Mixing quantitative and qualitative methods for sustainable transportation in Smart Cities

PhD thesis defense

Doctoral Program in Computer and Control Engineering - XXXI cycle

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Agenda

01 **Urban freight transportation: overview**

02 **A new approach to sustainable urban freight transportation and parcel delivery**

03 **Intermodal transportation**

04 **Mixing traditional and green business models for urban parcel delivery**

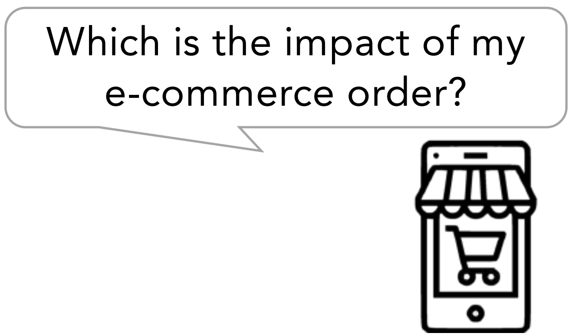
05 **Tactical capacity planning**

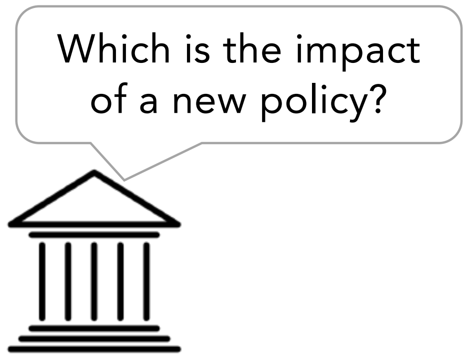
06 **Conclusions and future research**

07 **Other PhD activities**

Emerging needs and aims of the thesis

- The complexity of urban context makes needed ad-hoc methodologies to:
  - Simulate these situations
  - Aid the decision-makers to take the proper decisions
- Need of a holistic vision of the system
- Need for incorporating into simulation optimization tools a managerial perspective and representation of various business models



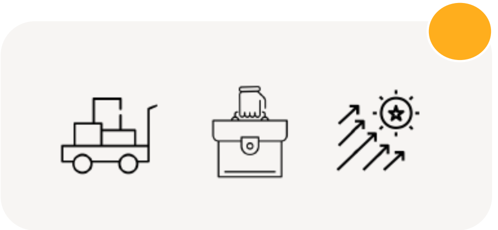


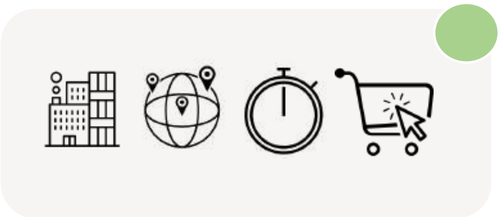
Research Questions

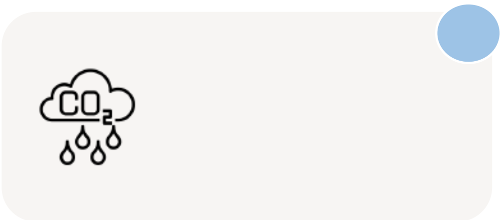
- Is the integration between business and operational models possible and valuable?

- Which are the benefits of such integration on the urban context and in particular, on the last mile?

Urban freight transportation: overview







Land of Honey

- Support the procurement and trading activities within the city
- Create job opportunities
  - **2-5%** of the total labor force
- Competitive factor at the national level

Stressed by

- Urbanization
  - **85%** of population will be urban in 2050
- Globalization
- New management and production principles (e.g., Just-In-Time)
- E-Commerce
  - **10%** of the overall logistics demand
  - Free return and shipping

Land of Blood

- Externalities
  - urban freight emissions account for the **25%** of urban CO2 emissions
  - **30-50%** other pollutants
  - Diseconomies of scale
  - **Sustainability**

Emerging challenges I

Paradigm shifts

- Before 1950s: Intra-business and B2B
- After 1950s: micro-small transport companies
- 1990s: medium-large transport companies
- Today: Demand-Driven Logistics

Multiple actors with different goals and objectives

- Shippers
- Carriers
- Administrations
- Customers

Common and scares resources

- Freight vehicles share and compete with people mobility for the use of infrastructure and resources

Emerging challenges II

Large scale problems

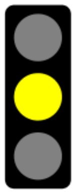
- Atomization of the parcel flows
  - About 4000 delivery/day in a medium-sized city
  - 30-50 tons of goods per capita per year
  - 0.1 delivery/pickup per capita per day
  - 40-50% of total goods traffic (road occupancy) for local business
  - 40-50% of total goods traffic (road occupancy) for private needs

Planning issues

- Strategic planning
- Tactical planning
- Operational planning
- Pre-tactical planning
- Uncertainty

City Logistics as first answer

The process for totally optimizing the logistics and transport activities by private companies in urban areas while considering the traffic environment, the traffic congestion and energy consumption within the framework of a market economy (Taniguchi et al., 2001)



GEOGRAPHICAL EXTENSION

City Logistics measures are usually related to a limited spatial coverage

They do not consider the complexity and phenomenal diversity of urban contexts

Dependence from local government interest and subsides

STAKEHOLDERS ENGAGEMENT

Lack of support and commitment from the different actors (particularly, private companies)

Lack of qualified expertise for the conflict resolutions among different participants in CL projects

APPROACH

Lack of a managerial perspective in designing sustainable policies

Gap between business and operational models

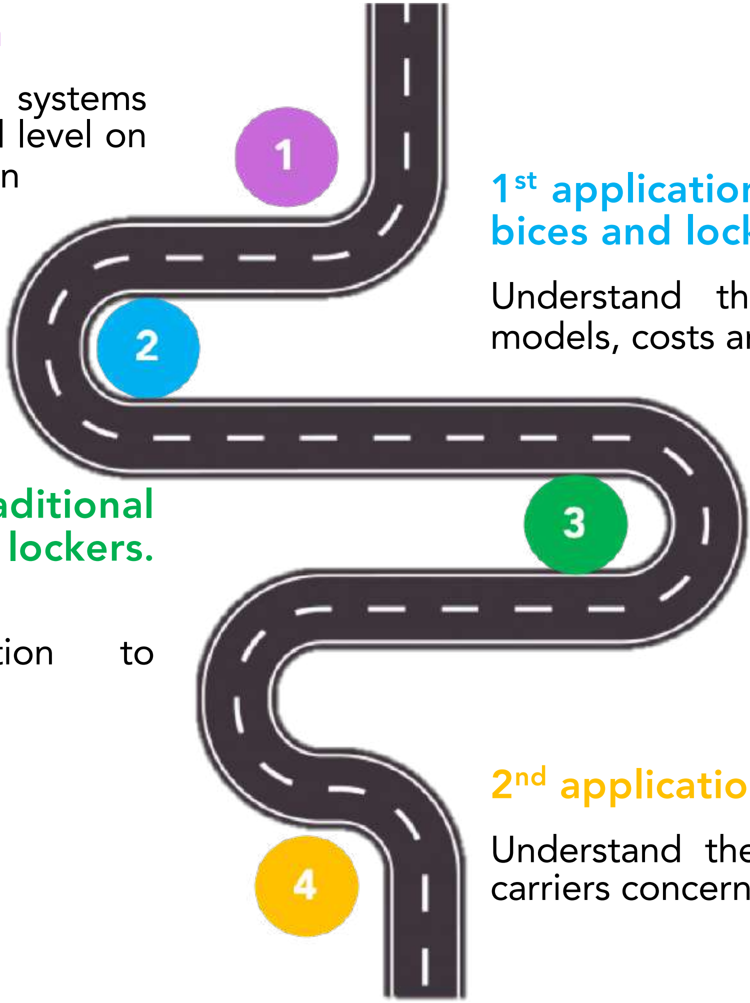
TAKE AWAY

Need of a holistic vision.
Consider both the different actors in the city and their complex interactions and the different technologies.

Roadmap

Intermodal Transportation

Understand how intermodal systems can be repurposed at a logical level on the urban freight transportation



1st application: Mixing traditional vans, cargo bices and lockers. Business models

Understand the actors involved, their business models, costs and revenues structures

1st application: Mixing traditional vans, cargo bices and lockers. Simulation-optimization

Apply simulation-optimization to extract mixed-fleet policies

2nd application: Tactical capacity planning

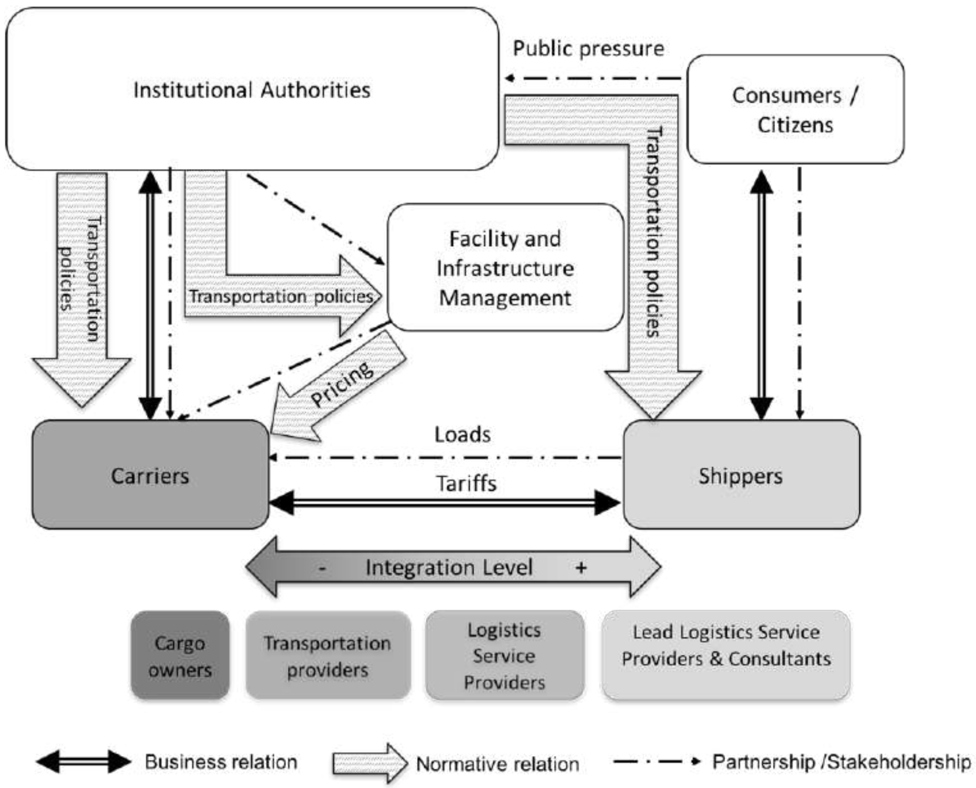
Understand the relationship between shipper and carriers concerning multiple type of capacity

Intermodality

Transportation of loads from the origin to the destination of a shipment, involving at least two transportation modes and services, such that the transfer from the one mode to the other is performed at an intermodal terminal.

- Backbone of international trade supporting the new business models in achieving sustainability
- Key component of environmental policies (Catte, 2014)
  - individual measures
  - viable alternatives to the traditional models

Social business network



Methodology and taxonomy

- Cluster-analysis based on a three-layer taxonomy with polythetic classes (Bailey, 1994, 2005)
- Literature from 2007 to 2017
- Screening and filters

Network Description			Planning			
Types	Modes	Territory	Decision Makers	Decision Objects	Objectives	Time Horizon
Unimodal	*RO*	*Urban*	*Shippers*	*Infrastructures*	*Economics*	*Strategic*
Multimodal	*RA*	*National*	*Carriers*	*Policy*	*Environment*	*Tactical*
Intermodal	*IWW*	*International*	*Inst. Authorities*	*Operations*	*Performances*	*Operational*
	M		*Facility and Infrastructure Managers*	*Cooperation*		
	A			*Technology*		

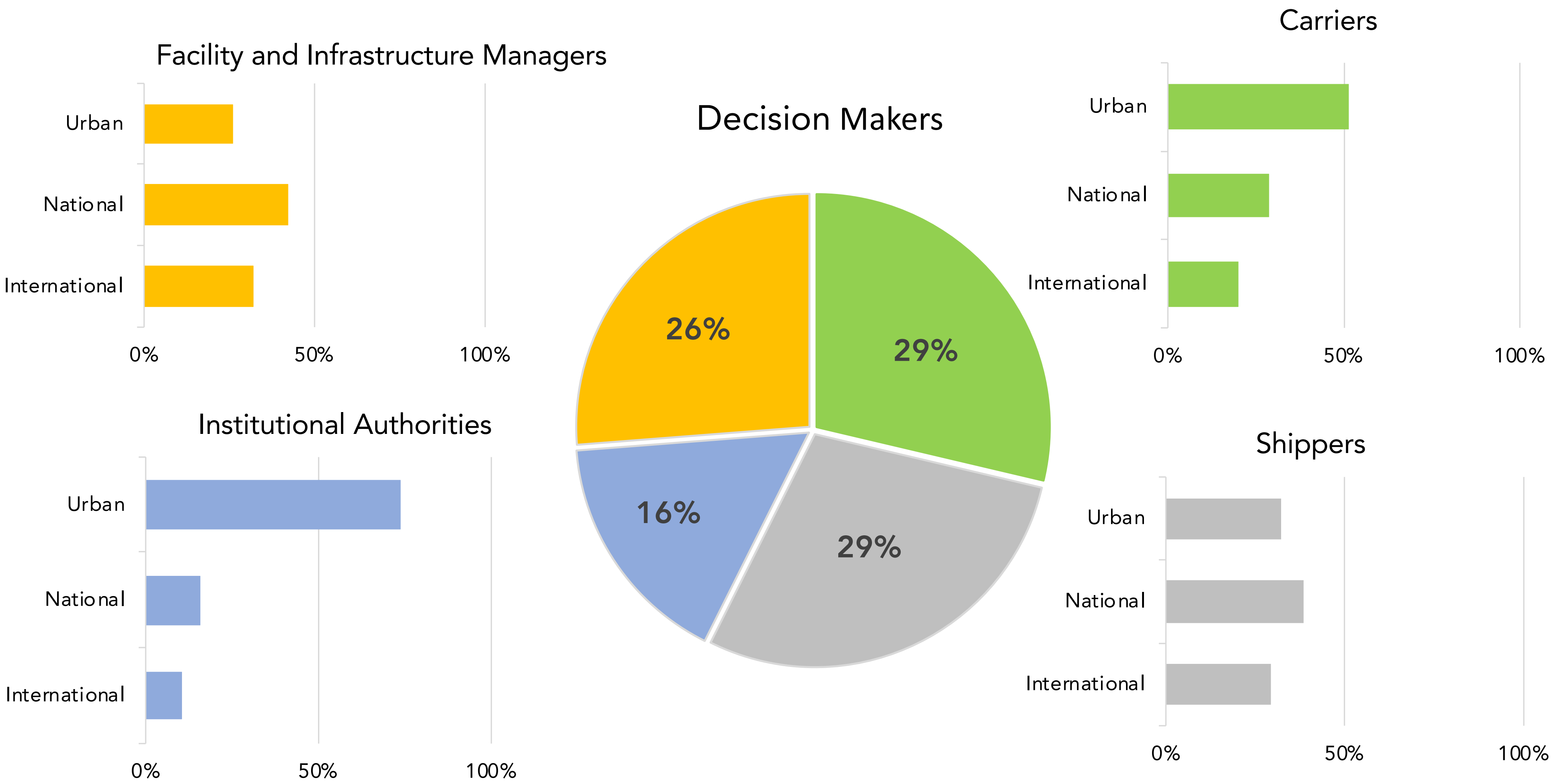
Simulation Method			Scope	
Numerical	Optimization	Simulation Optimization Relation	Simulated Objects	Simulation Objectives
Static-Deterministic	*Static-Deterministic*	*OSI*	*Behaviors and Interactions*	*What If*
Static-Stochastic	*Static-Stochastic*	*SOI*	*Flows*	*Forecasting*
Dynamic-Deterministic	*Dynamic-Deterministic*	*SSO*	*Static Scenario*	*Validation*
Dynamic-Stochastic	*Dynamic-Stochastic*	*ASO*	*Events*	*Enhancement*
		Simulation		

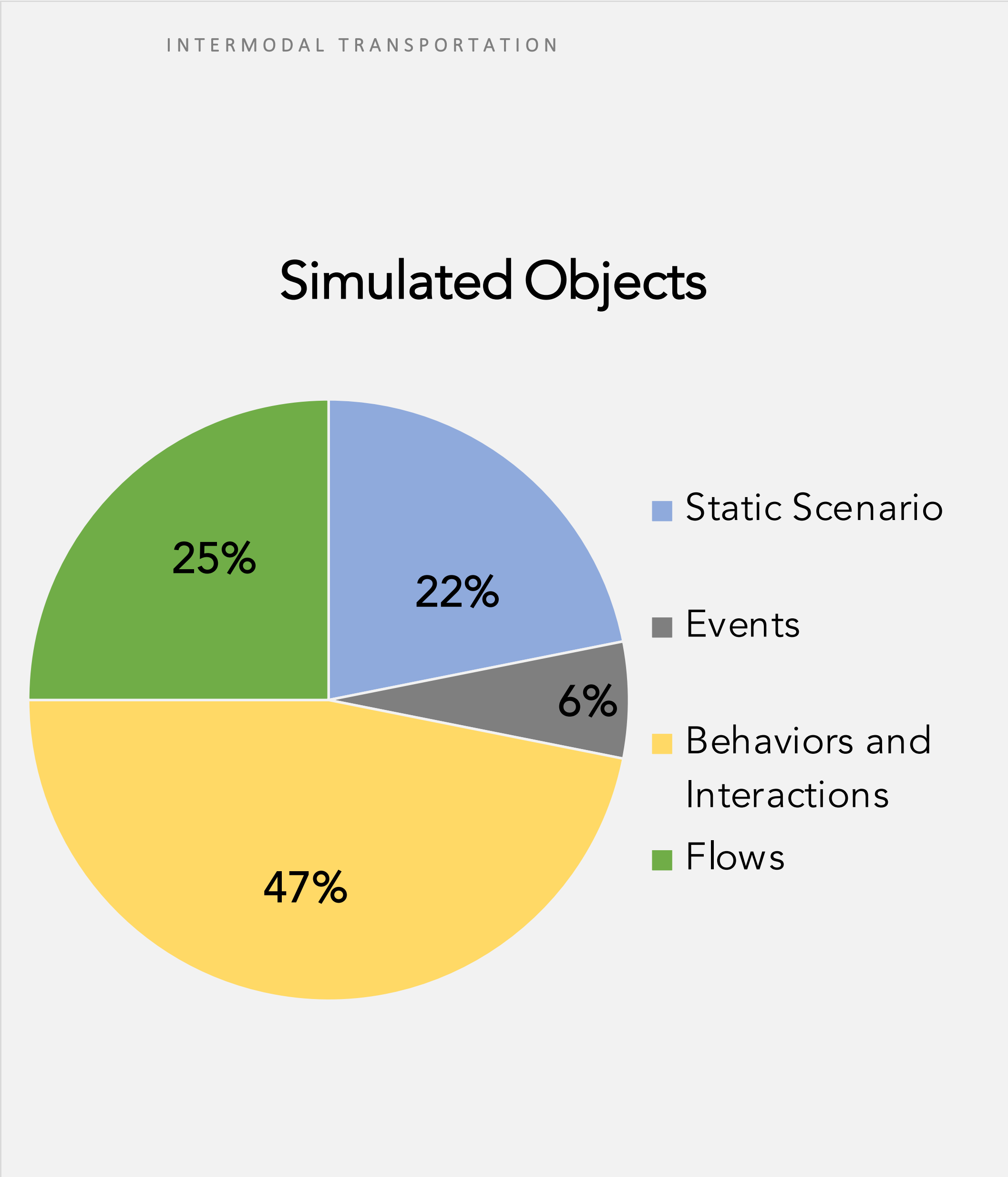
89 papers reviewed

Discussion of results

I. Need for new models, methods and tools to represent the complete system

- Public, individuals and freight transportation companies are modeled and optimized as separate systems
- Infrastructure and facility managers, and institutional authorities the most considered actors (42% of papers)
- Particularly at the national level
- Consider new business and organizational frameworks (e.g., Hyperconnected systems, Logistics 4.0)


Facility and Infrastructure Managers
Urban
National
International
0%
50%
100%
Institutional Authorities
Urban
National
International
0%
50%
100%
Decision Makers
26%
29%
16%
29%
Carriers
Urban
National
International
0%
50%
100%
Shippers
Urban
National
International
0%
50%
100%

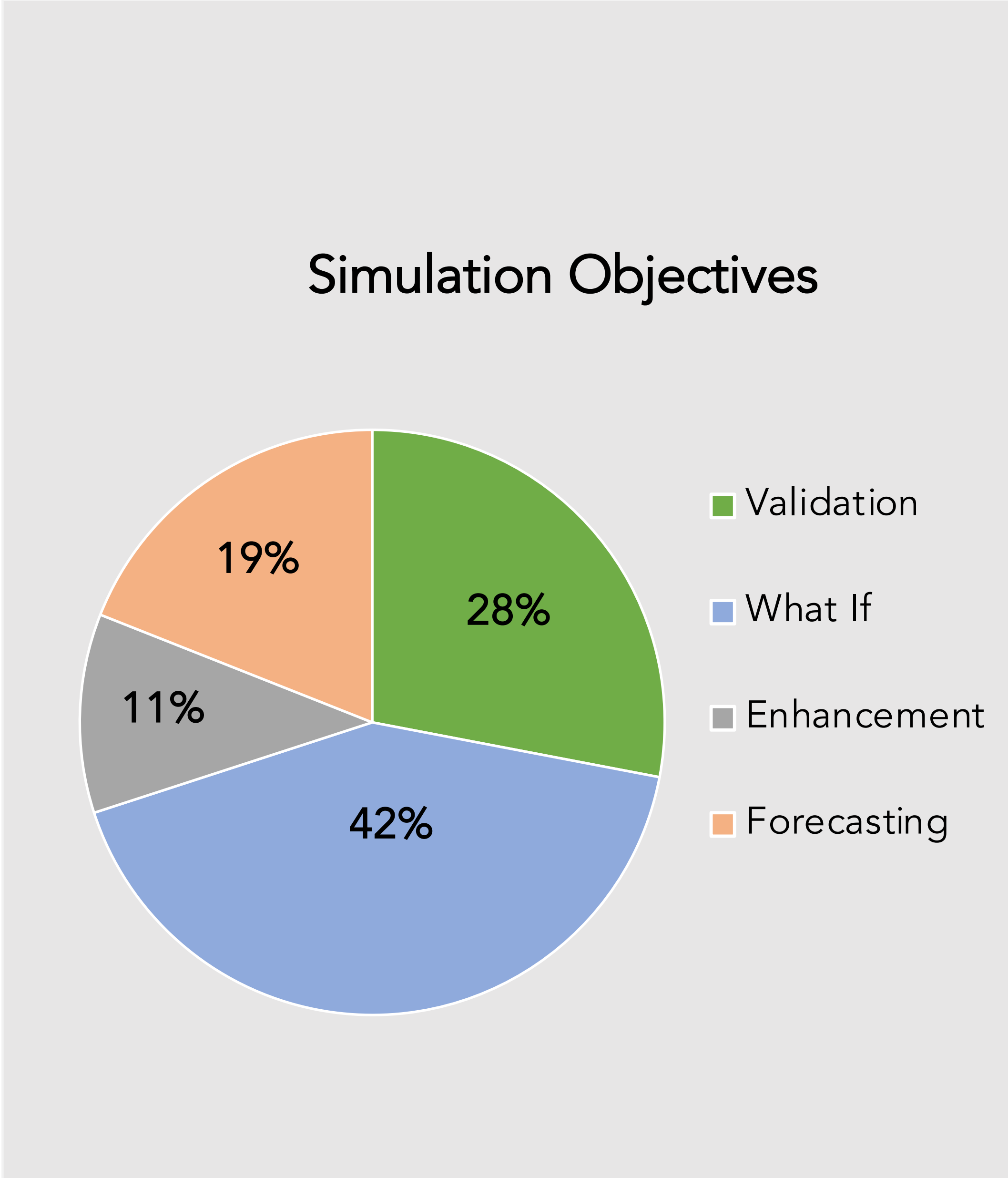


II. Need for more detailed and flexible models, and better integration of simulation and optimization

- Simplified description of the system
- Approach used in network representations and multi-agent simulations
  - Simulate the dynamic behavior of carriers, retailers or shippers
  - No significant presence of citizens and local authorities

III. Need for tools supporting policy makers

- Few studies address policy-making processes
- Incorporate into simulation and optimization tools a managerial perspective and, business and operational models.



TAKE AWAY

Need of a more comprehensive methodology that encourages qualitative and quantitative researchers from different communities to "speak" a common language. The aim is to support the policy-making process, considering all the stakeholders.

Multi-disciplinary approach

The GUEST Methodology

BEHAVIORAL ANALYSIS

Actors involved	5 Ws + H
Business models	Urban context

ECONOMIC ANALYSIS

Economic feasibility	Sustainability
Monitoring	

TECHNOLOGY SCOUTING

Technology type	Technology transfer
Optimization	Methods & models

DECISION PROCESS

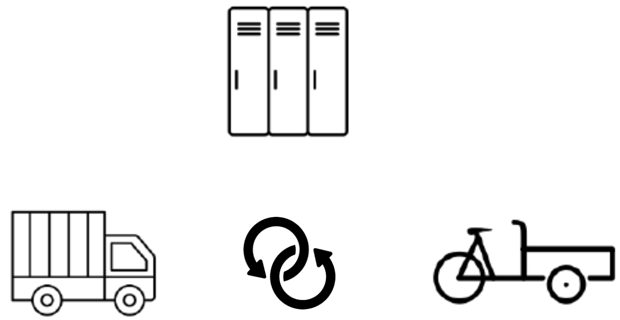
Evaluation	Public & Industrial policies

Multi-disciplinary approach

- Benefits and Contribution to the community:
  - automatic decision-making process
  - integration of real data from the context
  - integration of niche methodology and models
  - improve communication between technical and non-technical staff or with different expertise
  - actor-centric approach

1st Use Case

Mixing traditional and green business models



Problem description

- Last mile segment of the supply chain (expensive, pollutant, inefficient)
- Introduction of new delivery options and green vehicles (e.g., cargo bikes, electric vehicles, lockers)

Is this integration easy and always positive?

Mitigate effects of reducing marginal revenues

Reduce environmental issues

Increase efficiency of delivery activities

Multi-disciplinary approach

Holistic vision of the system

Go

- Full description of the stakeholder's profiles

Uniform

- Representation of relationships and interconnection
- Analysis of the business models

Innovative research and approach

Evaluate

- Cost and revenues structures analysis
  - Economic costs related to the operations
  - Social costs related to the environment
- Performance analysis

Solve

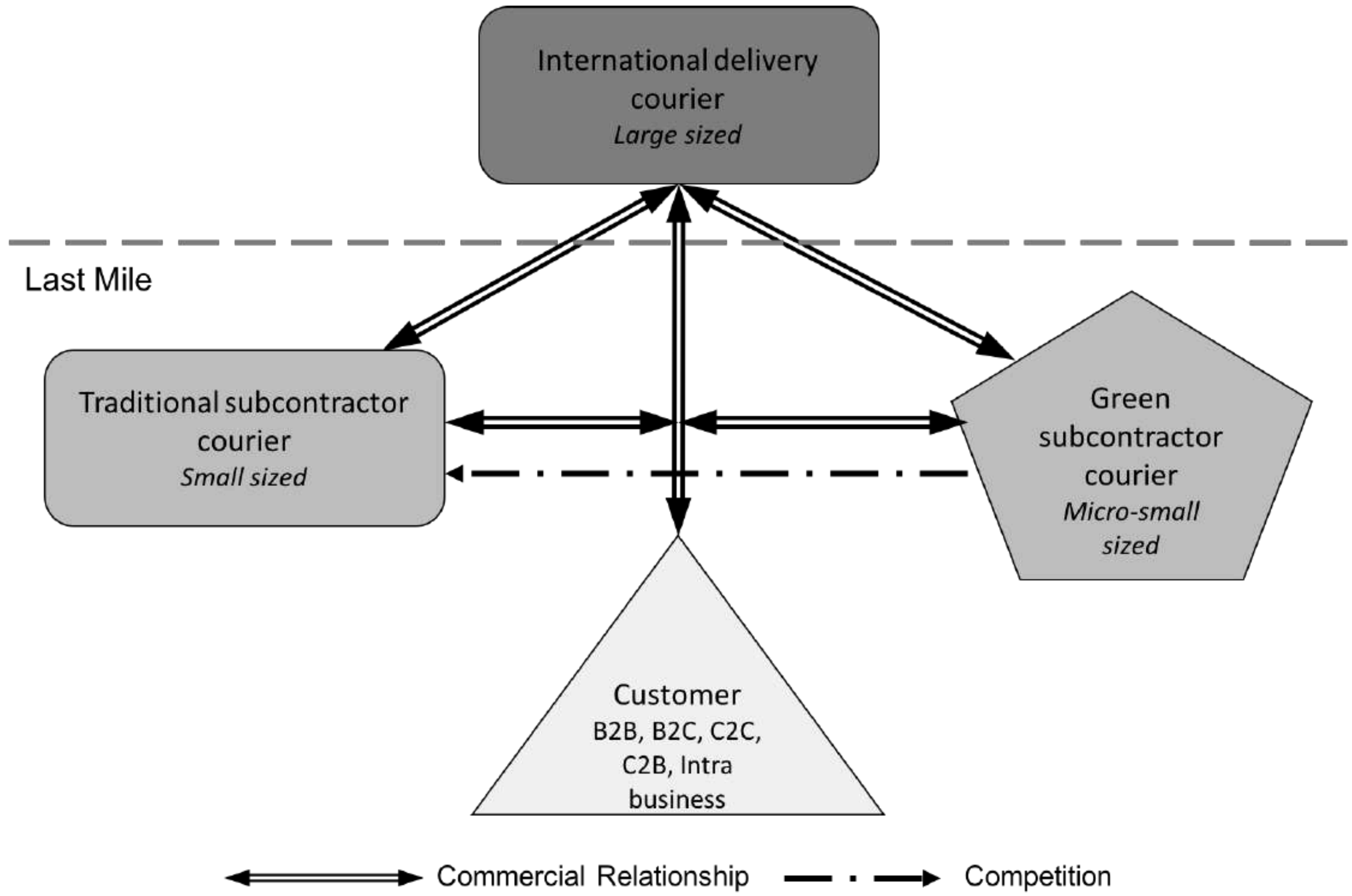
- Monte Carlo simulation
- Optimization

Test

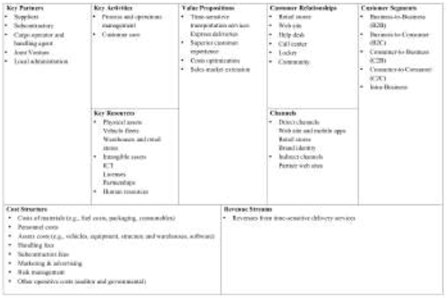
- Tests and deriving mixed-fleet policies

Qualitative + Quantitative analyses

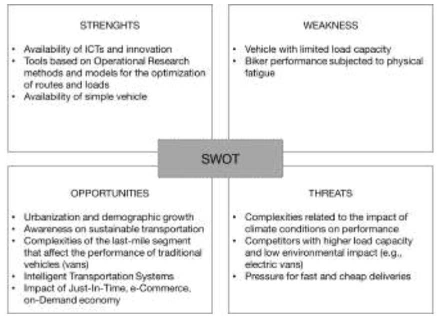
Parcel delivery business model analysis

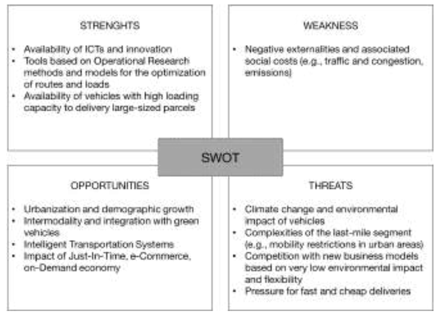


Business Models and SWOT Analysis



- Time sensitive deliveries
- Environmental impact:
  - Weakness for the traditional courier
  - Opportunity/Value proposition for the green courier
- Income from CO2 savings and carbon trading
- Vehicle as the main item of the cost structure
- Risk of cannibalization between models





Cost efficiency analysis of vehicular and cargo bike delivery

Operating costs

- Purchase cost of vehicles
- Vehicle taxes
- Personnel costs
- Fuel, insurance, tire costs
- Maintenance and repair costs

$$TCK = (OPC + OWC)/TK$$

Environmental costs

- Carbon tax

ISO-TS 14067:2013

Direct Indirect Equivalent

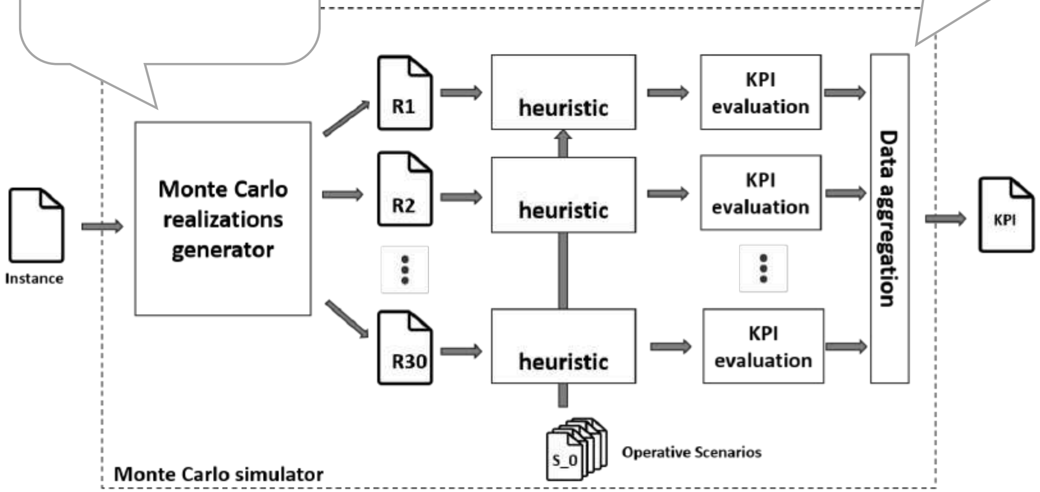
Cost efficiency analysis of vehicular and cargo bike delivery

Costs	Tariffs Carbon Tax [€/tons]	Fossil fuel vehicle [€]	Diesel fuel vehicle [€]	Electric vehicle [€]	Bike [€]
TCK [€/km]					
Annual kilometer cost		2.70	2.68	2.66	1.50
Environmental costs [€]					
Direct CO2 Emissions [tons]		4.15	3.38		
Indirect CO2 Emissions [tons]		4.15	3.38		
Equivalent CO2 Emissions [tons]		8.46	5.52		
Total Emissions [tons]		16.76	12.28		
Carbon Tax [€]	17.00	284.92	208.63		
	30.00	502.80	368.18		
	90.00	1508.40	1104.53		
	150.00	2514.00	1840.88		
Electric Battery Emissions [tons]				3.08	
Carbon Tax [€]	17.00			52.31	
	30.00			92.31	
	90.00			276.94	
	150.00			461.56	
Direct CO2 Emissions [tons]					0.00

Simulation

Monte Carlo simulation

Data aggregation and analytic module



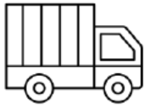
Last-mile optimization meta-heuristic

- Instance creation (n. parcels, volume, type)
- Creation of 30 realizations R with different destinations
- For each $r \in R$ build a VRP
- Scenario evaluation
  - optimization algorithm by Ropke and Pisinger (2006)
  - ruin and recreate paradigm
- Data aggregation module geo-references the routes and computes the fleet KPIs

Scenarios

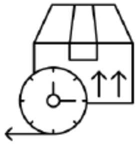
S_0	-	All
S_3_C	Mailers Center	Mailers Semi center Small + Large parcels
S_3_S	Mailers Center + Semi center	Small parcels + Large parcels
S_5_C	Mailers + Small parcels Center	Small parcels Semi center Large parcels
S_5_S	Mailers + Small parcels Center + Semi center	Large parcels

Key Performance Indicators



Equivalent Vehicles

- The number of equivalent vehicles used by the subcontractors.



Number of parcels delivered per hour

- It expresses the efficiency of a courier.

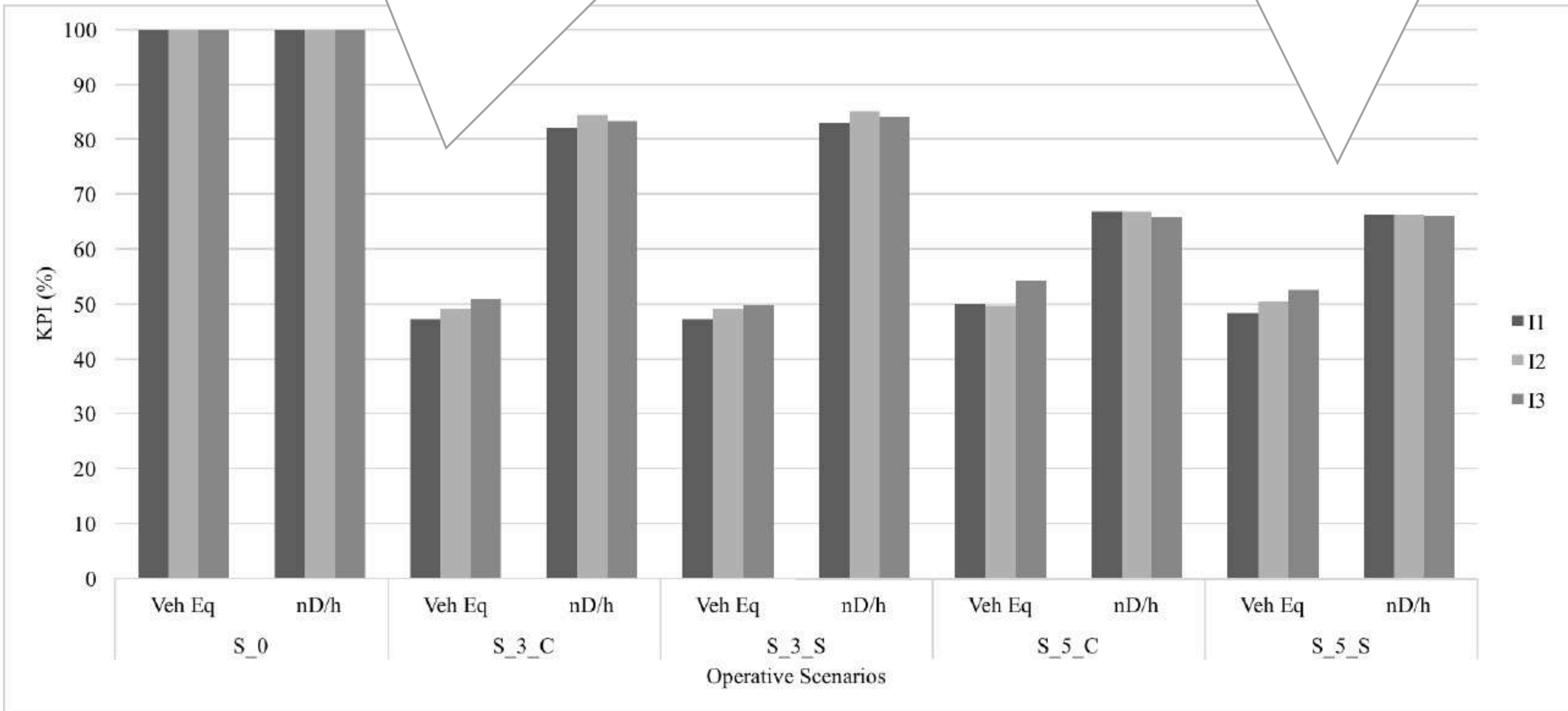
CO_2 savings

- Kilograms of CO_2 not emitted using green vehicles.

Results

The number of Eq.Veh is reduced by half

Loss of efficiency of the traditional courier
- Large parcels to handle
- Vans capacity saturate quickly
- Long distances



What happens if we introduce lockers and on-line requests?

- Analysis of the integration of vans, cargo bikes and lockers
- Tests in realistic urban scenarios
  - Answer to two lacks in the literature
    - unavailability of full data
    - difficulty of combining/reusing existing data
    - recently TRL = 6
- Simulation-optimization framework

Simulation-optimization framework

Operational context description:

- Describe the problem
- Different types of data sources

Scenario generation and simulation:

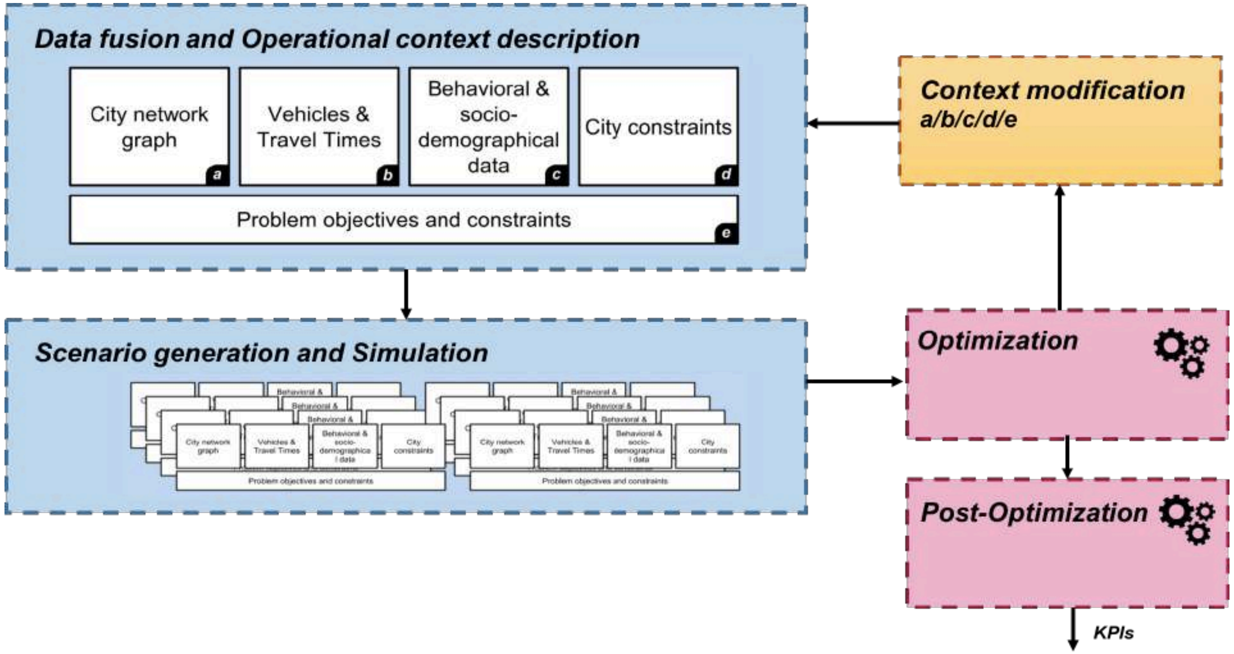
- Monte Carlo simulation
- City scenario as operational day

Optimization and post-optimization:

- Mathematical model (Pyomo)
- VRPTW with the load balancing
- Stochastic TSP
- Dynamic & Stochastic VRPTW

Context modification:

- Reiteration of steps 2 to 4



Simulation-optimization framework

- Optimization and post-optimization:

Economic sustainability

- Cost per stop

Environmental sustainability

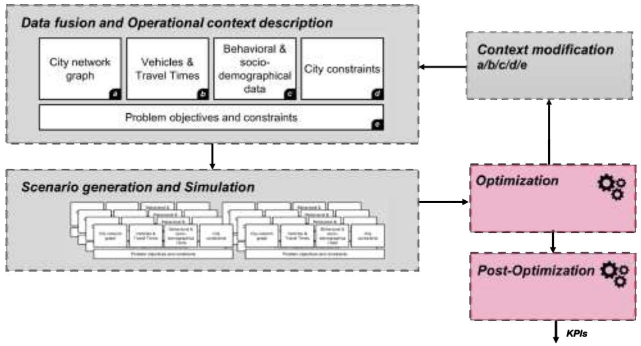
- CO_2 savings

Operational sustainability

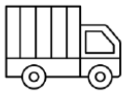
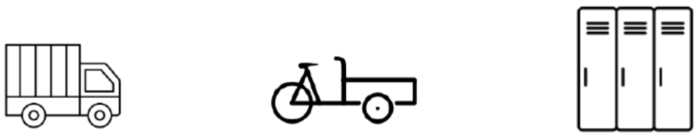
- No of deliveries/hours

Social sustainability

- Working conditions of drivers



Benchmarks

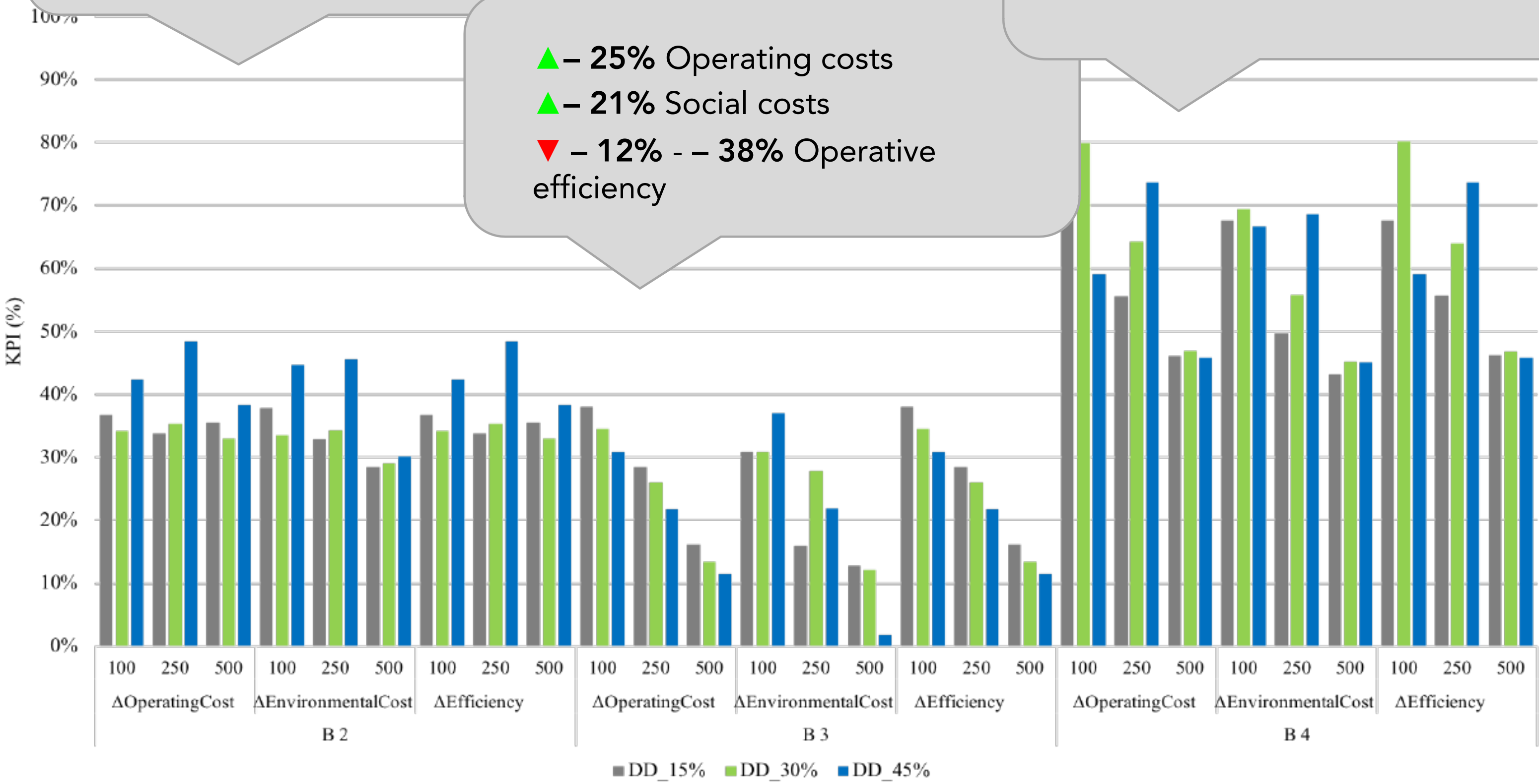
- **B_0** 
- **B_1** 
- **B_2** 
- **B_3** 

Results

▲– **37%** Operating costs
▲– **40%** Social costs
▼– **7%** - – **80%** Operative efficiency

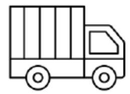
▲– **25%** Operating costs
▲– **21%** Social costs
▼ – **12%** - – **38%** Operative efficiency

▲– **60%** Operating costs
▲– **57%** Social costs
▲ ▼Inefficient usage of vehicles

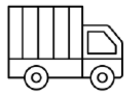


Suggested policies

- When the fleet is internal
  - 0-3 kg in center and semi-center
  - 3-5 kg in center
  - 3-5 kg in semi-center
  - >5 kg in center and semi-center



- When the fleet is external
  - 0-3 kg in center and semi-center
  - >3 kg in center and semi-center
  - New contractual schemes are needed
  - Internalize the cargo-bike fleet



TAKE AWAY

Although green vehicles and new delivery options are beneficial for the environment, their adoption must be carefully assessed and supported by a continuous process of planning.

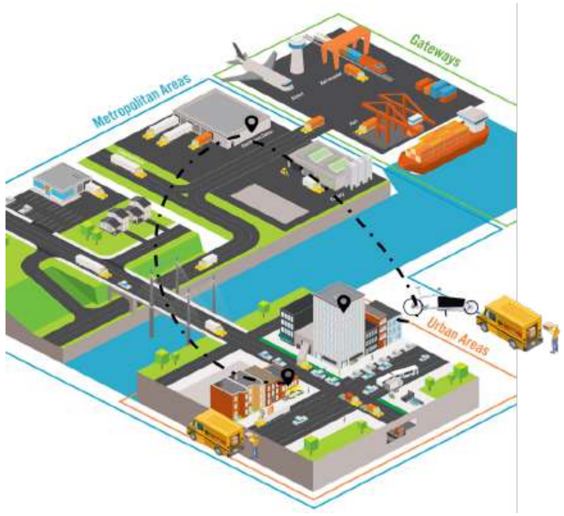
2nd Use Case

Tactical capacity planning

Tactical capacity planning

- The outsourcing of logistics activities in the last mile segment makes needed a complex planning activity
- Enterprises answer to the growing requests for fast and cheap deliveries of goods
- Need of securing/contract sufficient distribution capacity in the next period of activity

- Could we draw managerial insights?



Problem description

- Multiple-types Capacity
  - Transportation capacity
    - containers, ship or train slots, motor carrier tractors
    - vans, cargo bikes
    - different transportation modes
- Warehousing capacity
  - Warehousing space
- Bins as capacity unit
  - different types and characteristics (e.g., size, cost, thermal or refrigerated)
- Item as demand load unit
  - different characteristics (e.g., size)
  - must be packed into the available bins for shipment or storage

Modelling framework

- Tactical decision level: contract now for the future

- Uncertain environment
    - Demand fluctuation
        - number and characteristics of items e.g., weight, size
    - Additional (future) capacity, when needed
        - cost and availability in the spot-market
    - Availability of contracted capacity
        - number and characteristics, e.g., cost and volume
        - total or partial unavailability at the shipping day
        - characteristics of the transportation mode and the service considered could determine capacity restrictions e.g. mechanical failures, different characteristics of items, undelivered parcel

- Actual volume of contracted capacity must be considered **stochastic**

Modelling framework

- Tactical decision level: contract now for the future
- Uncertain environment
  - Demand fluctuation
    - number and characteri
  - Additional (future) capa
    - cost and availability in
  - Availability of contracte
    - number and characteri
    - total or partial unavaila
    - characteristics of the capacity restrictions e parcel

etermine
delivered

Gap in the literature

- Few papers address tactical and strategic planning applications
- Framework that considers these different sources of uncertainty in capacity planning, applicable to both contexts (long-haul transportation and urban distribution)
- Uncertainty on the availability of contracted capacity has not been addressed before in the literature

- Actual volume of contracted capacity must be considered **stochastic**

Modelling framework

- Stochastic Variable Cost and Size Bin Packing Problem with Capacity Loss SVCSBPPL
- Two-stage stochastic programming formulation with recourse
  - First stage: tactical decisions
    - selection a priori of the capacity to be made available
  - Second stage: operational decisions
    - recourse actions
      - acquisition of additional capacity on the spot market
      - rearranging the loads or the storage of goods
- Solution strategy
  - Progressive Hedging heuristic (Rockafellar and Wets, 1991; Crainic et al., 2016)

Modelling framework

First Stage

Second Stage

$$\min_{y} \sum_{t \in T} \sum_{j \in \mathcal{J}^t} f^t y_j^t + E_\xi\left[Q(y, \xi(\omega))\right]$$

$$\text{s.t.} \quad y_j^t \geq y_{j+1}^t, \qquad \forall t \in T, j = 1, \ldots, |\mathcal{J}^t| - 1,$$

$$y_j^t \in \{0, 1\}, \qquad \forall t \in T, j \in \mathcal{J}^t.$$

j = 1st stage bin
t = bin type

f^t = fixed cost of bin of type t
y^t_j = 1 if bin j is selected

$\xi(\omega)$ = realization of the random vector of all the stochastic parameters

(1) Total fixed cost of the tactical capacity plan, and expected costs of extra capacity and to adjust the plan ($E_\xi[Q(y, \xi(\omega))]$)

(2) Constraint to break the symmetry of the solution

(3) Integrality requirement on first-stage variable

Modelling framework

First Stage

Second Stage

k = 2nd stage bin
i = item

$$Q(y,\xi(\omega)) = \min_{z(\omega),x(\omega)} \sum_{\tau\in\mathcal{T}} \sum_{k\in\mathcal{K}^{\tau}(\omega)} g^{\tau}(\omega) z_k^{\tau}(\omega) + \sum_{t\in T} \sum_{j\in\mathcal{J}^t} c^t (V^t - V_j^t(\omega)) y_j^t \qquad (5.4)$$

$$\text{s.t.} \quad \sum_{j\in\mathcal{J}} x_{ij}(\omega) + \sum_{k\in\mathcal{K}(\omega)} x_{ik}(\omega) = 1, \qquad \forall i \in \mathcal{I}(\omega), \qquad (5.5)$$

$$\ldots(\omega) y_j^t, \qquad \forall t \in T, j \in \mathcal{J}^t, \qquad (5.6)$$

$$\ldots z_k^{\tau}(\omega), \qquad \forall \tau \in \mathcal{T}, k \in \mathcal{K}^{\tau}(\omega), \qquad (5.7)$$

$$x_{ij}(\omega) \in \{0,1\},$$
$$x_{ik}(\omega) \in \{0,1\},$$
$$z_k^{\tau}(\omega) \in \{0,1\},$$

g^{τ} = cost of extra bins
c^{t} = extra cost to rearrange the load
$V^{t}_{j}(\omega)$= actual volume of 1st stage bins

$x_{ij}(\omega)$ = 1 if item i is packed in bin j
$x_{ik}(\omega)$ = 1 if item i is packed in bin k
$z^{\tau}_{k}(\omega)$ = 1 if bin k is selected

(4) Total cost of extra bins and addit

(5) Each item is packed in a single bin

(6) and (7) Total volume of items packed into each bin does not exceed the bin volume

(8) to (10) Integrality requirements on second-stage variables

Managerial insights

Goals:

- Is considering the loss of capacity (actual volume of bins as stochastic) relevant in our contexts?
- What is the impact of uncertainty? Is it useful to build a stochastic programming model?
- Which is the relationship between the problem characteristics and the structure of the capacity plan?

Experimental plan

SET B
Without reduction of booked capacity

- 180 instances
- Number and volume of items
- Number of bins
- Availability of bins
- Cost of bins

SET T
With reduction of booked capacity

- 51840 instances
- Number and volume of items
- Number of bins
- Availability of bins
- Cost of bins
- Actual volume of first-stage bins
- Extra cost due to the loss of a unit of contracted capacity

TAKE AWAY

Managing uncertainty and having information in advance about the future is valuable, rather than the wait and see approach

Managerial insights

- EVPI is always greater than 8%
  - Particularly when the availability of extra bins is limited and costs of second stage bins is high
    - EVPI reaches a maximum value of 77%
- Gap between deterministic and stochastic models is always significant
  - VSS between 4.93% and 18%
- Enhancement from considering actual volume of bins as stochastic
  - VSS Without 6%
  - VSS With 12%

TAKE AWAY

The structure of the capacity plan is affected by:
- probability of suffering from a reduction of available capacity (TL)
- type of losses
- entity of losses (BL)

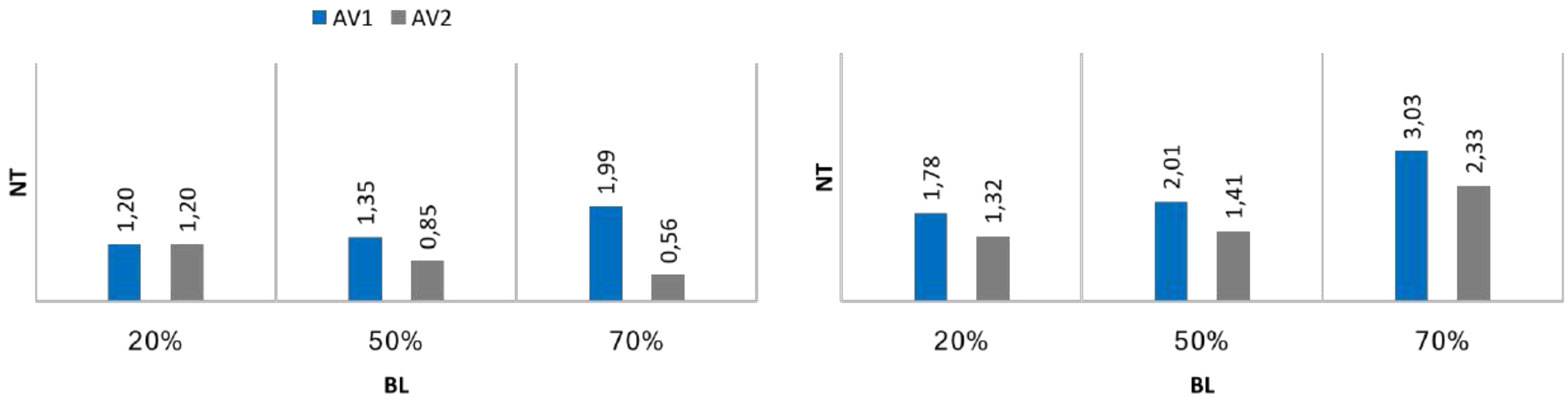
70% vs 30%

Managerial insights

- Uniform Losses (Long-haul)
  - Almost all capacity is booked in advance
    - Average CapFS > 69 %
    - Peak CapFS 83% when few types of extra bins with limited availability
  - More capacity is booked than needed
    - High probability of loosing a great amount of capacity (BL =70% and TL = 100%)
  - No capacity is booked in advance
    - CapFS = 0 % (BL =60-70% and TL = 100%)
    - High probability of loosing a great amount of capacity availability of extra bins is not limited

Managerial insights

- Localized Losses (Urban)
  - Same capacity as that one would buy without loss but with different types of bins
    - 2 types (T3)
    - 3 types (T5)



Conclusions

- Paradigm shifts due to the ecommerce
- Need to find factual solutions to the urban freight transportation issues
- Rethink and Optimize the urban freight transportation through tools for the policy assessment
  - Not only technology and models
  - Qualitative tools for a global vision of the system
  - Simulate *in silica* the whole system and then decide

Future research

- How the dynamics change after introducing other green vehicles or unprofessional users ”Uberization of the last-mile”?
- Capacity planning problem with carriers selection

Other activities

- Other research frameworks:
  - Startup failure
  - Smart Cities
- PhD Visiting at CIRRELT (Canada)
- Teaching activity

Thank you
for your attention