSP implemented by Kovács (2015) uses the Dijkstra’s algorithm for computing the shortest paths with a heap data structure. They also included some improvements over the node labelling technique, representation of the residual network, and arc information storage, which enhanced the algorithm practical performance. The overall worst-case scenario for this code is $O(nmU \log n)$, where U denotes the maximum value between supply and arc capacities (KIRÁLY; KOVÁCS, 2012).

The CAS algorithm can be seen as an improved version of the SSP, since it ensures that each path augmentation carries a larger amount of flow in each iteration, which then reduces the total number of iterations needed to solve the MCF problem (KIRÁLY; KOVÁCS, 2012). Because of the similarities between CAS and SSP, the abovementioned SSP data structure and algorithmic improvements were also implemented for CAS by (KOVÁCS, 2015). With this, worst-case scenario is reduced to $O(m \log U)$ (KIRÁLY; KOVÁCS, 2012).

On the other hand, COS scales upon costs. It is a primal-dual approach that applies push-relabel techniques based on the concept of pseudo-flow approximate optimality. It can actually be viewed as a generalization of the push-relabel algorithm for the maximum flow problem proposed by Goldberg and Tarjan (1988). Although Kovács (2015) tested different push-relabel methods, the author chose to implement the partial-augment-relabel method, which improves the runtime of the COS algorithm. COS runs in weakly polynomial time, with worst-case scenario $O(n^2 m \log(nC))$, where C denotes the largest arc cost (KIRÁLY; KOVÁCS, 2012).

Finally, the NS algorithm is a specialized version of the popular Simplex method devised by Dantzig in the late 40's. It relies on the concept of spanning tree solutions, which allows for the implementation of the Simplex concept by performing operations directly on the network without the need of the tableau, improving the overall efficiency of the algorithm (KOVÁCS, 2015). According to Kovács (2015), it has been proved that if an instance of the MCF problem has a solution, then it also has an optimal spanning tree solution. Here there are also different options for implementing labeling techniques and pivot rules. Kovács (2015) adopted the Extended Threaded Index as labeling technique to improve representation and storage of spanning trees, and the block search pivot rule for initializing the spanning tree solution. Beyond improving algorithmic performance, these modifications also help to cope with solution degeneracy issues. Runtime for the NS is $O(nm^2CU)$; nonetheless, Király and Kovács (2012) note that it does not reflect the typical performance of the algorithm in practice.

In general, these four algorithms are capable of solving different problem instances. Yet, the necessary time for solution can vary considerably (KOVÁCS, 2015) and may not comply with worst-case scenario predictions. The choice of an MCF algorithm is usually done by considering the lowest computational runtime, which is key to the decision-making process (ZHAN; NOON, 1998). Although the NS and COS algorithms have showed the best overall results in terms of time and robustness (KOVÁCS, 2015), the MCF problem modeled for road networks did not seem to follow this pattern. In this case, the author observed that CAS was the best performing algorithm, followed by SSP and NS. Since none of these algorithms run in strong polynomial time, practical performance still plays an important role in defining the fastest method for solving a problem.

3 EXPERIMENTAL STUDY DESIGN

In this work, we evaluate the performance of four algorithms for solving the MCF problem on road networks: SSP, CAS, COS and NS. All the implementations for these algorithms are available with full source codes as part of the LEMON optimization library, an open source C++ library dedicated to solving graphs and networks combinatorial optimization problems, available at https://lemon.cs.elte.hu/ (KIRÁLY; KOVÁCS, 2012). Codes were compiled using Visual Studio 2015, and experiments were conducted on an Intel® Core™ i7-2620M CPU @ 2.70GHz machine, with 8GB RAM memory, using Windows 7 operating system. The reported runtimes are related to the CPU time needed to process each algorithm and do not include the processing of data input or solution output.

For experimentation and analysis, we chose the entire Brazilian road network, as of 2013, shown in Figure 1. Brazil has a GDP of USD 2.246 trillion and a population 200.4 million inhabitants. Spread throughout and area of 8.5 million km², the road network is predominant in the country, with an extension of 1.8 million km, versus 29.165 km of railways and 41.634 km of waterways. A total of 61.1% of all freight is distributed by a fleet of 2.7 million trucks. The roads spatial distribution is concentrated in the south and southeast portions of Brazil, where most of industrial activity and consumption markets are located. The northeast region, although also presenting a high demographic and roadway density, has a less developed infrastructure, while the north is mainly served by waterways.

While previous works in the literature usually confront networks of various sizes, our test instances vary over the same graph. This allows us to assess the performance of algorithms having one network as base. Due to this, we have not evaluated the impact of the *m* number of arcs on runtimes. Still, the lack of uniformity in spatial distribution of resources and population in Brazil, as well as disparities in welfare (HADDAD, 2009), add diversity to test instances. These characteristics are directly related to the availability of goods and transportation infrastructure. The Brazilian network presents different levels of road topologies: i) highways, e.g., national highways, interstate and state highways; ii) lower capacity or suburban roads, e.g., those connecting close-by cities, or cities and ports; and iii) rural roads. Urban networks are not taken into consideration.

Figure 1 - The Brazilian road network.

The graph that depicts the Brazilian road network comprises 20.123 nodes, which represent cities, ports, border points, transshipment facilities and road crossings. There are up to 5.637 possible supply or demand nodes, which correspond to the number of cities, ports and border points in the country. Arcs denote the road connections available, in a total of 49.131 segments. We consider that all arcs have very large capacity, higher than the total supplied volume. This is consistent with the idea that it is very difficult to have roads congested at all times; therefore, adding low capacity restrictions to the arcs does not correctly represents real-world scenarios. Each arc in the network has an associated length in kilometers, and a transportation cost for each product, defined by individual freight curves measured in monetary units per ton-km. In order to represent better the characteristics of the roads, arc costs were further adjusted with a correction index that took into account the infrastructure condition in terms of the average speed of each road.

To the best of our knowledge, complete real-world test instances are still scarce in the literature. Kovács (2015), for example, determines the number of supply and demand nodes using a formula dependent on the total number of nodes. Our nodes, on the other hand, represent real locations of origins/destinations. The amount of products available, the demand and the transportation costs are also primary data, collected from enterprises, government agencies and trade associations. All information related to the road network, supply, demand, costs and infrastructure condition comes from the Logistics and Transportation State Plan of Santa Catarina, as seen in Luna et al. (2013), developed by the Supply Networks Group at the Federal University of Santa Catarina, Brazil.

Each tests instance corresponds to a product distributed between cities on the Brazilian network, that is, we consider the domestic network. A total of 215 products, from 12 different product chains, were selected according to their economic relevance. These chains differ according to the primary aspects of supply chain network structures, proposed by Lambert and Cooper (2000), which are related to the level of supply chain members and the complexity of processes across the links of the chain. A third aspect is associated with designing the dimension of the network, which was described above. Some products were broken down into more than one test instance in order to obtain a better representation of supply/demand relationships; this is the case of automobiles, which comprise 21 test instances (divided by automaker). The number of products and supply volume per supply chain can be found in Table 1. A description of all products selected is available in Appendix A.

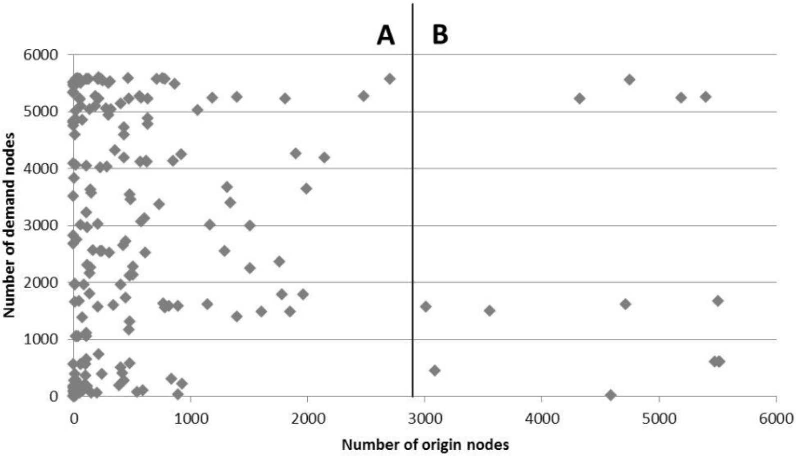
The diverse nature of products and production sites selected also lead to a great variety of origin-destination combinations as seen in Figure 2. The heterogenic distribution of test instances shown is a result of adopting real-world instances and explained by the number of supply-demand combinations for each product, which represent the peculiarities of each market. The products range from specialized goods that have monopolistic market structures, separated by short distances of less than 100 km in sparse sections of the graph, to consumer goods that need to be distributed throughout the entire country. To illustrate this behavior, Figure 2 is divided in two sections: A and B. Section B has few test instances because the products in this category are produced and consumed in many cities, e.g., eggs, beans, and bananas. Hence, there is not much room for variability of origins/destination combinations. On the other hand, Section A comprises test instances with fewer supply and/or demand nodes. In this case, many possibilities of test instances can be found by using different sections of the network.

Table 1 - Supply chains and amount of products considered as test instances.

SUPPLY CHAIN	N. OF PRODUCTS	SUPPLY VOLUME [MILLION TONS]
Animal byproducts	17	318,3
Forest agribusiness	17	190,3
Metal-mechanical	61	575,9
Nonmetallic minerals	30	962,2
Textiles	24	15,9
Petrochemical industry	13	91,9
Fertilizers	11	44,8
Leather	5	4,9
Fishery	4	1,9
Permanent agriculture	9	29,5
Temporary agriculture	21	91,7
Tobacco	3	1,2

Runtime and robustness were assessed with the use of formal statistical analysis, as suggested by Coffin and Saltzman (2000), available in the software Minitab®. Robustness was evaluated in terms of an algorithm's stability to solve problem instances, i.e. the more robust the algorithm, the less variation in solution time to solve different problem instances.

Figure 2 - Scatterplot of supply nodes versus demand nodes.



The four algorithms (i.e., treatments) were applied to 215 test instances. For each instance and treatment, 40 independent samples were taken. Boxplot graphs were adopted for the treatment of outliers. In order to identify the appropriate assessment tools, the first step of this study comprised a normality evaluation of test instances results. We applied the Anderson-Darling statistics to measure the fit of the 215 datasets for each algorithm with the normal distribution. For the majority of test instances, the null hypothesis for normality was rejected. In light of this, we performed individual distribution transformations in an attempt to fit the data with a variety of available distributions, including exponential, Weibull, and Gamma. Although we were able to fit a couple of test instances to those distributions, this was not consistent for all treatments – an important requisite for proper statistical analysis.

Meanwhile, the runtime data histograms showed that the majority of test instances had the same distribution shape for the four treatments in a continuous scale. Hence, it was possible to adopt the samples median as comparison indicator. In order to compare the efficiency of algorithms against each other, we employed the Mann-Whitney test for medians with a confidence interval of 95%. In the few cases where samples had different distribution shapes, a 2-Sample t test was adopted.

In addition to comparing the efficiency among algorithms, we evaluated the following network criteria regarding their impact on runtime: i) number of supply (SN) and demand nodes (DN); ii) number of demand nodes; iii) SN/DN ratio; and iv) supply volume. We assessed the correlation of each criterion with runtime for the four treatments by taking a sample of runtime medians. A two-variable cluster analysis was also carried out in an attempt to verify if the combination of supply and demand nodes showed any patterns regarding algorithmic performance. The Manhattan metric was adopted as distance measure of similarity and Ward's method as clustering algorithm. There was no need of standardization and samples were representative of the total population. The 215 test instances were classified in 29 clusters.

Finally, we assessed the robustness of the algorithms when solving different MCF problems on road networks. Again, the plot of runtime medians for each algorithm showed that runtimes were not normally distributed; a transformation to another distribution was not applicable and there was no consistency among runtime histograms. This non-parametric aspect led to the choice of Levene's test for variance analysis to evaluate robustness.

4 RESULTS AND DISCUSSION

In this study, the performance of four algorithms for solving the MCF problem were evaluated regarding: i) runtime efficiency; ii) influence of supply/demand nodes and supplied volume on runtime; and iii) algorithm robustness for solving different problem instances. Preliminary results revealed that COS was the least efficient algorithm and at least two times slower than all others for all test instances. Since the choice of an exact algorithm is usually tied to the fastest runtime, we have not included COS in further performance analysis, nor have addressed its robustness compared to other methods.

The results for the correlation analysis between the runtime of the three algorithms and the number of supply and demand nodes can be seen in Table 2. The Pearson coefficients show that the number of demand nodes may influence SSP and CAS runtimes, but not of NS. On the other hand, the number of supply nodes has similar impact on SSP and CAS, but it seems a little more influent on NS. It can be observed that the Pearson coefficients in both cases are somewhat similar for SSP and CAS, which may be explained by the fact that CAS is an improvement on SSP. Although worst-case scenarios may depend on the n number of nodes in the network, our results reveal that runtime is actually influenced by the function of each node in the network, especially for SSP and CAS, and practical performance will diverge from theoretical expectations.

Table 2 - Pearson coefficient for correlation analysis between problem variables and algorithm's runtime.

VARIABLE	**ALGORITHM**		
	SSP	**NS**	**CAS**
Supply nodes	0,385	0,48	0,38
Demand Nodes	0,635	-0,017	0,72
SN/DN	0	0,105	0,16
Supplied volume	0,268	0,156	0,03

On the other hand, the SN/DN ratio presented a very low correlation with runtime. Since different combinations of supply and demand nodes may result in the same ratio, the value of this variable actually represents distinct problem instances at the same time. This corroborates with the idea that performance is context dependent. The supplied volume also showed a low correlation index for the performance of SSP, NS, and CAS. Given that we considered very loose capacity constraints on arcs, it seems natural that there is not a relevant influence of the volume to be distributed on runtimes. Hence, the variable *U* present in worst-case scenarios for SSP, CAS and NS does not seem to play part on algorithmic performance.

Following our analysis, we compared the runtimes of NS versus CAS and SSP. The null hypothesis considered that runtime medians were the same for all algorithms, while the alternative hypotheses were H_1: $\eta_{SSP} > \eta_{NS}$, and H_2: $\eta_{CAS} > \eta_{NS}$, where η is the runtime median for a test instance. The null hypotheses were rejected for 198 test instances, which implies that NS usually outperforms SSP and CAS regarding runtime. This held true whenever $\eta_{SSP} > \eta_{NS}$ and $\eta_{CAS} > \eta_{NS}$, with p-value = 0. For 17 cases, we tested H_3: $\eta_{SSP} < \eta_{NS}$, and H_4: $\eta_{CAS} < \eta_{NS}$. Both hypotheses were accepted for 16 instances. We were not able to reject the null hypothesis just for one test instance, so all algorithms were considered equally efficient. Thus we can state that, in general, NS outperformed the other algorithms for solving the MCF problem on road networks. These results can also be observed in the surface graphs for the runtimes of each algorithm, depicted in Figures 3, 4 and 5.

Figure 3 - Runtime of SSP algorithm versus number of supply and demand nodes.

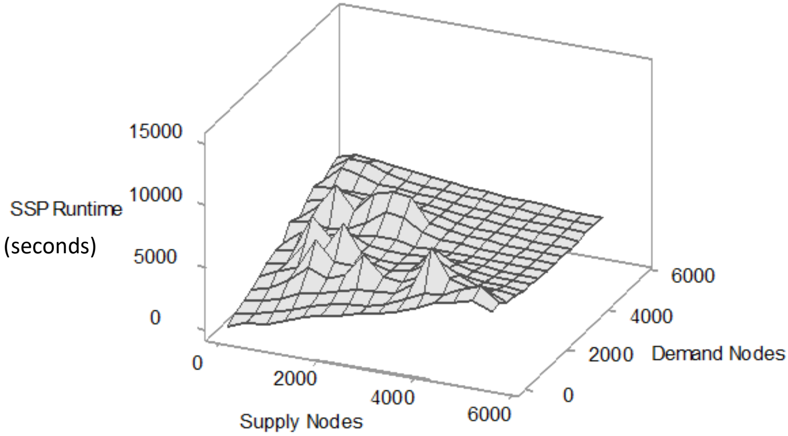


Figure 4 - Runtime of CAS algorithm versus number of supply and demand nodes.

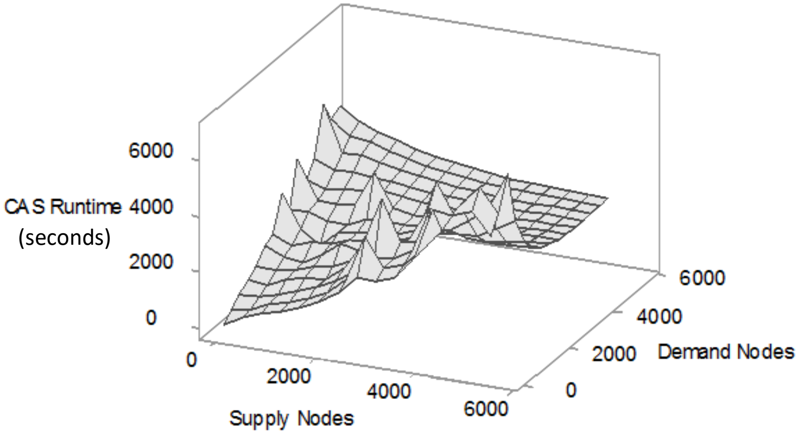
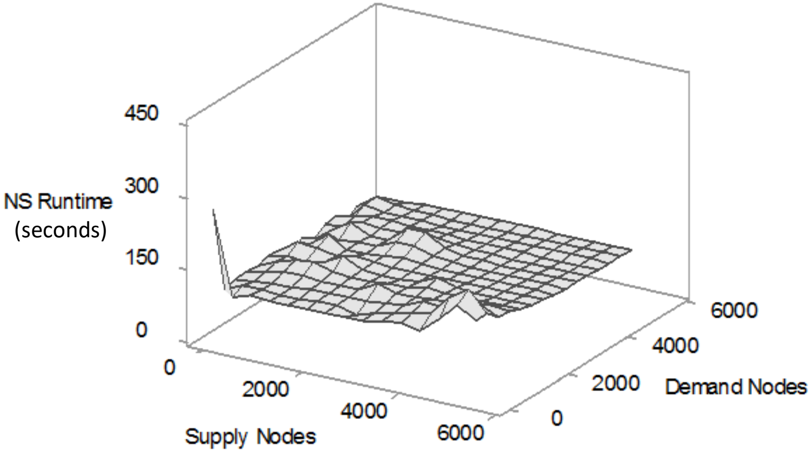


Figure 5 - Runtime of NS algorithm versus number of supply and demand nodes.



A second round of pairwise assessment compared SSP and CAS against each other. In this case, the null hypothesis also consisted of H_0: $\eta_{SSP} = \eta_{CAS}$ and the alternative hypothesis was H_1: $\eta_{SSP} > \eta_{CAS}$. In 154 out of 215 test instances, CAS outperformed SSP; i.e., the null hypothesis was rejected. This may be related with the observation made by Király and Kovács (2012) that CAS is an improvement on SSP. Yet, there were still many cases when SSP was more efficient than CAS, especially when the number of supply nodes was low (less than 40). For instances where there was up to 10 supply and demand nodes, we actually found that the null hypothesis could not be rejected, implying that the efficiency of both algorithms is similar. The performance behavior of CAS and SSP was also similar when test instances had very few or many supply and demand nodes, as observed in the shape of the surface curves depicted in Figures 3 and 4. For other combinations of supply and demand nodes, the algorithms actually present opposing behaviors.

The analysis of the correlation coefficients together with the surface graphs shows that, in general, as the amount of supply and demand nodes increased, so did the runtime of CAS and SSP. This is probably due to the need of more iterations to solve the MCF problem with these algorithms. Nonetheless, runtimes tends to stabilize for a high amount of supply and demand nodes. Since these algorithms are based on the concept of shortest path, this may be explained by the fact that the possibility of fulfilling demand increases with the availability of supply and demand nodes for flow distribution. In such cases, it becomes clear that runtime is influenced by the number of supply/demand nodes and by the supplied volume, besides network topology. Still, NS was altogether the least influenced algorithm by the variables in Table 2, indicating that it is more robust to these aspects.

Although the number of supply and demand nodes influenced the runtimes for CAS and SSP, there was no clear pattern regarding clustering of test instances, except for cases when there were less than 100 supply and demand nodes in total. These are actually the test instances for which SSP and CAS outperformed NS. Other results do not seem to have connections with clustering.

Variance analysis for robustness also showed that NS is the most robust algorithm when solving a great variety of test instances. The null hypothesis of equal variance for the algorithms was reject with p-value = 0 when comparing NS versus SSP and CAS, which corroborates with the shape of the surface graphs in Figures 3, 4, and 5. The NS algorithm was more efficient than the other methods most likely because ‘it is based on maintaining a spanning tree data structure and the tree update process depends only on the number of nodes’ in the graph (KIRÁLY; KOVÁCS, 2012). On the other hand, the confrontation of CAS and SSP showed that, although both algorithms have a resembling runtime behavior, CAS is more robust that SSP. This complies with that fact that CAS is an improvement over SSP, as implemented by Kovács (2015).

5 CONCLUSION

The aim of this paper was to assess the practical performance of four different algorithms for solving the MCF problem in road networks, namely COS, CAS, SSP and NS. To the best of our knowledge, this is so far the most comprehensive study with full real-world test instances. A total of 215 instances of MCF problems were tested using the Brazilian road network and flow of goods as basis, comprising data on supply, demand, and transportation costs. We benefit from using this network by adding diversity to test scenarios, which grants robustness to our results.

Using Brazil as a case study also brings insights to developing economies on how to identify the distribution of goods throughout road networks. Information of this nature should guide the definition of investments, either public or private, allowing them to be aligned with economic, social and/or political goals, especially due to the lack of resources in such countries. Results from investment evaluations help to identify if future projects would allow the reduction of logistics costs for businesses that operate in a certain region, boosting economic development. Having the proper techniques to find flow information also reduces the cost of processing analyses and gives support to decision making while addressing the challenges of developing economies.

With this in mind, we evaluated the impact of the number of supply and demand nodes, the ratio of supply/demand nodes, and the supply volume on algorithmic performance. Robustness for solving a variety of problem instances was also analysed. Differently from what was previously found in the literature, NS turned out to be overall the best performing algorithm for road networks. Although CAS and SSP were actually faster for some test instances, NS proved to be the most robust method for solving the MCF problem on this type of networks. Yet, if it is necessary to compute flows for one-to-one or one-to-few nodes scenarios, then CAS could be a better choice. Worst performance was encountered for COS, followed by SSP. The number of supply and demand nodes showed influence over the runtime of CAS and SSP, but not of NS. On the other hand, the supply/demand ratio and supply volume were not good performance predictors; yet, this may be related to loose arc capacity constraints.

We observed that the performance of a solution tool may also be tied to its algorithmic structure. CAS and SSP are based on Dijkstra’s shortest path algorithm and have somewhat similar solution behavior, even though the medians of runtimes differed considerably. On the other hand, given that NS uses a spanning tree structure that relies on the number of nodes in the graph, its performance is much more robust when considering different test instances.

Our results substantiate that network topology and problems features influence the efficiency of MCF tools. The fact that these features are not explicit in worst-case scenario evaluations may explain why theoretical performance differs from practice. In addition, we believe that the differences from other studies found in the literature regarding practical performance could be related to using some kind of computer-generated data, which hinders the accuracy of defining and locating supply/demand nodes, and network topology. Our work calls attention to the importance of using full real-world instances and indicates that this is an issue that reflects on the results and conclusions devised.

Hence, modelling and solving MCF problems in the context of transportation networks should take into account different real-life aspects, such as network topology and spatial syntax, product origin and destination, and transportation costs. The choice of a solution algorithm is part of the planning process, which will influence the amount of time needed to make decisions and the possibilities of scenario evaluation. Although we have considered only road networks, other modes of transportation could be represented in the same way if we translate characteristics such as capacity, speed, cost and quality conditions into arc weights. Future work, thus, could apply the MCF model also for evaluating intermodal infrastructures.

APPENDIX A – Description of products per supply chain.

SUPPLY CHAIN	PRODUCTS
Animal products	Animal food, Chilled dairy products, Non-chilled dairy products, Cattle, Corn grains, Eggs, Fluid milk, Livestock products, Pigs, Poultry, Poultry products, Raw milk, Soy beans, Soy chaff, Soy oil, Swine Products, Turkey products.
Forest Agribusiness	Cellulose pulp, Charcoal, Cooperage artifacts, Firewood, Hygiene and household products, Laminates, Lumber, Other paper and cardboard products, Packaging paper and cardboard, Paper, Cardboard, Products for commercial and office use, Wood logs from natural forests, Wood logs from silviculture, Wood artifacts, Wood furniture, Wood structures.
Metal-Mechanical	Alumina, Aluminum, Ash, Batteries and accumulators for motor vehicles, Bauxite, Cabins and automotive accessories, Calcined nickel, Calcined nickel ore, Cars, trucks, vans, buses and utility vehicles, Chrome ore, Copper concentrate, Copper drawn wire, Copper products (laminates, bars, wires, pipes and fittings), Electrical conductors, Electrolytic nickel, Electrolytic zinc, Electronic and optical devices, Equipment for control and distribution of electricity, Equipment for thermal installations, Cast iron, Galvanized products, Household appliances and air conditioners, Iron garters, Iron ore, Iron-nickel alloys, Lead, Machines and equipment, Manganese ore, Matte nickel, Metal frames, Metal packaging, Mineral coal, Nickel carbonate, Nickel concentrate, Pellets of iron, Pig iron, Pipes, fittings and hardware, Refined copper, Re-rolled and drawn steel profiles, Steel drawn, Steel products, Tubes and pipes with seam, Wires, cables and insulated conductors, Zinc concentrate.
Nonmetallic Minerals	Agricultural limestone, Coatings and porcelain tiles, Clay, Concrete mass and artifacts, Dolomite, Domestic and special glass products, Feldspar, Fire clay, Flat glass, Glass containers, Gravel, Gypsum, Industrial sand, Kali, Kaolin, Lime, Limestone, Magnesite, Phosphogypsum, Phyllite, Plastic clay, Portland cement, Quartz, Red clay ceramics (blocks, bricks and tiles), Refractory products, Sand, Sanitaryware, Tableware and China, Talcum powder.
Textiles	Artificial and synthetic fiber, Artificial and synthetic yarn, Cotton, Cottonseed, Cotton yarn, Fabric, Finished garments, Finished socks and accessories, Finished household products, Linen, Linter, Other natural textile yarn, Other finished textile products, Other unprocessed textile products, Processed fabric for garments, Processed fabric for household products, Processed fabric for other textile products, Processed fabric for socks and accessories, Silk, Unprocessed fabric for garments, Unprocessed fabric for household products, Unprocessed fabric for other textile products, Unprocessed fabric for socks and accessories, Wool.
Petrochemical Industry	Artificial and synthetic fiber, Fuel, Other processed plastic products, Plastic packaging, PET, Plastic artifacts, Polyethylene, Polypropylene, Polystyrene, PVC, Rolled and tubular laminates, Synthetic shoes, Tubes and plastic fittings for the construction industry.
Fertilizers	Ammonium nitrate, Ammonium sulfate, Anhydrous ammonia, Fertilizers, Monoammonium and diammonium phosphate, Nitric acid, Single and triple phosphate, Phosphoric acid, Potassium chloride, Sulfuric acid, Urea.
Leather	Leather clothing, Leather footwear, Rawhide, Leather suitcases and bags, Tanned leather.
Fishery	Fresh fish from aquaculture, Fresh fish from fishery, Imported fish, Industrialized fish products.
Permanent agriculture	Apple, Banana, Fruit Juices, Grapes, Orange, Yerba mate, Peach compote, Peach, Wine.
Temporary agriculture	Bakery products, Canned onions and potatoes, Cassava flour, Cassava starch, Cookies and crackers, Fresh beans, Fresh or chilled cassava roots, Fresh or chilled garlic, Fresh or chilled table tomatoes, Fresh or chilled industrial tomatoes, Fresh or chilled onions, Fresh or chilled potatoes, Fresh watermelons, Milled rice, Paddy rice, Pasta, Sauces and Catchups, Tomato purée and pulp, Wheat, Wheat bran, Wheat flour.
Tobacco	Cigarettes, Dry tobacco leaves, Stripped tobacco.

A MODEL TO EVALUATE THE HUBBING EFFECT ON TRANSPORTATION NETWORKS

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Sérgio Fernando Mayerle

Abstract

The spatial organization of logistics hubs affects the success of transportation networks design and supply chain management, influencing the distribution system as a whole. This impact is known as the hubbing effect, which reflects the dual relationship between infrastructure use and flow allocation. Yet, models available in the literature seem inappropriate to evaluate the hubbing effect on real transportation networks: they have limitations related to topology design, representation of supply-demand relationships, and implementation of economies of scale. In light of this, a new flow model is proposed, with a graph adaptable to different supply chains and freight networks – containing one or more hubs. While our proposal supports flow allocation, it also allows the evaluation of changes in infrastructure use and transportation costs due to the addition of one or more hubs. The proposed model was tested using real data from the Brazilian poultry industry and the road network of the state of Santa Catarina. Results ratify the importance of representing complete networks and applying economies of scale throughout the entire network. They further uncovered trade-offs between economies of scale and flow allocation, hub geographic coverage, demand fulfillment, and infrastructure availability.

Keywords: hub; hubbing effect; network flow; transportation infrastructure

1 INTRODUCTION

Moving goods efficiently depends on the design of transportation networks (GUASTAROBA; SPERANZA; VIGO, 2016); likewise, the transportation network should be designed considering the flow of goods. This dual relationship between infrastructure use and goods distribution reflects the nature of trade in supply chains (DABLANC;

ROSS, 2012; OKTAL; OZGER, 2013). In this context, logistics hubs have gained importance as network terminals where value-added operations are performed, flows are consolidated, and services and information are provided in order to increase service level and reduce logistics costs (GUASTAROBA; SPERANZA; VIGO, 2016). Hubs allow the development of flexible solutions for supply chain management, improving connections, cooperation between players, and flow regulation (DING, 2013; OKTAL; OZGER, 2013). Beyond that, they have become an important component of territorial organization and economic development, being strategically important for both businesses and the public sector (RODRIGUE; COMTOIS; SLACK, 2017; STEADIESEIFI et al., 2014; TANER; KARA, 2016; YAMADA et al., 2009).

The spatial organization of logistics hubs affects the success not only of operational logistics itself (TU et al., 2010), but also of supply chain management, influencing the distribution system as a whole (DABLANC; ROSS, 2012; MELO; NICKEL; SALDANHA-DA-GAMA, 2009; ŠKRINJAR; ROGIĆ; STANKOVIĆ, 2012). The possibilities of flow consolidation allow exploiting economies of scale and reduction of transportation costs between origins and destinations according to how the hubs are connected to the network (ALMEIDA; AMARAL; MORABITO, 2016; PEKER et al., 2016). This becomes also important in network planning, since “network design costs greatly dominate routing costs” (SÁ et al., 2009), promoting synchronization and ensuring a balanced transportation system (GAO; DONG, 2012; LIUM; CRAINIC; WALLACE, 2009).

The impact that hubs have on flow allocation has been coined as “hubbing effect” (FARAHANI et al., 2013). It has been mainly addressed in airline networks, where researchers concentrate on the effect of hubs on prices and flight traffic, such as Tan and Samuel (2016) and Mayer and Sinai (2003). The effects and externalities of airport hubs refer to the use of large terminals to handle the great majority of traffic, especially at the international level (RODRIGUE; COMTOIS; SLACK, 2017). Yet, in the context of freight transportation networks, the effects caused by the spatial interaction between supply and demand on flow intensities have not received explicit attention in the literature since the work of O’Kelly in 1986 (TANER; KARA, 2016). Farahani et al. (2013) also identified an investigation gap on the factors affecting flow allocation between hubs and other network nodes.

In order to identify and evaluate the hubbing effect, hubs should be properly located and connected to their transportation network. This process tends to be more complex than for industrial facilities or distribution centers since hubs are not intended to serve exclusively one product or supply chain, but a complex supply web. Hence, the design of networks which contain hubs should be associated with the transformation processes along the tiers of supply chains, taking into account supply-demand relationships, flow of goods, transportation connections available and logistics services offered (CAMPBELL; O'KELLY, 2012; LUNA et al., 2011; RODRIGUE; COMTOIS; SLACK, 2017). These aspects may be represented by the accurate location of supply volumes according to filière analysis of supply chains, representation of network topology, definition of transportation costs based on the type of product and infrastructure condition, location of hubs, serviced area and application of scale factors that depict the economies obtained with the use of such facilities.

However, traditional hub location models available in the literature seem inappropriate to deal with the addition of hubs to transportation networks and evaluation of their impact on network flows (VIEIRA; LUNA, 2016). They have limitations related to the definition of network topology, supply-demand relationships and economies of scale, preventing their applicability to real transportation networks. To work around these issues, Vieira and Luna (2016) suggested two-stage analytical approach to model hub networks and obtain flow information. The first phase should comprise the definition of one or more hub locations with a multi-criteria model that covers political, legal, environmental, and/or market aspects, inherent to this type of decision. Subsequently, a network flow model based on economic and business criteria should be adopted to allocate flow according to the hub(s) location.

This paper centers on developing a network flow model for the second phase of Vieira and Luna's proposed approach. First, a new graph model that represents real transportation networks comprising one or more hubs is presented, overcoming limitations found in literature. Considering the characteristics of the network, we identify the network flow problem that best describes the supply-demand relationships and define an algorithm for flow allocation. While this methodology supports flow allocation, it also allows the evaluation of changes in infrastructure use and transportation costs due to the addition of hub facilities, and renovation or construction of roads and railways. Flow information may also be useful for public authorities when making strategic and policy decision, as well as to real estate investors (TANER; KARA, 2016). The easiness to generate scenarios turns this model into a prescriptive tool for decision makers in the assessment of a variety of solutions they can choose from.

This paper continues in Section 2, with a review of the role of hubs when functioning as part of transportation networks. We identify modeling approaches to evaluate the hubbing effect and their limitations. Section 3 presents the proposed model for flow allocation, with special focus on the graph design. A practical application is described in Section 4, using real data from the poultry industry of the state of Santa Catarina, in south Brazil, including a variety of analysis that can be performed resulting from the proposed design. Finally, Section 6 concludes the paper with a summary of the major findings and future research directions.

2 HUBS IN TRANSPORTATION NETWORKS

Logistics terminals have their function in transportation networks distinguished according to the type of products that flow through each facility, terminal location, market served, and available infrastructure (CATAPAN, 2016). Under this perspective, hubs are facilities where there is a concentration of flows and polarization of logistics operations related to freight consolidation (CAMBRA-FIERRO; RUIZ-BENITEZ, 2009; ŠULGAN, 2006). They add value as elements of articulation and coordination (RODRIGUE; NOTTEBOOM, 2009) and may be strategically located for the convergence of transportation routes, functioning as access points to a variety of service areas and networks of different dimensions (DABLANC; ROSS, 2012; FERNANDES; RODRIGUES, 2009; MEIDUTĖ, 2005; RODRIGUE, 2004). Hubs, thereby, allow the establishment of efficient relations between supply chain players through better connectivity, flow integration and reduced logistics costs due to economies of scale gained by using such terminals (CAMBRA-FIERRO; RUIZ-BENITEZ, 2009; JURÁSKOVÁ; MACUROVÁ, 2013).

Besides such functional aspects, hubs may also serve as elements of economic development. The increase in flow intensity at the hub area tends to leverage local development due to the establishment of more convenient and economic connections, a result of services offered and availability of more frequent and less costly transportation connections (TANER; KARA, 2016). In many cases, besides logistics service providers themselves, industrial plants relocate to the surrounding hub area, or even become integrated to the own hub structure (SHEFFI, 2012). This reorganization of local business aids in the development of peripheral regions through the creation of jobs, promotion of new consumer markets (KABASHKIN, 2007) and increase in the volume of commercial transactions (DADVAR; GANJI; TANZIFI, 2011). Small business may take advantage of the hub structure and obtain expertise in logistics services, freight organization, and supply chain management (JARŽEMSKIS, 2007; SHEFFI, 2012).

The benefits obtained with the addition of hubs to transportation networks can be measured through the evaluation of the hubbing effect. The hubbing effect concerns the influence that this type of facility exerts in the distribution of goods, supply-demand relationships, and infrastructure use, resulting from flow allocation. It may even be useful for strategic decision on the hub location itself, providing prior insights on spatial distribution (PEKER et al., 2016; TANER; KARA, 2016). Since the 80's many researchers have investigated ways of modeling the effects of hub facilities on transportation costs; yet, such effects on flow intensities have not been explicitly addressed since the work of O'Kelly in 1986, especially in the context of transportation networks (FARAHANI et al., 2013; KARA; TANER, 2011; TANER; KARA, 2016). Without understanding flow allocation, it becomes consequently hard to evaluate the economies of scale which can be obtained with logistics hubs (FARAHANI et al., 2013).

The difficulty in evaluating the hubbing effect on transportation networks may be related to the fact that hub location models available in literature, which are closely related to the flow allocation problem, present limitations regarding network topology, establishment of supply-demand relationships and application of economies of scale (VIEIRA; LUNA, 2016). Other researches that analyze the hubbing effect and deal with air transportation or mail delivery also adopt topology restrictions and distribution rules that are not common to freight transportation (GUASTAROBA; SPERANZA; VIGO, 2016; VIEIRA; LUNA, 2016). Although some papers, like the one of Gelareh and Nickel (2011), relax some hub assumptions to obtain more realistic and practical models applied to urban transportation and maritime liner shipping, their network model is still characterized by the same topology adopted by the airline or postal industries.

According to Guastaroba, Speranza and Vigo (2016), two types of network topology arise in the literature concerning intermediate logistics facilities: pure and hybrid networks. Both network topologies may include one or more terminals. Pure networks, depicted in Figure 1.a, are modeled with straight connections between origins and hubs, hubs and destination, and between hubs. There are no transshipment points other than the hubs and all shipments are transferred through an intermediate facility, i.e. direct shipment is not possible. Models for the hub location problem usually imply the use of pure networks, as defined by Campbell and O'kelly (2012).

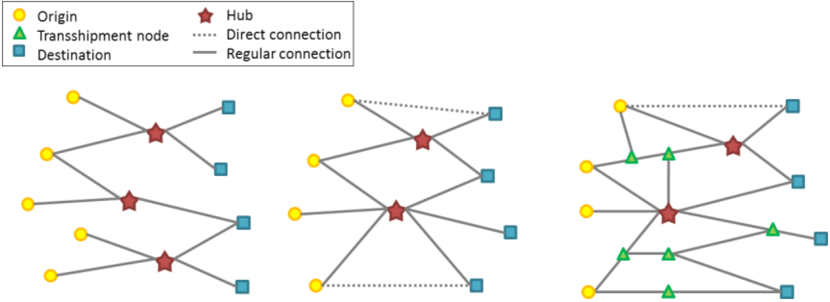
Hybrid networks, on the other hand, allow direct shipments, i.e. freight can be routed either through the hub or directly from origin to destination. Hybrid networks can be further subdivided into two topologies: single-edge and multi-edge. Single-edge hybrid networks comprise only straight connections, as shown in Figure 1.b. This means that there are no transshipment nodes in between origins and destinations, origins and hubs, hubs and destination, and between hubs. Although not common in hub location, this type of network is found in Ambrosino and Sciomachen (2012). In contrast, multi-edge hybrid networks include a variety of transshipment points, which can be interconnected (Figure 1.c). Researchers that consider intermediate facilities in transshipment problems, as identified by Guastaroba, Speranza and Vigo (2016), may take into account hybrid networks, but only single-edge topologies. However, real transportation networks take the shape of multi-edge hybrid topologies, as depicted by Luna et al. (2013) and Vieira and Luna (2017). Other aspects inherent of real networks are: links between origins, links between destinations, and origin and destination nodes in between network links; yet, these are not represented in Figure 1.c.

The evaluation of recent work on flow allocation using hubs, e.g. Guastaroba, Speranza and Vigo (2016), Taner and Kara (2016), reveals that this flexible structure of real transportation networks is still not being properly represented. While the available models abstract key features of such networks, they consequently ignore important aspects of the underlying freight distribution system, as also noted by Peker et al. (2016), Campbell (2013) and Campbell and O'kelly (2012). Some papers, such as the one of Almeida, Amaral, and Morabito (2016), develop hub location studies with multi-edge hybrid networks, but economies of scale are taken into account only for links with flows that are exclusive of hubs, functioning as a pure network. Additionally, Guastaroba, Speranza and Vigo (2016) verified that the possibility of hauling shipments between two or more hubs has been neglected, which is a common feature of networks comprising transportation corridors.

This may be related to the fact that few papers dealing with transport infrastructure planning take into account hub facilities, as observed by Dablanc and Ross (2012) and Ding (2013).

Figure 1 - Illustrative examples of networks with intermediate facilities.

Adapted from Guastaroba, Speranza and Vigo (2016).



(a) Pure Network (b) Single-edge hybrid network (c) Multi-edge hybrid network

The configuration of hub networks is strongly driven by the economies of scale obtained (KIMMS, 2006). Hence, the approach adopted to represent such economies in network edges plays a significant role in the definition of flow intensities because it directly affects the corresponding edge weight (TANER; KARA, 2016). Traditionally, researches have modeled the advantage of using a hub as a discount factor applied to transportation costs (PEKER et al., 2016). The most common approach among researchers is to adopt a predefined constant discount rate α, as introduced by O'kelly (1986), which is taken from the literature (OKTAL; OZGER, 2013), defined based on interviews (ALUMUR; KARA; KARASAN, 2012) or varied to generate different evaluation scenarios (CAMPBELL; O'KELLY, 2012). The value of α is dependent on the transportation mode used and technologies deployed (CAMPBELL; O'KELLY, 2012), typically ranging from 0.2 for high-speed railways (BLANCO; PUERTO; RAMOS, 2011) to 1 for roads (CUNHA; SILVA, 2007). For example, a range of scale factors from 0.4 to 1 is adopted by Cunha and Silva (2007) while designing a hub network for freight transportation in Brazil. Although not usually found in the literature, the scale factor could also be represented by a negative value, as seen in the approach of Ahuja, Magnanti and Orlin (1993) for negative costs.

Scale factors may also be represented by a function of flow volume or travelled distance (CAMPBELL; O'KELLY, 2012). O'kelly and Bryan (1998), Klincewicz 2002) and Racunica and Wynter (2005) adopt a piecewise linear approximation for a non-linear concave cost function to represent economies of scale, which is flow dependent. Likewise, Wagner (2008) proposes a discount factor which is determined by a non-increasing function of flow volumes. Kimms (2006), on the other hand, derives an alternative discount function to also take into account other sources of economies of scale such as quantity discounts when a third party is employed, fixed costs, and multiple modes.

Besides defining the value of the discount factor, either by a constant or a function, one should determine how it will be applied on the network edges. Economies of scale can be implemented in two ways: i) as a discount in an interhub arc, when the hub is represented by two nodes and a connecting edge; ii) as a discount on other networks edges, which connect origins to hubs and hubs to destinations. Most of studies known from the literature model economies of scale by incorporating the discount factor on the cost of interhub arc (FARAHANI et al., 2013; PEKER et al., 2016; ŠKRINJAR; ROGIĆ; STANKOVIĆ, 2012; TANER; KARA, 2016). Yet, the discount factor should be preferably used in any pair of nodes (WAGNER, 2008). While Racunica and Wynter (2005) apply the discount to the interhub arc and to all hub-to-destination links, Kimms (2006) expands their approach and considers economies of scale on all hub and non-hub links. Although Kimms' approach is a better representation of flow allocation criteria, it is difficult to determine optimal solutions for such more appropriate problems (WAGNER, 2008), especially those that consider multi-edge hybrid networks, due to the difficulty to distinguish the amount of flow that uses the hub from that of non-hub connections.

3 METHODOLOGY

The main goal of this paper is to present a model for the analysis of the hubbing effect, which closely represents real transportation networks that comprise one or more hubs, destined for freight transportation. Although this is a theoretical development, a practical study over a real road network adds to the quality of the model, showing its applicability and possible analysis outcomes. The methodological approach adopted consists of three steps: i) definition a graph model for the network; ii) choice of network flow problem that describes supply-demand relationships in goods distribution and solution algorithm; and, iii) practical application.

The first issue that needs to be overcome in representing real transportation networks with hubs is related to network topology. For this, we adopted a multi-edge hybrid network topology including all links that are part of transportation networks. Since the scope of our analysis comprises full supply chains with a variety of intermediate production facilities and consumer markets, it seems natural that these links are available for goods distribution. This means that there is full flexibility in the choice of transportation service model; the decision on whether a product will flow through the hub or through straight origin-destination connections (without the hub) will be made within flow allocation according to the lowest transportation costs, not by a topology tied to a previous design decision.

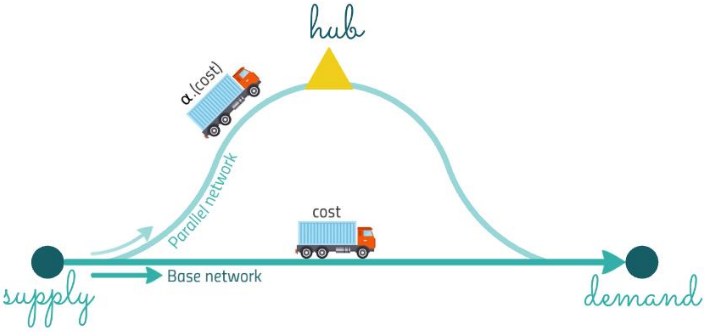
Transportation costs for flows that go through the hub should be discounted to represent economies of scale. One of the approaches found in the literature to address this matter lies in representing the hub as two nodes with an interhub arc where costs are discounted. Yet, this does not take into account the full advantages of freight consolidation, a main feature of hubs, especially for longer routes. Hence, the best way to represent the economies of scale would be to apply α to all arcs of the network, as suggested by Wagner (2008). However, an important modeling issue arises: how to differentiate, in each arc, the volume of products that will use the hub from the one that does not, in order to correctly discount the cost of the hub flow? This becomes even more complex if more than one hub is connected to the network because supply/demand nodes may be assigned to different hubs, with different discount factors, which serve different market areas.

To address the abovementioned issues, and having in mind that the results of flow allocation should allow evaluating the hubbing effect, we adopt a two-level network topology, as shown in Figure 2. In this structure, the bottom level represents a regular network, where products flow without using a hub. The upper level represents the hub network, through which cargo can flow with lower transportation costs. Freight vehicles can use one network or the other, depending on the costs incurred to deliver goods from origin to destinations using the hub.

To build this structure we start by designing a regular transportation network (B-network), which will function as reference network to the addition of one or more hubs. Using the B-network as foundation, we design the upper network, containing one or more hubs

(H-network). The fundamental idea behind the H-network is to have one graph comprising of two subgraphs: i) a B-subgraph, equal to the B-network, where supply and demand volumes are allocated, including regular transportation costs, and ii) a parallel network (P-subgraph), connected to the B-subgraph, that offers economies of scale characterized by lower transportation costs and higher service level, translated by the application of a discount factor and hub service costs. During flow allocation in the H-network, products may leave supply nodes at the B-subgraph and use the P-subgraph when appropriate, going back to the B-subgraph to fulfill the demand. The details of building both the B-network and the H-network are presented below, followed by the network flow problem and solution algorithm.

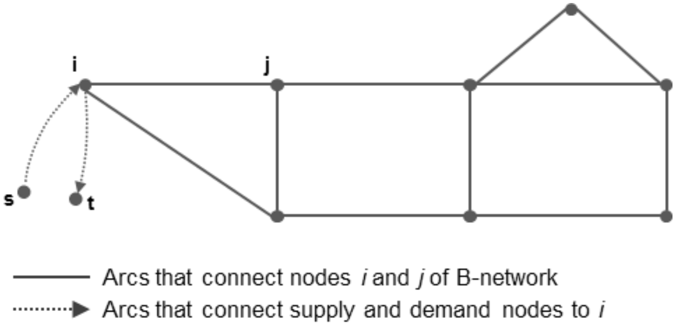
Figure 2 - Two-level network topology



3.1 BASE NETWORK

The graph that represents the B-network is composed of four types of nodes and two types of arcs, as seen in Figure 3. Node *i* represent cities, where production facilities, ports and consumer markets can be found. The supply and demand volumes are allocated to nodes *s* and *t*, respectively, which are directly connected to *i*. Nodes *s* and *t* are directly connected to *i*, and arcs *si* and *it* are used to aid in modeling the transportation costs. Transportation costs are composed of a fixed portion, which accounts for expedition costs per volume, and a variable portion, which accounts for freight cost per volume and distance. Arcs *si* and *it* connect supply and demand nodes to the rest of the network and have the fixed portion of cost allocated, denoted either by c_{si} or c_{it}. The variable portion of costs is denoted by c_{ij}. Node *j* represents road connections between cities, such as highway crossings. All possible freight paths and connections between origin and destination nodes, including direct links, are depicted by undirected arcs connecting nodes *i* and *j*.

Figure 3 - Base Network.



3.2 HUB NETWORK

The step-by-step of the H-network design can be followed in Figure 4 from a to f. The H-network graph is composed of two subgraphs: one identical to the B-network, which we refer to as the B-subgraph, and the P-subgraph, used for the flows that use the hub. Taking the B-subgraph as basis, we begin building the P-subgraph by identifying the location of the hub in the B-subgraph, node *h* (Figure 4.a). Next, we create nodes *k* and *m*, which represent the hub H_1 in the P-subgraph (Figure 4.b). Node *k* denotes the way in the hub and node *m* the way out. These two nodes are connected with a directed interhub arc *km*, with has an associated cost c_{km} that represents the costs of using the infrastructure and services offered at the hub. This cost is dependent on the type of logistics activities performed at the hub and on the products that go through the facility. Nodes *k* and *m* are then connected with direct arcs to node *h* in the B-subgraph (Figure 4.c).

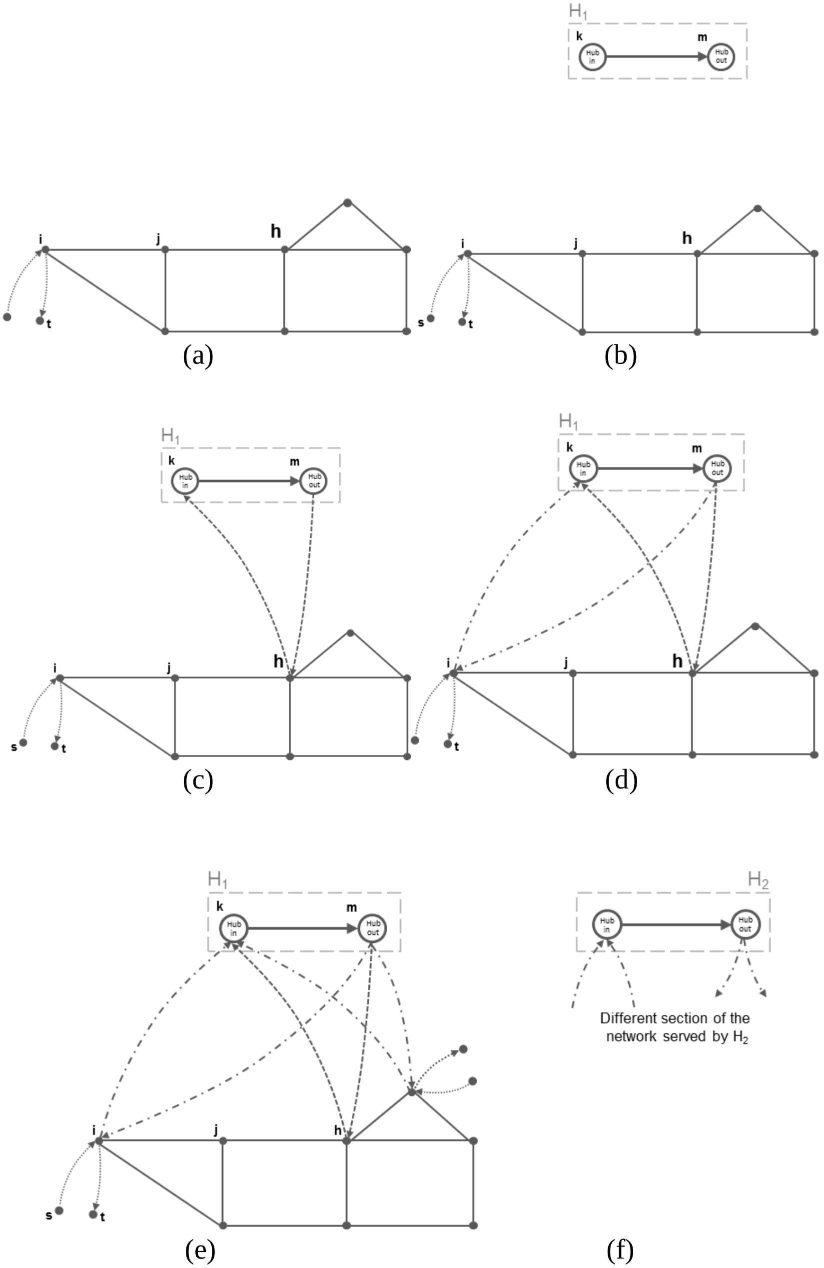
The next step lies in connecting every node *i* in the B-subgraph to nodes *k* and *m*. For each node *i*, we find the shortest path from *i* to *h* using Dijkstra’s algorithm. Then, we build a new path, called a mirror-path, which is a copy of the shortest *ih* path, and includes all nodes and arcs. This mirror-path is used to connect *i* and *k* with directed arcs from *i* to *k* (Figure 4.d). We duplicate the mirror-path path, reverse the arcs directions and use it to connect *m* to *i* (Figure 4.d). These paths are called mirror-paths because they hold the same structural attributes of the shortest path in the B-subgraph, such as geographic location, arc length, and arc speed. Nonetheless, it is important to notice that nodes do not have supply/demand volumes associated to them and there are no links between nodes of different mirror-paths in the P-subgraph.

Such straight connections guarantee that once the decision to use the hub is made, the product goes through the hub and keeps travelling on the P-subgraph throughout the shortest path to the demand node. Hence, the use of the P-subgraph complies with the notion that flow allocation will be made through the shortest paths available. It also prevents that a product uses only part of the P-subgraph without actually going through the hub. Using the complete H-network, i.e. with all i nodes linked to the hub, as shown in Figure 4.e, one can observe that it is possible to connect all supply and demand nodes either through the B-subgraph, the P-subgraph, or a combination of both.

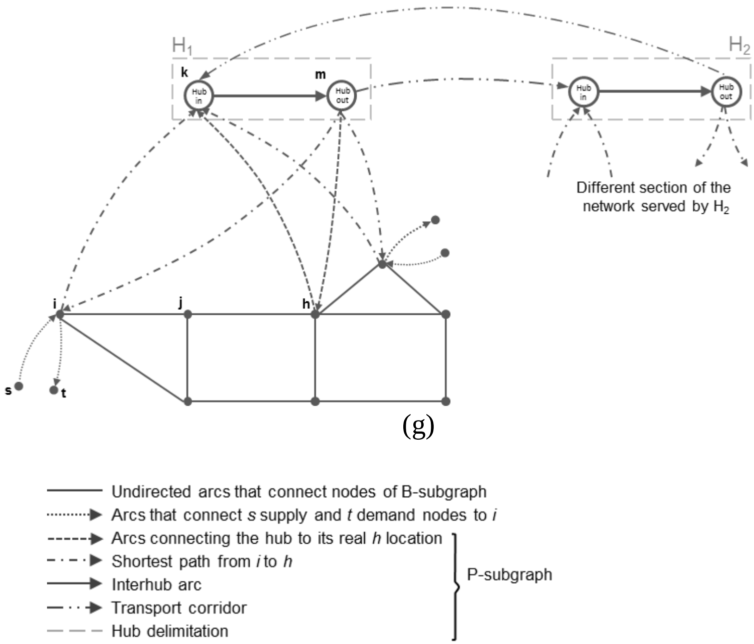
The supply and demand volumes are allocated to nodes s and t, and each arc has a respective cost. The transportation costs for the P-subgraph arcs are discounted by a factor α that represents the economies of scale obtained when using each corresponding hub. Because the P-subgraph arcs mirror the base network, this actually means considering the scale economies in all arcs of a given network. With this approach, we can use the representation of multi-edge hybrid networks to evaluate the hubbing effect on all sections of the network, between hub and non-hub nodes, as suggested by Farahani et al. (2013).

The assignment of a node to a hub is not only affected by the economies of scale obtained at the facility, but also by the ability of that facility to serve a market area and to interact with other hubs in the network. In this sense, the P-subgraph arcs connect hub H_1 to the B-subgraph, as shown in Figure 4.e, delimiting an influence area for this specific facility. Other hubs may also be installed using the same procedures, connected to specific nodes that represent distinct market areas (H_2 in Figure 4.f). In a network with more than one hub, facilities may be connected by transport corridors (Figure 4.g). Corridors are built using the same procedure to connect nodes *i* to *k* and *m*, i.e. by finding the shortest path between the hub nodes and building mirror-corridors. Transportation corridors – and actually all other H-network arcs – may actually portray a variety of transportation modes, such as roads or railways. Transshipment terminals between modes of transportation can be modeled directly into the graph with the use of an additional node and an arc that contains the cost of transferring freight from one mode to another.

Figure 4 - Procedure to build the H-network.



(a) (b) (c) (d) (e) (f)



3.3 FLOW ALLOCATION

The choice of flow problem and solution algorithm for products distribution in hub networks depends on topology, type of problem and its restrictions. The detailed configuration of the B- and H-networks allows us to adopt a discrete analysis for flow allocation. In this case, the minimum-cost flow problem is the one that best represents the supply-demand relationships and is applicable to the topology of both networks. It also has a special structure that, together with the proposed graph design, leads to the use of specialized and efficient flow allocation tools for finding the lowest transportation cost of the network (AHUJA; MAGNANTI; ORLIN, 1993; KIRÁLY; KOVÁCS, 2012).

To avoid using seasonal data for goods volumes and costs, a one-year analysis interval was defined. As consequence, no capacity restrictions were considered on arcs. This is consistent with the fact that roads are not congested at all times, especially when considering long-term investments. Because arc capacities are loose, the addition of flows from different products is achieved by the summation of single-commodity problem instances, solved individually for each product. Hence, the uncapacitated single-commodity minimum-cost flow (MCF) problem was selected for the network flow allocation.

Each single-commodity instance of the MCF problem can be formally modeled as a directed graph $G = (V, A)$, connected, consisting of de $n = |V|$ nodes and $m = |A|$ arcs. Although Figure 4 distinguishes the hub nodes by the specific indexes k, m, h, supply and demand nodes by indexes s and t, and transshipment nodes, nodes may all be generically represented by indexes i and j without losing their function in the network. Each node i and $j \in V$ holds a supply or demand b_i. Supplies are represented by positive values, demands by negative values and transshipment nodes have $b_i = 0$. The variable x_{ij} represents the amount of flow between nodes i and j. Arcs have a transport cost c_{ij}, and distance d_{ij}. Infrastructure conditions are accounted for in terms of the average speed of each road section, which are related to its speed limit, paving quality, and track geometry. These are represented by correction index v_{ij}, relative to a standard speed of 75km/h. Every arc $ij \in A$ has an associated minimum capacity $l_{ij} = 0$ and maximum capacity u_{ij} much greater than the total supply volume. The cost of each arc is also multiplied by the discount factor α_{ij}, which equals 1 for B-network and B-subgraph arcs, and less than 1 for P-subgraph arcs.

The set of equations that describe the relationship between problem criteria and variables is presented below in a simplified way, where:

$$Min\, z(x) = \sum_{(i,j)\in A} \alpha_{ij}(c_{ij}d_{ij}v_{ij})x_{ij} \qquad (1)$$

subject to

$$\sum_{\{j:(i,j)\in A\}} x_{ij} - \sum_{\{j:(j,i)\in A\}} x_{ji} = b(i) \quad \forall\, i \in V \qquad (2)$$

$$0 \le x_{ij} \le u_{ij} \quad \forall\, (i,j) \in A \qquad (3)$$

The objective function is represented by equation (1) and seeks to minimize the total transport cost based on network characteristics. The first term is the discount factor α_{ij}, used to reduce the cost c_{ij} of arcs in the P-subgraph. Since the cost c_{ij} is represented by a curve in terms of monetary value per distance.volume, the arc length d_{ij} is applied to obtain the cost of each arc per volume of goods. The correction index v_{ij} is modeled in terms of relative speed: we divide an optimal speed by the real speed of each arc, and apply this factor to increase the transport costs for lower condition roads.

Flow conservation restrictions are denoted by the set of equations (2) and, capacity restrictions, by equation (3). We assume that all arc costs are non-negative, capacities are finite, and that a possible solution exists (AHUJA; MAGNANTI; ORLIN, 1993). The network is considered balanced, thus the supplies volume is equal to the demand volume, which implies in $\sum_{i\in V} b_i = 0$.

Due to the network topology and spatial syntax, network simplex (NS) was chosen as solution tool. Among the algorithms available for solving the uncapacitated single-commodity MCF problem, NS is the best performing algorithm for road networks in practice, both in terms of speed and robustness (VIEIRA; LUNA, 2017). All algorithms used in this study are available with full source codes as part of the LEMON optimization library, an open source C++ library dedicated to solving graphs and networks combinatorial optimization problems, available at https://lemon.cs.elte.hu/ (KIRÁLY; KOVÁCS, 2012). Visual Studio 2015 was used for compilation of codes and their implementation was conducted with an Intel® Core™ i7-2620M CPU @ 2.70GHz machine, with 8GB RAM memory, using Windows 7 operating system. The interface used to input data, access the algorithm and write a results file can be found in Appendix A.

The construction of maps for the visualization of flow allocation was made in Fusion Tables, an experimental data visualization web application available from Google which incorporates Google Maps geographic data.

4 PRACTICAL APPLICATION

The practical applicability of the proposed model is demonstrated using the road network of the state of Santa Catarina, in the south of Brazil[1], using one hub. We built the B- and H-Network graphs considering the state roads where the majority of freight flows. For the sake of computational implementation, every road connection in the B-

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[1] The details about data collection and processing used in this practical application are described in Appendix B.

network and B-subgraph was denoted by two opposite directed arcs, which represent the following roadways: i) highways, e.g., national highways, interstate and state highways; and ii) lower capacity or suburban roads, e.g., those connecting close-by cities, or cities and ports. Urban networks were not considered. The B-network contains 2,482 directed arcs and the H-network, 18,347. The graphs also comprise 1,313 and 8,948 nodes, respectively, which represent cities, ports, road intersections, supply/demand nodes, and the hub (in the H-network). Although the H-network is built based on the B-network, its size is not necessarily related to the amount of nodes and arcs on the B-network. The increase in the number of nodes and arcs in the H-network is rather due to the amount of supply and demand nodes, as well as to their distance to the hub. Hence, different products will lead to different configurations of H-networks.

Goods from the poultry supply chain[1] were selected to evaluate the hubbing effect. This choice was based on the importance of the poultry industry for the region: Santa Catarina is actually responsible for 39% of Brazilian poultry exports. Testing was performed for frozen chicken products, such as frozen chicken parts and frozen pre-cooked chicken meals. Their supply and demand volumes were allocated according to the filière analysis of the poultry supply chain. Since these types of products have similar characteristics, such as origin, destination, transport costs and mode of transportation, they were grouped into a single class of products in this study. They account to a total volume of 2.8 million tons of products to be distributed. Table 1 gives a summary of the problem's dimension.

Table 1 – Characteristics and dimension of the problem.

DESCRITION	SIZE
B-network dimension	2,482 arcs and 1,313 nodes
H-network dimension	18,347 arcs and 8,948 nodes
Volume of products	2,800,989 tons
Fixed transportation cost	$ 26,44
Variable transportation cost	$ 0.13/ton
Discount factors applied	0.9,0.8, 0.7, 0.6, and 0.5

The volumes relative to the supply and demand of other Brazilian states were allocated in two source nodes and two sink nodes, one of each located to the south and to the north of Santa Catarina. These nodes were connected by direct links to the roads that cross state borders and their location was chosen to improve the graphic representation of flows; that is, it has no relationship to specific geographic coordinates. The addition of sink and source nodes is very important since, in practice, supply and demand are not exclusive of a single region. Import and export volumes were allocated to port nodes located in the east and west borders of the State.

All information related to the road network, supply and demand volumes, transportation costs and infrastructure conditions was retrieved from the Logistics and Transportation State Plan of Santa Catarina (PELT-SC), as seen in Luna et al. (2013), developed by the Supply Networks Group at the Federal University of Santa Catarina. Figure 5 depicts the distribution of flows when there is no hub in the road network, i.e. the B-network. The tip of the darker blue lines in the west of Santa Catarina, seen in Figure 5, indicate the location of major chicken meat suppliers, especially in the regions of Chapecó, Xanxerê and Concórdia. Figure 6 to Figure 11 display flow allocations according to different economies of scale obtained when a hub is installed in Chapecó.

Due to the size of the problem and the amount of data used, it becomes impractical to present a complete listing of all data. Hence, Tables 2 and 3 exemplify the input data used to solve the problem, the results data, and geographic information used to draw the flow maps.

Table 2 - Example of input data for nodes.

NODE LABEL	CODE	VOLUME b_i [tons]	LATITUDE	LONGITUDE
712	Sink-S	-117	-29.51	-51.24
713	Source-N	39,767	-25.48	-51.24
714	Source-S	594,667	-29.51	-51.24
715	SBR421640	0	-29.22	-49.81
716	SBR421605	0	-27.27	-50.44
717	SBR420213	0	-26.27	-50.46
718	SBR420330	955	-26.19	-49.26
719	SBR421820	1,274	-26.82	-49.27

Table 3 - Example of input data for arcs and flow allocation results obtained for α = 0.9

ARC LABEL	***i***	***j***	**CAPACITY l_{ij} [tons]**	**CAPACITY u_{ij} [tons]**	**DISTANCE d_{ij} [km]**	**SPEED [km/h]**	**VARIABLE COST [\$/tons]**	**FLOW RESULT [tons]**
0	0	1	0	100,000,000	7	40	1.7*	0
1	2	3	0	100,000,000	5	0**	999,999**	0
2	154	4	0	100,000,000	4	53	0.7	384,135
3	6	5	0	100,000,000	7	64	1.0	169
4	5	8	0	100,000,000	15	64	2.3	0
5	7	9	0	100,000,000	4	80	0.5	0
6	12	13	0	100,000,000	25	40	6.2	0

*Variable tarnsport cost calculated based on a standard speed of 75km/h, so that $v_{ij} = 75/speed$.
**Road out of service. In this case, a very high cost was assigned.

Figure 5 - Flow allocation for the B-network (no hub).

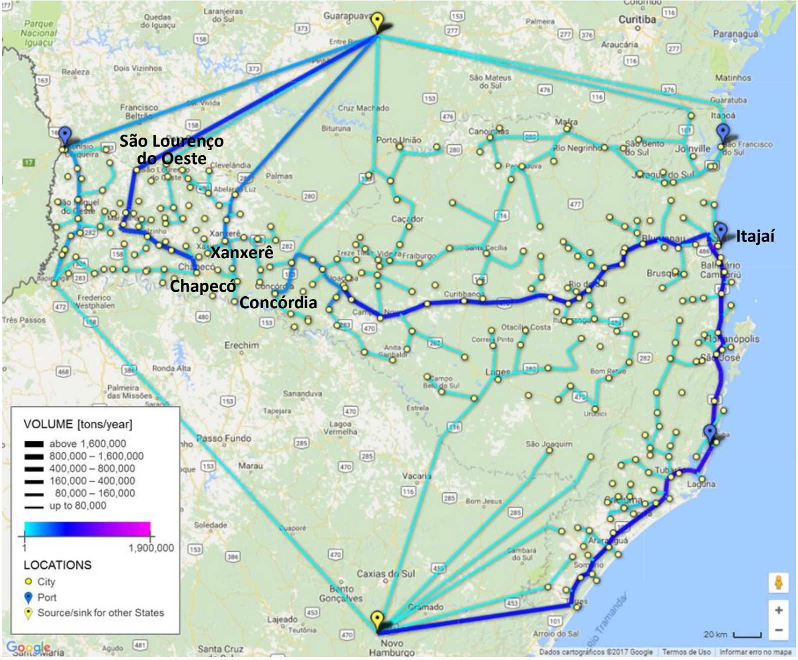


Figure 6 - Flow that goes through the hub for α = 0.9.

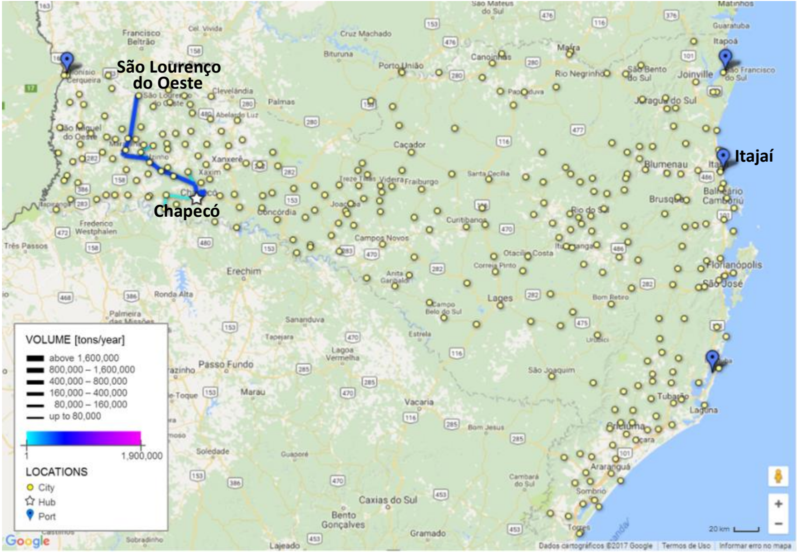


Figure 7 - Full flow allocation for α = 0.9.

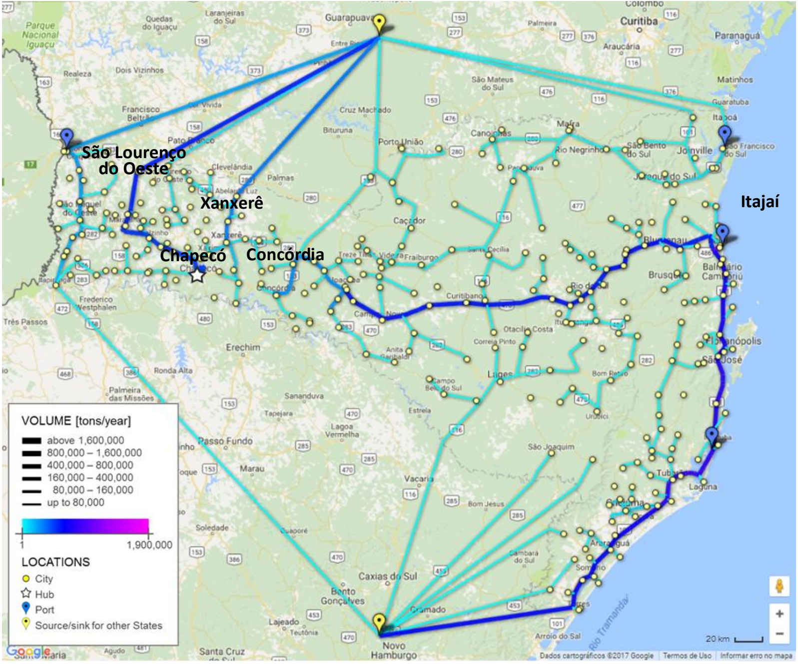


Figure 8 - Flow that goes through the hub for α = 0.7.

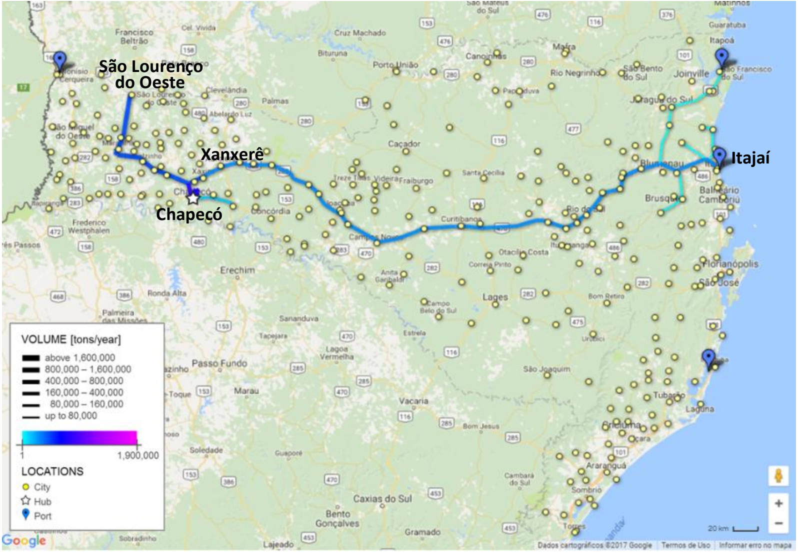


Figure 9 - Full flow allocation for α = 0.7.

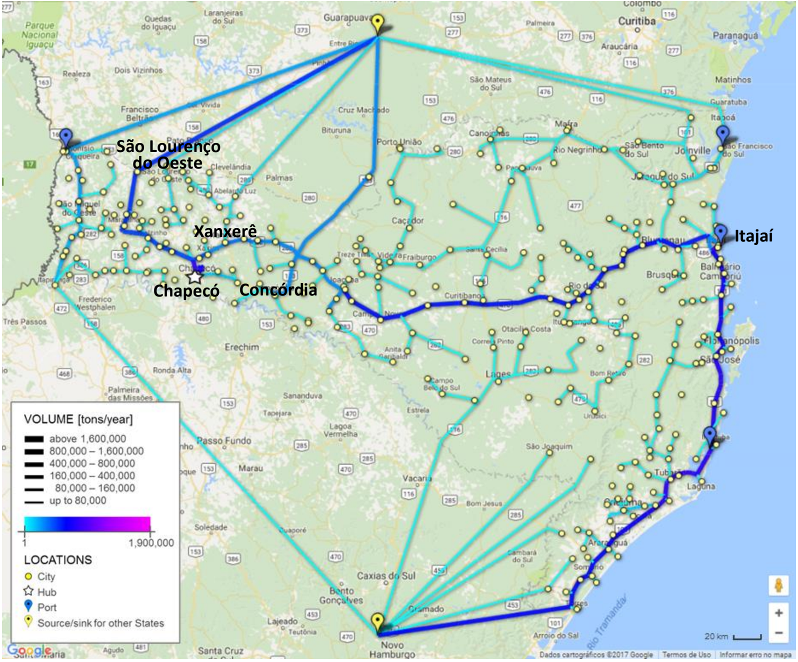


Figure 10 - Flow that goes through the hub for α = 0.5.

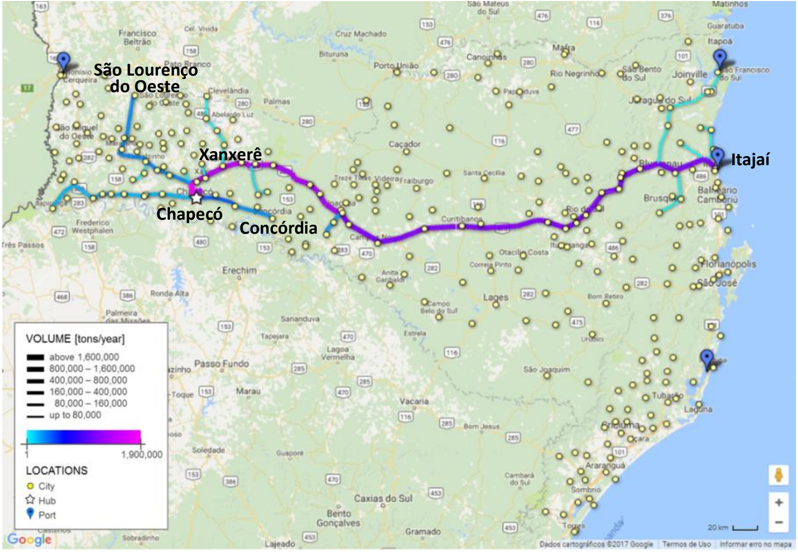
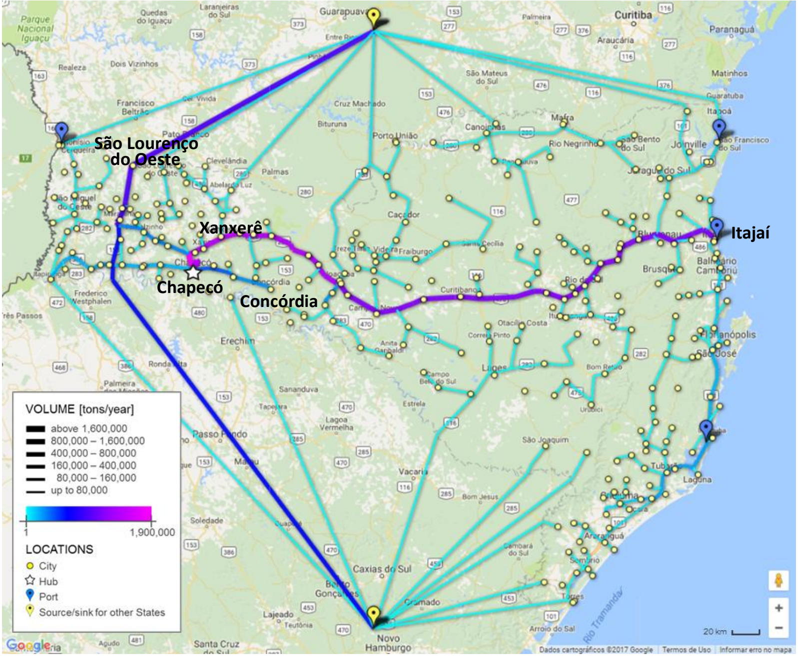


Figure 11 - Full flow allocation for α = 0.5.



A multi-criteria analysis performed by Boudouin and Luna (2012) identified a candidate location[1] for a hub which could serve this supply chain, near the poultry farming and industry based in Chapecó, a city in the west of Santa Catarina. The shortest paths for the H-network were determined from Chapecó to all cities in the State. To evaluate different allocation scenarios and observe the hubbing effect, we followed the common approach in the literature to adopt a constant α. The problem was solved for the B- and H-network with α ranging from 0.5 to 0.9, which represent different economies of scale, in order to observe the magnitude of the hub influence.

4.1 NETWORK DESIGN

The network topology proposed for the H-network is generic enough as to allow the adaptation of the graph to different types of transportation networks and supply chains. This could be observed during the process of adding the hub in Chapecó and building the links for the P-subgraph. The easiness to add new graph elements and set transportation costs enabled the evaluation of a variety of scenarios without changing the properties of the network. One could even add more hubs, set to serve specific areas and products, just by changing node assignment through the creation or elimination of P-subgraph links. This H-network topology enabled the evaluation of the hubbing effect for the terminal located in Chapecó throughout the entire Santa Catarina network, both on goods distribution and on transportation costs, considering the hub consolidation capability in terms of economies of scale. The use of mirror nodes allowed straightforward comparisons between node potentials π of two available service models: using the hub versus hauling shipments only through the base network.

Thanks to the design of the P-subgraph, it was possible to apply the discount factors to all arcs of the network. Although constant values of α were adopted for the entire network, different discount factors could be applied to specific network sections, taking into consideration aspects like the type of product, flow volume, distance from the hub, coverage area or mode of transportation. The cost of using the hub was assigned to the interhub arc (i.e. c_{km}). Since we solved single commodity problem instances, the cost of using the hub could be modeled according to the services offered at the hub, which can be specific to each supply chain; yet, in this study a fictitious value was adopted as the cost of using the hub. To the best of our knowledge, models available in the literature so far have not allowed such an approach to economies of scale and hub service costs.

4.2 HUBBING EFFECT

The maps depicted in Figure 6 to Figure 11 present the effects of the hub location decision and of economies of scale on flow intensities. In spite of the hub location itself, which has been previously defined, the discount factors that describe the economies of scale play a key role in the model since transportation costs in the P-subgraph are calculated based on α. The hubbing effect can be observed throughout the network as the value of α decreases from 0.9 to 0.5 from three different perspectives: i) concentration of flows in the hub location; ii) hub coverage area and markets served; and, iii) intensity in the use of infrastructure links. Although the first effect may be naturally expected, the maps exhibit some interesting shifts in allocation related to the application of discounts, which cause effects ii and iii.

4.2.1 Consolidation of flow at the hub location

As economies of scale are obtained flow concentrates at the hub facility, as seen in Figure 6, Figure 8, and Figure 10 for α values 0.9, 0.7 and 0.5, respectively. While for a 10% discount the hub coverage area concentrates in the western region (Figure 6), as the discount increases to 30% (Figure 8), and then to 50% (Figure 10), it becomes more interesting to consolidate volumes from farther production sites. As expected, there is a tendency to route longer haul shipments through the hub, especially those destined for export through the port of Itajaí. For high discount rates, the advantages of using the hub may even surpass issues related to the quality of the road infrastructure, known to be lower in the hub region. This is the case of Concórdia, a city in the Midwest, where a 50% discount makes using the hub more profitable for producers located in the area, as seen in Figure 10.

Flow consolidation at the hub is related to the provision of better connection between nodes, which is translated in our model by lower transportation costs. This means that production sites that previously adopted straight routes to the East coast will be allocated to the hub according to economies of scale, even though that may result in the use of lower speed/quality roads and in an increase in the travelled distance. The results shown in Table 4 ratify that the use of intermediate logistics facilities results in longer distances and travel times, as also pointed out by Guastaroba, Speranza and Vigo (2016). Nonetheless, straight delivery is still possible if the total transportation cost is lower when fulfilling demand. This behavior generates a trade-off between total cost and transportation moment, observed in Table 4.

For example, when α = 0.5, the transportation moment generated with the use of the hub represents an increase of 40.58% when compared to the B-network. In this case, the P-subgraph moment actually corresponds to more than 80% of the total H-network moment, i.e. the majority of flow is routed through the hub. This trade-off between cost and traffic hub is an issue that should be considered in infrastructure planning, since it will influence the amount of capital invested on maintenance and construction of roads.

Table 4 - Changes in transportation costs and transportation moment.

DISCOUNT FACTOR	TOTAL COST [MILLION $]	COST REDUCTION	P-SUBGRAPH MOMENT [1,000 T.KM]	FULL NETWORK MOMENT [1,000 T.KM]	H-NETWORK MOMENT VARIATION
B-Network	$ 1,782	-	-	609,098	-
0.9	$ 1,775	- 0.37%	56,366	609,099	0.00%
0.8	$ 1,767	- 0.82%	56,368	606,990	-0.35%
0.7	$ 1,745	- 2.07%	198,997	649,477	6.63%
0.6	$ 1,707	- 4.17%	269,458	670,900	10.15%
0.5	$ 1,648	- 7.50%	719,013	856,249	40.58%

4.2.2 Hub coverage and markets served

Although there is a flow concentration at the hub area, it is not compulsory that all regions will haul more shipments through the hub with an increase in economies of scale. That is, as the value of α varies, a change in which suppliers are assigned to the hub is possible due to the need of maintaining supply-demand relationships. A comparison between flow intensities for α = 0.9 and 0.5 reveals this effect. The analysis of Figure 6 and Figure 10 shows that the volume of flow routed between the hub and the city of São Lourenço do Oeste, in the northwest border, decreases at some point with an increase in the discount, an effect that can be visualized by the color change in flow lines from darker blue to a lighter tone. This means that the discount factor influences not only the hub coverage area by assigning more suppliers to the hub, but it also impacts the patterns of demand fulfillment by defining which suppliers will serve each consumer market in an attempt to provide an overall efficient transportation. This highlights the importance of applying economies of scale to all arcs in the network, especially when discounts are modeled as functions of flow intensity or network parameters.

The evaluation of node potentials may bring further insights about the changes in flow allocation. Node potentials can be obtained through the analysis of reduced costs, which represent the transportation costs applied to reach each node of the network. Thereby, one can measure the gains and losses in terms of transportation costs at any network section when the hub is used. The fact that transportation costs reduce as α decreases is shown by the increase of flow at the hub area and is displayed by the changes of colors from blue to purple in Figure 7, Figure 9, and Figure 11. This is also seen by the spread of darker blue and purple shades starting from the hub with the increase in the discount. This type of evaluation, which has not been found in the hub location literature, is possible thanks to the approach used to build the H-network.

4.2.3 Intensity of infrastructure use

The hubbing effect also impacts on how the transportation infrastructure is used. Figure 7, Figure 9, and Figure 11 show the full distribution of goods in Santa Catarina with $\alpha = 0.9$, 0.7 and 0.5. Discounts of up to 20% cause small changes in infrastructure use, ratified by the transportation moment and node potential data in Table . Yet, as economies of scale increase, a shift in the use of roads is observed, including even routes used to fulfill demand of other states. For example, in Figure 9 we can see a higher concentration of flow from the Midwest section of Santa Catarina to the north of Brazil, when compared with the B-Network (Figure 4). Nonetheless, for $\alpha = 0.5$ the consolidation of flow in the hub leads to a shift of flow intensity back to the western region. From that, we can see that two extra connections to the southern state also arise for high discount rates. The highway that serves as main transportation corridor along the east coast of Brazil, and is currently used to reach the south of the country, actually displays a strong decrease in the volume of goods when $\alpha = 0.5$, while other roadways start playing a more relevant role in flow allocation.

Two major transportation corridors emerge as economies of scale increase. The first connects the hub to port facilities in the northeast of Santa Catarina, highlighted in shades of purple in Figure 11. This east-west corridor actually resembles a long-time discussed railway project for the state. If a new railway is able to offer the same advantages as the delineated corridor, the results of our model could actually help to substantiate the decision on this new investment. The second transportation corridor found in Figure 11, marked in dark blue, creates in the west a north-south connection for the distribution of products that crosses Santa Catarina and connects the rest of the country. It is interesting to notice that this corridor is not connected directly to the hub, i.e. it does not appear in Figure 10, although part of the volume that flows through that corridor has been routed via hub. This shows that the hubbing effect may actually influence allocation patterns of non-hub flows because of the need to fulfill demand. This result confirms the importance to consider not only the flow that goes through the hub, but also those allocated through regular distribution channels in the same analysis.

Although the values of the discount factors are hypothetic, one may question if the increase of flow seen in Figure 10 is acceptable, and if relaxing arc capacities would not lead to an amount of flow that is impractical for the infrastructure available. Taking into account the amount of tons/year when $\alpha = 0.5$, and an average truck capacity of 30 tons, the highest amount of flow would account for 173 trucks per day, for frozen chicken parts. On the other hand, high traffic highways in Brazil may experience truck flow anywhere from 2.000 to 5.900 vehicles per day (DNIT, 2016). Although we are considering only one type of product, a quick analysis of these numbers shows that there is enough room for the implementation of the proposed hub.

Although the traffic increase seen in our tests might be handled by the roadways available, this increase could result in the reduction of vehicle speed if roads become too congested. This could be taken into consideration by applying a second correction index to the transportation costs that translates congestion. Road capacity could be restrained, but that would lead to the configuration of a multi-commodity network flow problem, resulting in higher problem complexity and need to adopt different solution tools. On the other hand, relaxing road capacity allows identifying if infrastructure improvement, such as the construction of new road lanes, would be in demand.

As additional products are included in this analysis, a more robust decision can be made regarding the configuration of transportation corridors and multimodal infrastructure alternatives that bring advantages to the entire network.

5 FINAL THOUGHTS

This paper presented a network flow model to include logistics hubs as components of transportation networks and evaluate the hubbing effect on goods distribution, supply-demand relationships and infrastructure use. While hub location models developed so far allowed us to perceive the set-up of hub networks, there is a complementary value in better understanding the influence of hubs resulting from flow allocation. To the best of our knowledge, this is the first model that enables the evaluation of the hubbing effect on fully represented transportation networks and allows modeling economies of scale in each arc of the network, which may be represented by constant discounts or functions of parameters such as flow intensity or distance from the hub. Our design keeps the optimization complexity of the problem in a lower level due to the segmentation of the hub location decision from flow allocation, as suggested by Vieira and Luna (2016). With this, it is possible to adopt solution tools such as NS, which guarantees efficient and robust computations.

The proposed model was tested using real data from the Brazilian poultry industry and the road network of the Santa Catarina state. Results documented the importance of representing complete networks and applying economies of scale throughout the entire network. They further uncovered trade-offs between the advantages obtained with a hub and flow allocation, geographic coverage, demand fulfillment and infrastructure availability. It is interesting to notice that these trade-offs are directly related to the aspects that guide the classification of logistics terminals, i.e. products, infrastructure and market, which will then influence the definition of scale economies based on the associated hub functions.

The aggregated knowledge generated by the model may also be useful to improve location decisions and regional spatial organization, foreseeing how future hubs affect flow allocation. Decision makers may start with suboptimal hub projects in earlier phases of the analysis, and then use hubbing effect information to provide insights on flow intensities in order to accelerate network design. The choice a city or geographic region as likely hub location may aid in the evaluation of economic development improvements, since the new hub will attract logistics service providers and industrial facilities to the region. The easiness to adjust the scale factor allows verifying which conditions would have to be achieved in order to draw businesses to the hub area due to changes in transportation costs and served markets.

Flow allocation information is likewise valuable for businesses, which could gain insights on plant location, identification of supply routes, and visualization of changes in consumer markets. Node potential analysis allow establishing trade-offs between transportation costs and profit margins. Although the graph model has been designed for large scale networks, it can be applied for tactical decisions on the service model, e.g. whether to use direct shipments or use hubs for consolidation. It may also help in the development of partnerships between supply chain players to consolidate less than truckload shipments in hub facilities. Ultimately, understanding the hubbing effect aids in improving at the same time supply chain integration and coordination.

A variety of extensions of this study are possible. There is an overreliance of our model on specific parameters such as the discount factor and the interhub arc cost, which are simplifications of real-world aspects. Hence, a promising area for future research lies in solving the problem with alternative functions for economies of scale. The changes in flow intensities highlight the importance of correctly dimensioning a discount that describes hub advantages. Similarly, there is a need to develop studies about the interhub arc cost. Since the areas served by each hub are designed by the decision maker, different hub facilities may also be tested at the same time in the network. Our graph model also opens new avenues for testing network problems with different restrictions which may influence flow allocation, such as hub capacity. Future research could extend the proposed model to address uncertainties and the location of the hub, although the latter would highly increase the models complexity. This would lead to the development of faster algorithms.

APPENDIX A – Code interface used to input data, run the Networks Simplex algorithm and write results.

```
#include "stdafx.h"
#include <iostream>
#include <fstream>
#include <string>
#include <stdio.h>
#include <stdlib.h>
#include <lemon/random.h>
#include <lemon/smart_graph.h>
#include <lemon/maps.h>
#include <lemon/capacity_scaling.h>
#include <lemon/network_simplex.h>
#include <lemon/cost_scaling.h>
#include <lemon/lgf_reader.h>
#include <lemon/lgf_writer.h>
#include <lemon/time_measure.h>
#include <iomanip>
#include <ctime>
#include <chrono>

using namespace std;
using namespace lemon;

int main() {

   ofstream fout;
   string filename;
   string fileoutput;
   string algorithm;

   //Defines file characteristics
   char cadeia[36] = "ProteinaAnimal";
   char *produtos[] = { "PRT-AAV_SC" };
   int size = sizeof(produtos) / sizeof(produtos[0]);

   algorithm = "Network Simplex";

   fout.open("MedidaTempoSC.txt", ios_base::app);
   if (!fout.is_open()) {
      cerr << "Error: Could not creat file." << endl;
      exit(1);
   }
```

```
   fout << "Algorithm: " << algorithm << ".Cadeia :"
   << cadeia << endl;
   fout.close();

   for (int m = 1; m <= 1; m++) { // iterates tests
   for constructing mean and standard deviation

     cout << "Processamento: " << m << endl;

     for (int k = 0; k < size; k++) {

        //Creates directed graph, node and arc maps
        DIGRAPH_TYPEDEFS(SmartDigraph);
        SmartDigraph g;
        SmartDigraph::ArcMap<int> capacity(g),
lower(g), cost(g);
        SmartDigraph::NodeMap<string> geocode(g);
        SmartDigraph::NodeMap<int> supply(g);

        char filenameChar[52];
        std::sprintf(filenameChar, "%s.lgf",
produtos[k]);
        filename = filenameChar;

        //Reads .lgf file and builds nodes and arcs
maps
        try {
          digraphReader(g, filename).
             arcMap("capL", lower).
             arcMap("capU", capacity).
             arcMap("custo", cost).
             nodeMap("geocodigo", geocode).
             nodeMap("qtdeDisp", supply).
             run();
        }
        catch (Exceptionand error) {
          cerr << "Error: " << error.what() << endl;
          return -1;
        }

        std::cout << "File opened: " << filename <<
endl;

        //Defines the algorithm type to be used
        typedef NetworkSimplex<SmartDigraph> MCF;
```

```
        //Creates MCF algorithm object
        MCF mcf(g);

        //Inicializes algorithm parameters
        mcf.lowerMap(lower).upperMap(capacity).costMap
        (cost).supplyMap(supply);

        //Starts timer
        chrono::steady_clock::time_point begin =
        chrono::steady_clock::now();
        Timer timer;

        MCF::ProblemType result = mcf.run();  //
Executes Algorithm

        if (result == MCF::OPTIMAL) {
          std::cout << "Total flow cost (long long):
          " << mcf.totalCost<long long>() << endl;
        }
        else {
          std::cout << "Feasible flow NOT found!" <<
endl << endl;
        }

        chrono::steady_clock::time_point end =
        chrono::steady_clock::now();
        std::cout << "Running time = " <<
        chrono::duration_cast<chrono::milliseconds>(en
        d - begin).count() << " milliseconds" << endl
        << endl;

        //Save running time measures
        fout.open("MedidaTempoSC.txt", ios_base::app);
        if (!fout.is_open()) {
          cerr << "Error: Could not open file for
appending." << endl;
          exit(1);
        }

        fout << produtos[k] << " Timer: " <<
        chrono::duration_cast<chrono::nanoseconds>(end
        - begin).count() << " nanoseconds." << endl;
        // << " TimerLemon: " << timer << endl;
        fout.close();
```

```
        //Save results in a txt file
        char fileoutputChar[52];
        std::sprintf(fileoutputChar, "F:/Visual
        Studio/ExampleSSP/Release/%s/Resultado%s.txt",
        cadeia, produtos[k]);
        fout.open(fileoutputChar);

        if (!fout.is_open()) {
          cerr << "Error: Could not creat file." <<
endl;
          exit(1);
        }

        fout << "Results of NS algorithm for product
        type: " << filename << endl << endl;
        fout << "Running time: " <<
        chrono::duration_cast<chrono::milliseconds>(en
        d - begin).count() << " milliseconds" << endl;
        fout << "Running time: " << timer << endl <<
        endl;
        fout << "Total Cost: " << mcf.totalCost() <<
        endl;
        fout << "Arc flows:" << endl;

        for (ArcIt a(g); a != INVALID; ++a) {
          fout << "Arc " << g.id(g.source(a)) << "-"
          << g.id(g.target(a)) << ": " << mcf.flow(a)
          << endl;
        }
        fout.close();
      }
    }

    return 0;
}
```

APPENDIX B – Data collection and processing for the practical application.

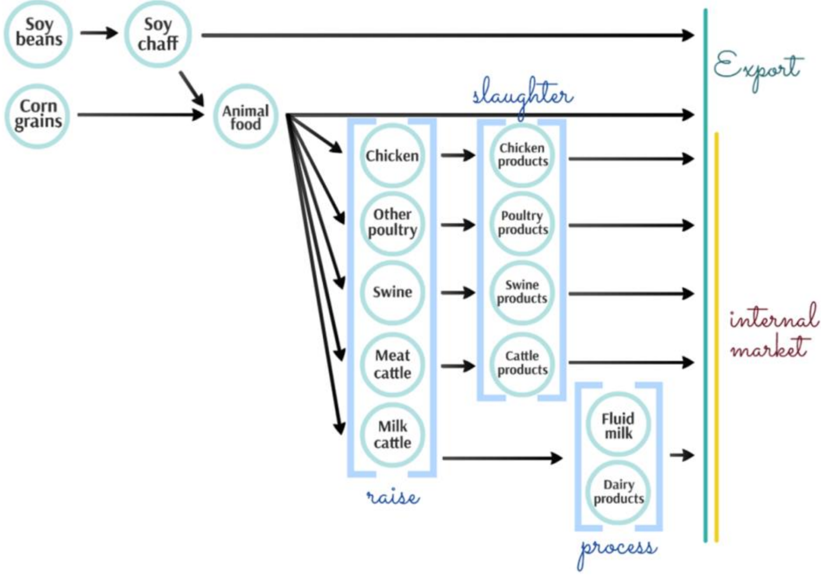
To perform the practical application of our flow allocation model, four sets of data that define the context of hub operations are used, which are related to: goods, supply/demand location, transportation infrastructure, and hubs. The first consists of data about the goods to be distributed, such as type, volume, and transportation costs. The second is related to the market coverage, consisting of the position of supply, demand and transshipment nodes throughout the network. Next, the transportation infrastructure available is identified, including the characteristics that play a key role in amending the cost functions for each arc, such as type of infrastructure, distance, capacity, and speed. Finally, the location of the hub and the discount factors for each section of the network should be defined.

In the next sub-sections, the process to build this database is described. All the data used in this thesis has been first collected for the Logistics and Transportation Plan of Santa Catarina – PELT-SC, developed by the Supply Networks Group of the Federal University of Santa Catarina (LUNA et al., 2013). The model was solved for frozen goods from the poultry supply chain, such as frozen chicken parts and frozen pre-cooked chicken meals, using the road network of the state of Santa Catarina, in south of Brazil. Results were organized to represent the flow in each arc of the network. To portray the flow allocation, data was plotted into maps using Google Fusion Tables, a data visualization web application.

SUPPLY CHAIN AND PRODUCTS

Data collection began with the filière analysis of the supply chain of animal products. Although we focus on poultry products, this entire supply chain was mapped in order to understand its configuration and properly establish the supply-demand relationships from raw materials to finished goods. Hence, the supply chain design included goods from poultry, cattle, and swine, as depicted in Figure . Next, volumes of supply and demand for each product were identified, including those of import and export. A variety of data sources were used in this step, which were available through sectoral statistical reports, commodities and trade statistics databases of the Brazilian government, international databases from the United Nations, and scientific papers about industrial transformation processes.

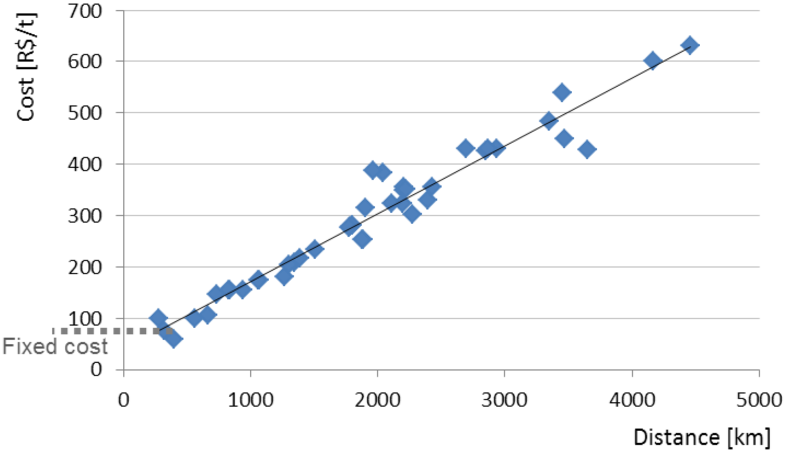
Figure 1 - Animal products supply chain.



The goods volumes were allocated to all Brazilian cities using as distribution criteria the location of production facilities and markets, the GDP, and the number of citizens. Such data was also available through government portals. It should be noted that, although the scope of the practical application is the state of Santa Catarina, there is naturally flow of products from other locations in the country; hence data collection was performed for Brazil as a whole.

Transportation costs are represented by freight curves that reflect costs practiced by freight forwarders for each product. They are defined based on transportation modes used, distance travelled, and specific product characteristics such as weight and volume. The costs database contains the following attributes for each product sample: supplier and customer location, distance between the two, cost per ton, freight service model, type of vehicle used and vehicle capacity. Thereby, a cost curve of $/ton per km was built for each product, as exemplified in Figure 2. From that, a transportation cost equation was estimated using linear regression, composed of two terms: i) a fixed cost, referring to activities of order processing, loading, unloading, and transshipment when freight is transferred to port areas; and ii) a variable term, corresponding to the cost per ton and distance travelled throughout the network.

Figure 2 - Cost curve for meat products.

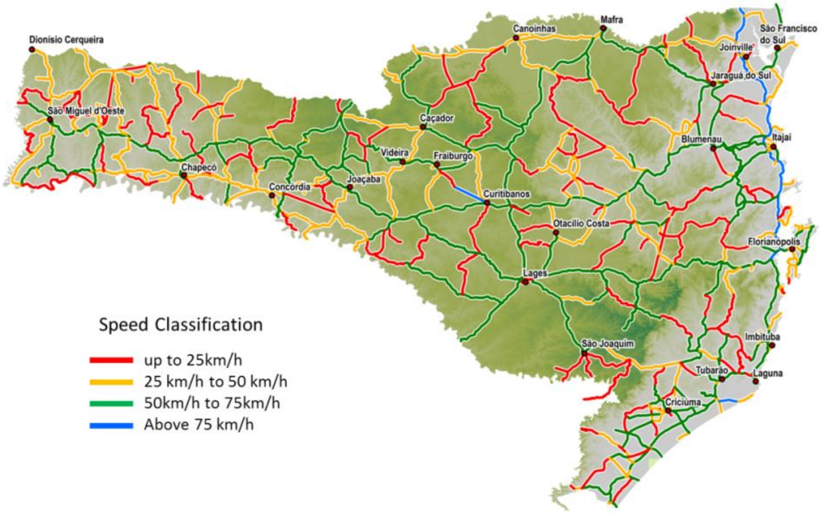


ATTRIBUTES OF THE TRANSPORTATION INFRASTRUCTURE

The Brazilian freight infrastructure contemplates all modes of transportation. Yet, the road network is dominant in the state of Santa Catarina, although freight hauling through coastal shipping lines has been increasing since the past 5 years due to the high port activity in the east coast. Railways are present in Santa Catarina, but in a small extent when compared to roads, being used mainly for commodities such as soy, rice and coal. In order to maintain a consistent analysis, algorithmic tests and practical applications were performed using a road network composed of national and state highways; urban networks were not taken into account. Roads are represented by arcs, with their corresponding length. Crossings and connection points are depicted as nodes in the graph, including those of transshipment to maritime ports, important sources of goods supply and demand.

As represented in the mathematical model, transportation costs can be adjusted by a relative speed index that depicts the actual infrastructure conditions. This index was built by dividing an ideal standard speed of 75m/h by the speed of each arc, which is then multiplied by the respective arc cost of each product. Thus, the lower the quality of the infrastructure, either due to poor paving or design, the higher the impact on the transportation costs. Consequently, a very high cost value may be applied to the arcs in order to inactivate certain paths or transportation modes in the network. The speed for each road stretch in Santa Catarina can be seen in Figure 3.

Figure 3 - Road speed in Santa Catarina. Source: Luna et al. (2013).



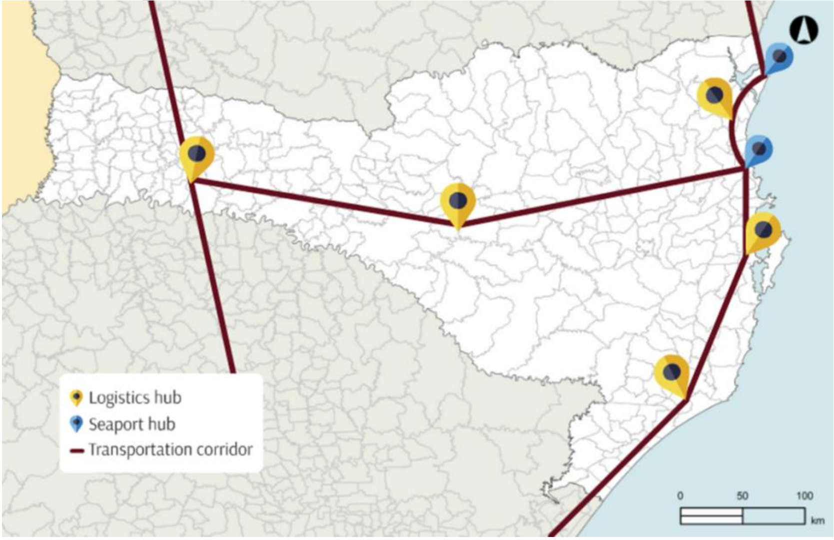
HUB LOCATION AND ECONOMIES OF SCALE

The definition of the hub location in this study is based on the analysis performed by Boudouin and Luna (2012), which positioned a variety of hubs in Santa Catarina and designed possible transportation corridors to connect such hubs, as shown in Figure 4. To determine hub location, the authors first detected the most appropriate regions taking into account macroeconomic and market aspects, especially those related to the concentration of consumer markets. Then, the definition of the location itself in each region was performed considering: i) the presence of nodes that concentrate flows and transportation routes; ii) the availability of transportation infrastructure; and iii) the proximity to markets and industry.

While the abovementioned criteria are related to the infrastructure availability and market proximity, de choice of which hub will be implemented is intrinsically related to the type of products that will be handled at the facility. Taking into account the filière analysis of the poultry supply chain, the products to be tested, and the location of origins and destinations, the hub located in the western area of Santa Catarina is the most appropriate to serve this application context. One should notice that the mathematical model design favors the segmentation of flows in the hub by type of product and market coverage, a very important aspect in the evaluation of the hubbing effect.

Since our goal is to evaluate the behavior of the models and the influence of the hub in the network, a variety of hubbing effect scenarios were evaluated using different discount factors ranging from 0.5 to 0.9, which translate the ability of the hub in aggregating economies of scale to the transportation costs of the network.

Figure 4 - Proposal of hubs location and transportation corridors in Santa Catarina. Adapted from Boudouin and Luna (2012).



THESIS CONCLUSION

Logistics terminals have been around for some time – yet, it has been only recently that a concern about measuring the impact of logistics hubs on goods distribution has emerged. While the lack of an appropriate model to evaluate the hubbing effect is evident in literature, its effects can also be observed in a variety of inefficient hub transportation networks found in practice. In an effort to close this research gap, a holistic approach that included both qualitative and quantitative analyzes lead to the design of a model that strongly supports this task as it considers the main aspects inherent to freight distribution throughout transportation networks with one or more hubs.

The development of the model set off with an understanding about the classification of logistics terminals and the concept of logistics hubs. We explored the function of such facilities, the type of network to which it belongs, as well as their ability to cover markets due to the advantages that could be obtained in fulfilling supply-demand relationships. As these aspects were being identified, it became clear that the theoretical models available in the literature for flow allocation presented some intrinsic limitations. While they were a good fit to hub networks that held the characteristics of air transportation and postal services, those exhibiting the capillarity of roadways required further detailing of their graph structure.

It was interesting to notice that, although the proposed model represents the complex environment of logistics and transportation systems, the attributes of the network and the modeling approach adopted allowed the application of a well-established – and rather elementary – mathematical model, which makes the model easy to apply. Having in mind the idea to develop a full framework that encompassed the most appropriate tools available, a computational analysis of different solution algorithms was also performed.

A variety of evaluation avenues opens with the implementation of the proposed model, especially due to two main characteristics of the graph design. The first concerns the two-level topology design, which allows evaluating separately the flows that traverse the hub from the ones that do not. Defining the type of products to be handled at the hub played an essential role in this partitioning. The second aspect is related to the degree of detail used to draw the network connections, which, together with the two-level topology, enables the application of specific economies of scale to any section of the network. Furthermore, it is also possible to model the costs of using hub facilities and specific services.

Hence, the proposed topology renders an important benefit due to the easiness to adapt its structure to different infrastructure and supply chain scenarios.

The analysis of flow allocation enabled through the practical application uncovered a variety of trade-offs between economies of scale and flow allocation, hub geographic coverage, demand fulfillment, and infrastructure availability. A closer look into these trade-offs reveals that they are directly related to the framework that guides the classification of logistics terminals, which is based on product type, market coverage and infrastructure. This consistency between the results obtained and the characteristics of hubs as transportation network elements provides reliability to the proposed model, evidencing its appropriateness to evaluate the hubbing effect.

Besides assessing future infrastructure projects, an analysis of existing logistics hubs could also be performed with the proposed model. A comparative evaluation between the existing flows handled at a hub and those delineated in its project would allow verifying if the desired outcomes have been achieved for the facility. The model could be employed to evaluate possible improvements in the services and infrastructure available at the hubs, as well as the implementation of transportation corridors to connect different types of facilities. One could further observe shifts in flow concentration due to changes in supply-demand relationships related to the relocation of production sites and consumer markets.

Although constant discount factors were used in the practical evaluation, scale economies could be better represented (i.e. through a function) in order to obtain results that are more reliable for decision-making. Hence, future research on modeling the discount factor is welcome, as well as investigations on the differentiation of discounts according to the type of product and geographic coverage. Actually, the model's applicability is dependent on the value, or function, assigned to represent economies of scale.

Although this study evaluated only one hub location, future work could analyze the addition of more other hubs at the same time (as well as other locations), for the same supply-demand scenario and network, considering even the definition of transportation corridors. The hub location decision could be incorporated in an integrated way, evaluating the pros and cons of using this type of approach against the two step method adopted in this thesis. Our model leaves room for more detailed modeling of hub costs and transportation costs; these are important matters and, depending on the model’s application, one might need to re-think the proposed mathematical model to incorporate certain specific cost functions.

A sensibility analysis also could be performed based on the dual variables and relative costs associated to the optimal solution found. Likewise, uncertainty in the problem’s parameters could be taken into account in other studies through robust optimization. While we presented only one optimal solution, future research could evaluate the differences in flow distribution for other possible solutions available.

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