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MULTILOG PROCEEDINGS
CONNECTED CORRIDORS IN A FRAGMENTED WORLD

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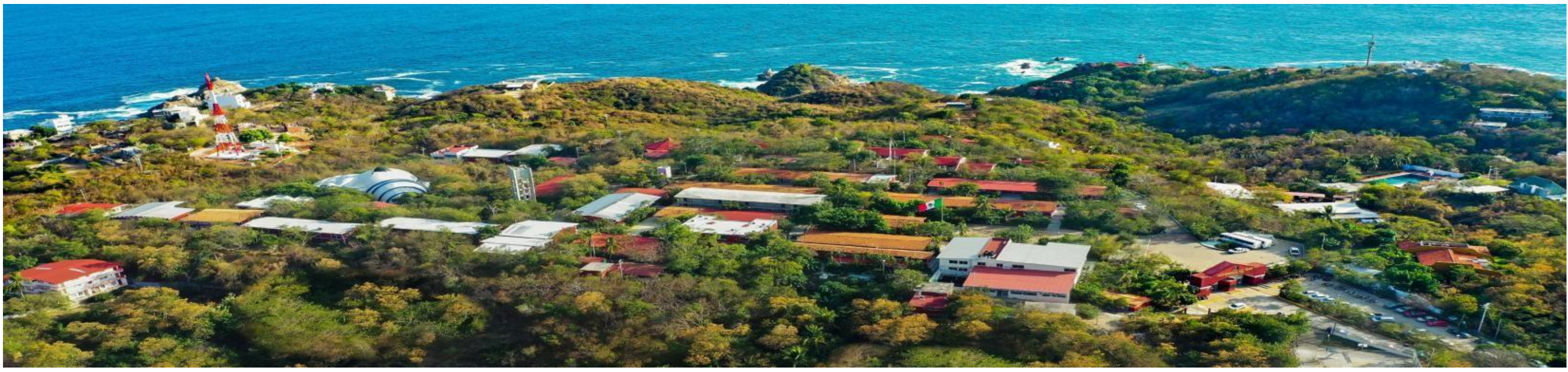

Preface Multilog 2025

Connected Corridors in a Fragmented World

The 2025 edition of the Multilog Conference is framed by the theme Connected Corridors in a Fragmented World. This theme reflects the growing mismatch between increasingly interconnected transport and logistics systems and a global context characterized by geopolitical uncertainty, climate pressures, supply chain disruptions, and uneven technological development. Today's systems must remain functional, resilient, and sustainable even when operating under fragmentation, partial connectivity, and degraded conditions.

The papers collected in the Multilog 2025 proceedings address these challenges through a strong focus on modeling, simulation, and data-driven decision-support. Rather than assuming fully integrated and globally optimized networks, the contributions analyze transport, logistics, and mobility systems as interconnected systems of systems, where infrastructure, digital technologies, human behavior, and governance interact dynamically.

Several recurring themes emerge. A first group of contributions focuses on resilience and disruption management, particularly in supply chains and port systems, demonstrating how simulation, digital twins, and scenario-based approaches can support proactive mitigation of disruptions and cascading failures. A second thematic cluster addresses automation and internal logistics, with studies on AGV systems, metamodeling, and multi-objective optimization aimed at supporting design and operational decisions. A third area concentrates on sustainability and environmental performance, including decarbonization strategies, electromobility, and emissions modeling using system dynamics. Finally, a number of papers highlight the growing importance of advanced data sources and intelligent analytics, such as mobile network data for urban mobility planning or passenger-centric optimization in airport operations.

Across these domains, a clear methodological convergence is visible. Simulation is increasingly used not only for evaluation, but as a central component of decision-support systems and digital twins that integrate data, behavior, and policy. The contributions show how these approaches enable stakeholders to explore scenarios, test interventions, and reason under uncertainty in complex, real-world settings.

Multilog 2025 also underscores the changing skill requirements for professionals in transport and logistics. The ability to work across abstraction levels, combine modeling with data analytics, and translate technical results into actionable insights is becoming essential as systems grow more complex and interdependent.

The Multilog conference series continues to provide a platform for dialogue between academia, industry, and public institutions, fostering shared understanding of emerging challenges and solutions in transport and logistics.

We thank Universidad del Mar for hosting the 2025 edition of Multilog, the Scientific Committee for their rigorous reviews, and the authors and Local Organizing Committee for making this edition possible.

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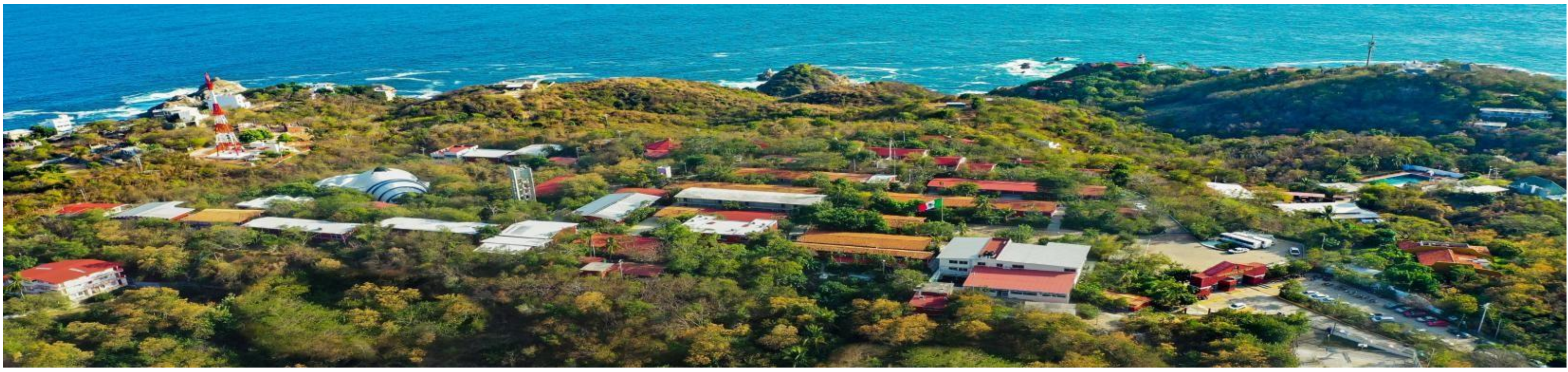

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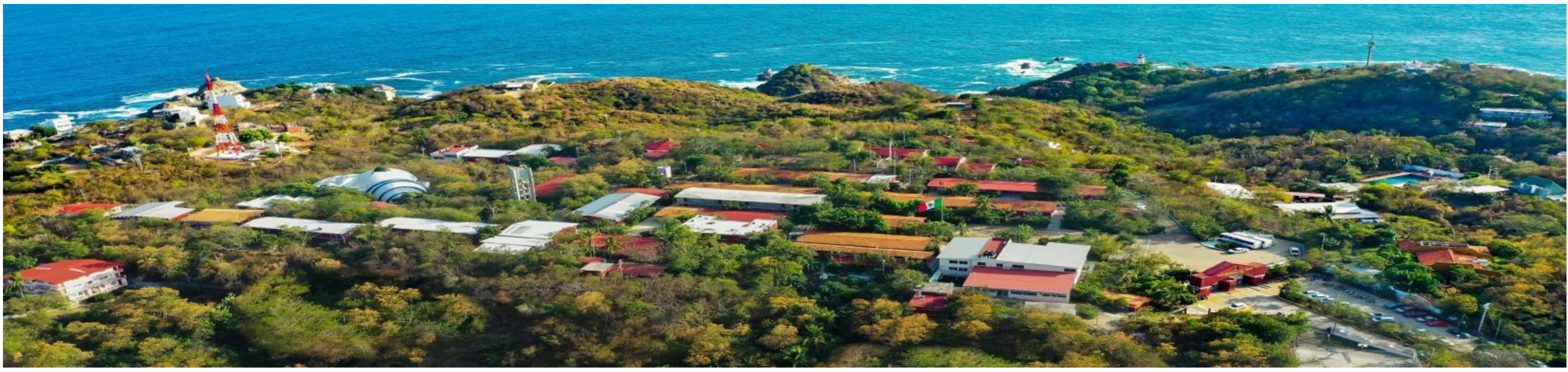

1- Sustainable Mobility and Environment

- **Analysis of CO2 emissions from electric and internal combustion vehicles using a systems dynamics approach to measure CO2 emissions over time.**
  - Gonzalo Paul López Cruz
  - Salvador Hernández González
  - José Alfredo Jiménez García
  - Edgar Augusto Ruelas

- **Sustainable mobility as Saltillo's new competitive driver**
  - Mónica Castañeda Chavez
  - Luisa de Moura Chaves
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Analysis of CO2 emissions from electric and internal combustion vehicles using a systems dynamics approach to measure CO2 emissions over time.

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***Resumen*—The study conducted in this research is important for gaining a more robust understanding of the development of electromobility in Mexico. It is expected that these models will lead to a reduction in greenhouse gas emissions, specifically in the CO2 emissions generated by these vehicles in the coming years. One way to obtain this information is through System Dynamics, which helps us model the system encompassing hybrid (HEV), electric (EV), and internal combustion engine vehicles (ICEs), the vehicles studied in this project. Using this mathematical model, we will model a CO2 emissions system for vehicles (HEV, EV, and ICE). This system aims to project the future emissions of these vehicles over a 20-year period. The model is based on vehicle sales since 2016. This starting point will allow us to compare the current emissions of each vehicle with their projected emissions in the coming years. The research will give us a clear answer as to whether there will be a decrease in CO2, whether it will remain the same or increase over time.**

Autor keywords; Electromobility, Sustainability, Systems dynamics

I. INTRODUCCIÓN *(TÍTULO 1)*

The shift towards electromobility has generated various challenges in achieving adaptability. This is due to the global dependence on fossil fuels in transportation, which compromises the progress, economy, and social well-being of countries that do or do not possess this non-renewable natural resource. Therefore, the automotive industry offers various electric propulsion models, such as hybrid electric vehicles (HEVs), electric vehicles (EVs), and plug-in hybrid vehicles, in order to reduce the burning of fossil fuels. Mexico is one of the countries embarking on this necessary change to reduce greenhouse gas (GHG) emissions. Currently, internal combustion engine (ICE) vehicles predominate in the vehicle fleet, which is alarming because greater electromobility is expected over the years. This has raised questions about whether there will truly be a decrease in CO2 emissions, since transportation is one of the most polluting sectors. It also raises questions about whether there will be a decrease in internal combustion engine vehicles and an increase in electric propulsion vehicles. Therefore, this document studies vehicle fleet sales trends, evaluating the CO2 emissions produced by automobiles using systems dynamics, allowing for the modeling of the CO2 emissions system over time. This study includes ICE, EV, and HEV, calculating CO2 emissions over time periods.

BACKGROUND

Systems Dynamics formally emerged with the work of Jay Wright Forrester, a professor at MIT. He developed an approach that understands the behavior of complex systems through feedback loops, stocks, and flows. The central idea was that many organizational problems do not stem from external

factors, but rather from the system's internal structure and the way its elements interact dynamically [2]. Forrester extended this approach to other contexts, specifically cities. In Urban Dynamics, he demonstrated how well-intentioned policies can generate counterproductive effects due to time lags and emergent behaviors. It became a tool for analyzing policy, urban growth, poverty, housing, and transportation [3].
Carbon dioxide (CO_2) emissions from transportation have increased since the 20th century, driven by the growth of motorized transport and dependence on fossil fuels. Currently, it accounts for about a quarter of global energy emissions, and its upward trend continues due to increased mobility and urbanization [12].

II. HERRAMIENTAS Y MÉTODOS

Systems dynamics allows for the modeling of complex systems over time. This model helps to understand, organize, and develop the causes that influence the system's behavior. It requires the application of four phases: conceptualization, data collection, formulation, and evaluation.
In the first phase, the problem is explained. How this problem will be solved is also proposed. Relevant concepts and data are presented to aid in understanding this research. In the second phase, data is collected to model a dynamic system. This information is required to understand the system, feed the mathematical model, and create the Forrester diagram. Sometimes, this involves calculations in obtaining the data. The third phase is divided into two parts. The first is the development of the Forrester diagram. Consequently, the equations that will model the CO_2 emissions system are developed. Finally, there is the evaluation, which is the simulation of the model, obtaining the results of the projected emissions over time.

III. CONCEPTUALIZATION

Electromobility began in Mexico in 2016 when the National Institute of Statistics and Geography (INEGI) published its first sales figures for electric vehicles. These sales figures are fundamental because they mark the beginning of this study. Furthermore, these sales allow us to visualize the demand for these vehicles (HEV, EV, and ICE), as shown in Table 1.

Table 1. Vehicle sales in Mexico

Time	HEV	EV	ICE
2016	7490	254	1,598,900
2017	9349	237	1,524,389
2018	16022	205	1,517,040
2019	23964	305	1,292,119
2020	21970	449	925,658
2021	42447	1140	902,984
2022	40859	5631	898,998
2023	54368	14172	875,745
2024	92026	24283	825,760

The table shows that sales of internal combustion engine vehicles are decreasing, unlike those of electric vehicles, which are growing very slowly [9]. With this information, planning for the replacement of internal combustion engine vehicles becomes a complex task, since the rationale behind electric vehicles is to mitigate greenhouse gas (GHG) emissions. Therefore, the importance of this research lies in determining whether there will actually be a decrease in GHG emissions in the transportation sector in the coming years. Consequently, using Systems Dynamics, this study proposes to specifically examine the CO_2 emissions of internal combustion engine vehicles, hybrid vehicles, and electric vehicles based on sales figures recorded in Mexico, projecting these emissions over a 20-year period.

IV. DATA COLLECTION

The INECC (National Institute of Ecology and Climate Change) developed emission factors (EF) for the main fuels consumed in Mexico, which are necessary for this research. Gasoline is considered with a factor of 2.322 kg CO_2/L of fuel [7].The emission factor for calculating indirect greenhouse gas emissions from electricity consumption is essential for EVs. The figure obtained by the national electricity system is 0.438 tCO_2/MWh [13]. It is important to mention that the INECC stipulates an average annual distance traveled by a vehicle of 15,000 km [1].
The first step is to gather historical vehicle sales data, presented in the table above. Subsequently, a summary of the best-selling vehicle models is compiled, starting with 2016 models, the first year for recording electric vehicle sales, and continuing with 2019 models. Therefore, HEV, EV, and ICE (Internal Combustion Engine) models are presented in Tables 2, 3, and 4.

Table 2. ICE model sales

	ICE 2016		ICE 2019	
	Vehicle	Sales	Vehicle	Sales
1	Versa	90543	Versa	88707
2	Aveo	80052	Aveo	70947
3	Vento	63201	Beat	70114
4	Spark	60598	NP300	62989
5	Jetta	60561	March	49493
6	March	55918	Vento	47179
7	Tsuru	49337	Rio Sedan	26132
8	Sentra	45977	Sentra	21904
9	Sonic	49305	Jetta	20469
10	Xtrail	30488	CR-V	19069
11	Trax	26777	kicks	17837
12	NP 300	23516	Forte	17712
13	Attitude	20356	Hilux	17654
14	CR-V	19161	HR-V	17175
15	Sportage	18772	Sportage	15876
16	HR-V	18603	Trax	15250
17	Tida	17830	Figo	14663
18	Figo	17703	3 Sedan	14553
19	3	17443	Tiguan	14548
20	City	16286	RAV4	13913
21	Gol	15419	CX-5	13742

22	Gol Sedan	9533	Xtrail	13415
	Total	**807379**	**Total**	**663341**
	% of total	**50.4959**	**% of total**	**51.3375**

Table 3. HEV model sales

	HEV 2016		**HEV 2019**	
	Vehicle	**Sales**	**Vehicle**	**Sales**
1	Prius	6560	Prius	5966
2			Ioniq	1615
3			Niro	1334
4			Insight	638
5			Fusion	209
6			MKZ Lincoln	60
7			Escape HEV	13
	Total	**6560**	**Total**	**9835**
	% of total	**87.5834**	**% of total**	**40.9864**

Table 4. EV model sales

	EV 2016		**EV 2019**	
	Vehicle	**Sales**	**Vehicle**	**Sales**
1	Leaf	130	Leaf	130
2	i3	79	i3	94
3	Twizy	20	Twizy	53
4	I-Pace	0	I-Pace	17
	Total	**229**	**Total**	**294**
	% of total	**90.1574**	**% of total**	**96.3934**

The tables are numbered from highest to lowest according to demand [10]. Each table contains the percentage of total vehicle sales for 2016 and 2019 that these models represent, as presented in Table 1. The INECC, through its Eco-Vehicles portal, provides useful information on the technical characteristics of light vehicles, such as fuel efficiency, relevant for HEV and ICE models [1]. The fuel efficiency of each vehicle model was also analyzed individually, as shown in Tables 3.1 and 3.2.

Table 5. Performance of ICE models, 2016

	Model	**Sales**	**Performance**	**Version**
1	Versa	90543	13.96 km/l	SEDAN 4PTS 1.6L 4CIL 106HP MAN
2	Aveo	80052	13.74 km/l	4PTS 1.6L 4CIL 103HP MAN
3	Vento	63201	14.24 km/l	SEDAN 4PTS 1.6L 4CIL 105HP MAN
4	Spark	60598	15.26 km/l	CLASSIC LS 5PTS 1.2L 4CIL 81HP MAN
5	Jetta	60561	11.49 km/l	MKVI 4PTAS 2.0L 4CIL 115HP MAN
6	March	55918	13.7 km/l	5PTS 1.6L 4CIL 106HP MAN
7	Tsuru	49337	12.56 km/l	GS 4PTAS 1.6L 4CIL 105HP MAN
8	Sentra	45977	13.79 km/l	4PTAS 1.8L 4CIL 129HP MAN
9	Sonic	49305	13.53 km/l	LS SEDAN 4PTS 1.6L 4CIL 115HP MAN
10	Xtrail	30488	11.41 km/l	2ROW 4X2 5PTS 2.5L 4CIL 169HP CVT
11	Trax	26777	11.53 km/l	LT FWD 5PTS 1.8L 4CIL 140 AUT
12	NP 300	23516	8.65 km/l	CHASIS 2PTS 2.5L 4CIL 158HP MAN
13	Attitude	20356	17.17 km/l	4PTAS 1.2L 3CIL 76HP CVT
14	CR-V	19161	9.8 km/l	EX-L 2WD 5PTS 2.4L 4CIL 185HP CVT
15	Sportage	18772	10.75 km/l	5PTAS 2.0L 4CIL 151HP AUT
16	HR-V	18603	11.66 km/l	EPIC 5PTAS 1.8L 4CIL 141HP CVT
17	Tiida	17830	11.3 km/l	4PTAS 1.8L 4CIL 125HP MAN
18	Figo	17703	16.11 km/l	SEDAN 4PTAS 1.5L 4CIL 110HP MAN
19	3	17443	14.4 km/l	i SEDAN 4PTAS 2L 4CIL 155HP MAN
20	City	16286	12.81 km/l	DX 4PTS 1.5L 4CIL 118HP MAN
21	Gol	15419	12.89 km/l	HATCHBACK 5PTS 1.6L 4CIL 101HP MAN FRONT
22	Gol Sedan	9533	12.89 km/l	SEDAN 4PTS 1.6L 4CIL 100HP MAN FRONT

Table 6. Performance of ICE models, 2019

	Model	**Sale**	**Performance**	**Version**
1	Versa	88707	13.65 km/l	4PTS 1.6L 4CIL 106HP MAN
2	Aveo	70947	14.8 km/l	LS SEDAN 4PTAS 1.5L 4CIL 107HP MAN
3	Beat	70114	15.51 km/l	ACTIV SEDAN 4PTAS 1.2L 4CIL 81HP MAN
4	NP300	62989	8.45 km/l	PICK UP 2PTS 2.5L 4CIL 158HP MAN
5	March	49493	12.66 km/l	ACTIVE CARGO 5PTS 1.6L 4CIL
6	Vento	47179	12.51 km/l	SEDAN 4PTAS 1.6L 4CIL 105HP MAN
7	Rio Sedan	26132	14.73 km/l	HATCHBACK 5PTAS 1.6L 4CIL 121HP MAN
8	Sentra	21904	11.71 km/l	4PTS
9	Jetta	20469	11.49 km/l	MKVI 4PTAS 2.0L 4CIL 115HP MAN 2017
10	CR-V	19069	11.36 km/l	2WD 5PTAS 2.4L 4CIL 188HP CVT 2017
11	kicks	17837	13.85 km/l	HR16 5PTS 1.6L 4CIL
12	Forte	17712	13.36 km/l	4PTAS 2.0L 4CIL 150HP MAN
13	Hilux	17654	8.48 km/l	DOBLE CABINA 4PTS 3.0L 4CIL 166HP
14	HR-V	17175	9.95 km/l	LX6MT
15	Sportage	15876	10.99 km/l	G4FJ
16	Trax	15250	11.08 km/l	4PTAS 1.8L 4CIL 140HP AUT
17	Figo	14663	15.81 km/l	5PTAS 1.5L 3CIL 121HP MAN
18	3 Sedan	14553	14.84 km/l	i SEDAN 4PTAS 2L 4CIL 155HP AUT 2018
19	Tiguan	14548	12.27 km/l	5PTAS 1.4L 4CIL 150HP DSG FSI FRONT TURBO
20	RAV4	13913	12.18 km/l	LE 4PTS 2.0L 4CIL 176HP
21	CX-5	13742	12.61 km/l	i 2WD 5PTAS 2L 4CIL 154HP AUT
22	Xtrail	13415	11.41 km/l	2ROW 4X2 5PTS 2.5L 4CIL 169HP CVT

Table 7. Performance of HEV models, 2016 - 2019

	Model	**Sale 2016**	**Performance**	**Version**
1	Prius	6560	19.85 km/l	HÍBRIDO 5PTAS 1.8L 4CIL 96HP CVT
	Model	**Sale 2019**	**Performance**	**Version**
1	Prius	5966	19.86 km/l	HÍBRIDO 5PTAS 1.8L 4CIL HP CVT
2	Ioniq	1615	21.29 km/l	HYUNDAI / IONIQ / 2019
3	Niro	1334	20.97 km/l	G4LE
4	Insight	638	21.37 km/l	HIBRIDO
5	Fusion	209	19.91 km/l	HIBRIDO 4PTAS 2L 4CIL 188HP AUT
6	MKZ Lincoln	60	8.69 km/l	HIBRIDO 4PTAS 3L 6CIL 350HP AUT
7	Escape HEV	13	-	Sin registro INECC

The tables show different performance figures for each model; Therefore, it is necessary to calculate a single overall performance figure using a weighted average for HEV and ICE models with equation (1). This calculation utilizes the sales and performance data for the models presented in the previous tables. This performance information is presented in Table 8 for ICE models and Table 9 for HEV models.

$$Weighted\ average = \frac{\Sigma(Sales * Performance)}{\Sigma Sales} \quad (1)$$

Table 8. Weighted ICE performance for 2016 and 2019

ΣSales models 2016	807379	ΣSales models 2019	663341
ΣSales*km/l	10655446.23	ΣSales*km/l	8460438.66
Performance 2016	**13.1976 km/l**	**Performance 2019**	**12.7543 km/l**

This calculation is repeated for HEV. However, for 2016 sales, the Toyota Prius model accounted for 87.58% of sales, maintaining a fuel efficiency of 19.85 km/l, and Table 9 presents the figures for 2019.

Table 9. Weighted HEV performance for 2019

ΣSales	9822
ΣSales*	199158.74
Performance 2019	**20.2768 km/l**

With this information, the emissions calculation can be performed. Using the overall performance of the car models obtained previously, the average distance traveled by a vehicle per year, the emission factor, and the total vehicle sales, the CO_2 emissions can be calculated. Equation (2) estimates the kg of CO_2 emissions from HEVs and ICE vehicles, based on sales recorded in 2016 and 2019.

$$Emissions = \frac{Distance}{Performance} * EF * Total\ sales \qquad (2)$$

The result of these emissions is shown in the following table 10.

Table 10. Emissions HEV and ICE

ICE emissions for the year 2016	4219690366 kg de CO_2
ICE emissions for the year 2019	3528579829 kg of CO_2
HEV emissions for the year 2016	13142403.02 kg of CO_2
HEV emissions for the year 2019	41163599.6 kg of CO_2

On the other hand, the technical information for EVs is obtained from the technical specifications provided for each vehicle model. Table 11 below summarizes this information. This data is based on electrical consumption (kWh/100km).

Table 11. Technical specifications of EV models, 2016 and 2019

		Year 2016	Battery	Consumption	Autonomy
	Vehicle	Ventas	KWh	KW/100km	km
1	Leaf	130	30	15	200
2	i3	79	18.8	12.9	145.736434
3	Twizy	20	13	16.25	80
4	I-Pace	0			
		Year 2019	Battery	Consumption	Autonomy
	Vehicle	Ventas	kwh	kwg/100km	km
1	Leaf	130	40	16.6666667	240
2	i3	94	27.2	13.6	200
3	Twizy	53	13	16.25	80
4	I-Pace	17	90	19.1489362	470

EVs have different characteristics compared to the other two vehicles, HEV and ICE, such as battery, consumption, and range. It is necessary to average again, but this time in kWh per year, which is annual energy consumption. With equation (3), we can determine the number of recharges these vehicles require to travel 15,000 km.

$$Recharge = \frac{Distance}{Autonomy} \qquad (3)$$

This equation calculates the number of recharges these vehicles require per year. It assumes they are completely discharged. The results are shown in the following table. Furthermore, the annual kWh consumption for each vehicle model is calculated by multiplying the number of recharges by the battery capacity.

Table 12. kWh de EV 2016 and 2019

	Battery	Autonomy	#Recharge	kWh por año
Model	KWh	km	Distance/Autonomy	#Recharge*Battery
Leaf	30	200	75	2250
i3	18	145.73	102.9255	1935
Twizy	13	80	187.5	2437.5
I-Pace				
	Battery	Autonomy	#Recharge	kwh por año
Vehículo	kwh	km	Distance/Autonomy	#Recharge*Battery
Leaf	40	240	62.5	2500
i3	27.2	200	75	2040
Twizy	13	80	187.5	2437.5
I-Pace	90	470	31.9148	2872.3404

The table provides useful information for calculating CO_2 emissions. The kWh of the vehicle models per year are averaged and converted to MWh for reference. The indirect emissions factor of 0.438 tCO_2/MWh is used. Equation (4) yields the tons of CO2 from the EV.

$$Emissions = EF * Average\ MWh\ of\ year \qquad (4)$$

Table. 13 EV emissions

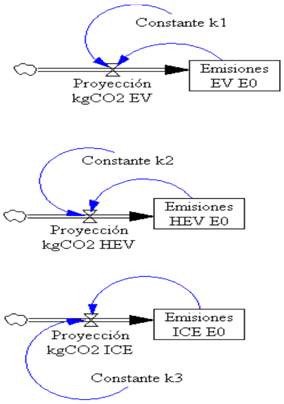
EV emissions for the year 2016	0.9667 t of CO_2	966.855 kg of CO_2
EV emissions for the year 2019	1.0785 t of CO_2	1078.557 kg of CO_2

These calculations of emissions from HEV, EV, and ICE vehicles are the final step in this second phase. This data collection allows us to obtain reliable information and understand the underlying causes of the system. The next step will be to model the CO_2 emissions system using the steps completed previously.

V. FORMULATION

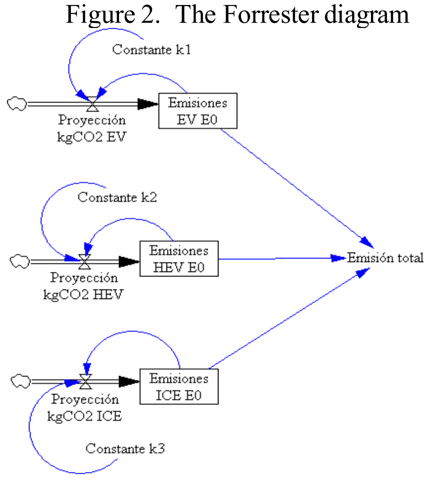
The third phase is the graphical construction of the system dynamics model. This model represents the CO_2 emissions of each vehicle (HEV, EV, and ICE). Initially, it comprises a simple CO_2 emissions feed model for each vehicle. This model has a level variable, represented as emissions E_0, as shown in Figure 1. This level variable is fed by a flow variable called the kg CO_2 projection. Additionally, two auxiliary variables are connected to the system: one called the constant k, and another that connects emissions E_0 to kg CO_2 projections. This system corresponds individually to each vehicle: EV, HEV, and ICE. Figure 1 shows the initial structure of the vehicle emissions model. The diagram was developed using the Vensim software.

Figure 1. Initial structure of the model



Finally, since each model has its own CO_2 emissions system, it's necessary to connect these to another auxiliary variable: total CO_2 emissions. This allows us to independently obtain the emissions of each vehicle (EV, HEV, and ICE) and their total projected emissions over the coming years. Figure 2 shows the completed Forrester diagram.

Figure 2. The Forrester diagram



The Forrester diagram presented here provides a system that encompasses both total and individual emissions. With this system, the formulation phase completes its first part; therefore, the equations that will govern the system are defined. The mathematical model is presented below. This study applies first-order differential equations, useful for identifying increases or decreases in CO_2 emissions. The sales patterns of different vehicle models over time are used to feed the equation that models CO_2 emissions.

$$\frac{dE}{dt} = kE \tag{5}$$

Where:
E(t): Indicates CO_2 emissions at time t,
K: Is the proportionality constant, which describes the behavior.
If k>0, the kg of CO_2 increase, and if k<0, the kg of CO_2 decrease.
First, the differential equation is solved, starting from $E=E_0$, where E_0 represents the kg of CO_2 in 2016. Using the emissions from 2016 and 2019, we obtain the percentage (%) increase or decrease in kg of CO_2 between these two points: $E=\%E_0$. Consequently, at t=0, E_0=c, and when t=3, representing 3 years, we obtain k. Therefore, we get the following equation:

$$E = \%E_0 e^{kt} \tag{6}$$

This equation is calculated individually, as each vehicle has different emissions. Therefore, we have the following equations for HEV, EV, and ICE vehicles.

$$E_{ICE} = \%E_0 e^{-0.0548t} \tag{7}$$
$$E_{HEV} = \%E_0 e^{0.38057t} \tag{8}$$
$$E_{EV} = \%E_0 e^{0.09742t} \tag{9}$$

These equations model the emissions system, where the value of k is an auxiliary variable, the initial emissions of each vehicle are E_0, and the flow variable is k multiplied by E_0. With this information, the Forrester diagram describing the emissions system and the equations that will model this system and project the kg of CO_2 are ready.

VI. RESULTS (EVALUATION)

According to the Forrester diagram shown in Fig. 2, it is possible to project emissions for the next 20 years. This simulation, performed using Vensim software, is summarized in the table.

Table 14. Total emissions from each car

Year	Emissions EV	Emisisons ICE	Emissions HEV
0	245589	4.24E+09	1.31E+07
1	270718	4.02E+09	1.92E+07
2	298419	3.80E+09	2.81E+07
3	328954	3.60E+09	4.12E+07
4	362614	3.41E+09	6.02E+07
5	399718	3.22E+09	8.81E+07

6	440618	3.05E+09	1.29E+08
7	485704	2.89E+09	1.89E+08
8	535403	2.74E+09	2.76E+08
9	590187	2.59E+09	4.04E+08
10	650577	2.45E+09	5.91E+08
11	717146	2.32E+09	8.64E+08
12	790527	2.20E+09	1.26E+09
13	871416	2.08E+09	1.85E+09
14	960582	1.97E+09	2.71E+09
15	1.06E+06	1.86E+09	3.96E+09
16	1.17E+06	1.76E+09	5.80E+09
17	1.29E+06	1.67E+09	8.48E+09
18	1.42E+06	1.58E+09	1.24E+10
19	1.56E+06	1.50E+09	1.82E+10
20	1.72E+06	1.42E+09	2.66E+10

This table contains the emissions of each vehicle over a 20-year period. It also includes CO_2 emissions in kilograms. These results are projections for HEV, EV, and ICE vehicles, based on a mathematical model and applying the Forrester diagram. This, combined with systems dynamics applied to CO_2 emissions in the transition from electromobility to internal combustion, provides an overview of what to expect in Mexico in the coming years.

VII. CONCLUSION

Dynamic systems analysis shows that CO_2 emissions are not decreasing, contrary to expectations that HEVs would have lower emissions. On the other hand, EV CO_2 emissions are still relatively small but are gradually increasing. Unlike these two models, ICE emissions are starting to decrease, but they remain quite high. No decrease is expected in the coming years; therefore, electromobility is not making a significant difference. Scenarios must be considered where ICE sales are very low and demand for HEV and EV models increases. This research demonstrates that Mexico will not experience the expected decrease in CO_2 emissions following the introduction of these models. Different strategies must be planned to achieve a reduction in CO_2 emissions in the transportation sector. Finally, electromobility needs to be more accessible through increased purchasing power, charging stations powered by renewable energy, and public awareness campaigns promoting the reduction of fossil fuel consumption and offering electric vehicles.

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Sustainable mobility as Saltillo's new competitive driver

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***Abstract*—Despite its thriving economy and high urban competitiveness, the rapidly expanding Mexican city of Saltillo faces significant mobility challenges that threaten to undermine its development. This paper demonstrates how the use of new data sources, specifically mobile network data, can be leveraged to effectively analyse the city's complex travel dynamics and enhance data-driven decision-making in transportation. The project, executed by Red Planners with technical assistance from Nommon, employed Mobility Insights, a tool developed by Nommon that integrates anonymised mobile network data with sociodemographic statistics to construct precise Origin-Destination (OD) matrices and critical mobility indicators. This methodological approach offered several advantages over traditional household travel surveys, providing a superior sample size, full traceability of journeys and a substantially reduced execution time. These findings are essential for informing the city's public transport route restructuring project.**

Keywords-Mobile Network Data; OD Matrices; transport planning, urban mobility

I. INTRODUCTION

Located in the Coahuila Desert, the Mexican city of Saltillo stands out for its thriving economy and a high urban competitiveness index [1]. In recent years, the city has undergone a fast-paced growth, driven by its strategic location within one of Mexico's most industrialised regions. This expansion is set to be further enhanced by the upcoming passenger train project, part of the National Rail Programme, which will connect Saltillo with Nuevo Laredo on the northern border [2].

This flourishing growth of the city demands a corresponding development of the current public transport infrastructure to meet the rising demand generated by people's everyday activities. Nevertheless, Saltillo's public transport system struggles to keep pace with the mobility needs of its population. The latter, aligned with the rapid demographic expansion and industrial concentration, has led to a significant reliance on private transport. This dependency negatively affects the quality of life of Saltillo's inhabitants, manifesting as higher commuting costs and an elevated exposure to mobile-source pollutants, including particulate matter, nitrogen oxides, sulphur dioxide, carbon monoxide and carbon dioxide [3].

Addressing this complex infrastructure challenge requires innovative planning tools and strategies grounded in objective and empirical evidence. Traditionally, transport studies have relied on household travel surveys. These surveys are an important source of information that provides rich travel and demographic data to estimate travel demand and patterns, but also suffer from a number of major shortcomings. First, they depend on users' availability and willingness to answer, which may result in people simplifying their answers or giving incorrect and/or imprecise information. Second, they are expensive and require months to complete, which limits the size of the sample and the frequency with which the information can be updated. And third, their high cost usually limits the information to traditional days (e.g., weekdays), lacking data about special periods and events that have a significant influence on today's mobility. These limitations undermine the capacity of household surveys to provide relevant, up-to-date data for effective decision-making.

Consequently, the use of alternative data sources for mobility studies, such as Mobile Network Data (MND), has become indispensable for informing investment decisions in infrastructure and operational reorganisation in fast-changing urban areas. These alternative sources are opening new opportunities to collect rich spatio-temporal data about human mobility, making it possible to complement and/or replace traditional travel surveys.

This paper examines the potential of MND to contribute to more sustainable and equitable cities, specifically through the generation of high-resolution origin-destination (OD) matrices in Saltillo, Mexico. The robust and extensive nature of MND, which offers a significantly larger and more representative sample than conventional surveys, provides the basis for a precise understanding of travel demand and mobility patterns. The results of the generated OD matrix will serve as the core analytical foundation for the reorganisation of public transport routes of the city, enabling the municipal authorities to increase ridership by designing a system that is both operationally efficient and financially sustainable. This study highlights the urgency for reliable and updated data that facilitates the deepening of diagnostic insights and the comprehension of urban and user mobility patterns. In this context, data derived from mobile phone networks represent a compelling and viable alternative for generating these essential diagnostics.

The paper is organised as follows. Section II gives an introduction to MND and OD matrices in transport planning. Section III details the methodology used for the study in Saltillo, covering data processing and the generation of the OD matrix. Section IV presents the main findings of the analysis, followed by a discussion on the benefits and limitations of this approach in Section V. Finally, Section VI outlines the conclusions.

II. NEW DATA SOURCES FOR TRAVEL DEMAND

A. *The role of origin-destination matrices in transportation*

Origin-Destination (OD) matrices are one of the main inputs to most transport analysis procedures and transport analysis models. They describe mobility patterns in a selected geographical area, divided into zones that are identified as origins and destinations of trips across the area [4].

Traditional mobility analyses have historically relied upon data derived from household travel surveys. However, the collection of this information requires a considerable investment of time and resources, turning the subsequent data processing extremely expensive. The magnitude of this data-collection effort often consumes a vital portion of the total available resources allocated for such large-scale studies, frequently leaving insufficient economic and time resources for the more crucial tasks of preparing, evaluating, and implementing strategic transport plans. While the assessment of macro-level mobility patterns is important, the primary utility of conventional travel survey data is to provide the basis for strategic transportation modelling. Consequently, the focus remains predominantly on revealing the quantitative relationships between trip origins and destinations, rather than on obtaining the deeper, qualitative behavioural determinants that underpin individual travel choices [5].

The high cost and the large amount of time spent on data collection and processing also limit the number of days household travel surveys are able to analyse. Traditionally, those surveys focus on labour days with the intent to gain deeper knowledge of an average working day. Nevertheless, today's mobility has been highly impacted by crises (e.g. COVID-19 pandemic), working behaviour (e.g., remote or hybrid work) and disruptive mobility technologies (e.g., ride-hailing apps such as Uber and Did), increasing the necessity to understand mobility patterns for different days and periods of time.

Lastly, household surveys also depend on the user's willingness to answer. In many cases, the user's answers are simplified, generating gaps of information (e.g., trips not reported) or incorrect and/or imprecise information.

B. *Mobile Network Data*

Data from new sources such as mobile phone records and GPS traces from mobile apps are emerging alternatives for the study of travel demand and patterns. Mobile network data (MND) is particularly interesting, thanks to the possibility of obtaining very large samples of geopositioned data with a high temporal resolution and including most population segments.

MND encompasses all interactions between mobile devices and the antennas of the Mobile Network Operator (MNO)[6]. The resultant records contain spatio-temporal information regarding the position and the time at which each interaction took place. This raw data is subsequently processed using a sophisticated pipeline for an accurate reconstruction of door-to-door passenger journeys. This methodology enables the exploration of compelling research lines, such as longitudinal studies. Furthermore, previous academic research[7] has demonstrated that using MND provides significant benefits over traditional methods like household travel surveys:

- **Superior Sample Size:** traditional household travel surveys typically rely on small samples representing only 1-2% of the population. In contrast, MND offers a significantly larger and more representative sample, often ranging between 20-30%, leading to a more precise understanding of mobility patterns.
- **Increased Efficiency:** the study's execution time is drastically reduced, enabling public authorities to gain faster insights for decision-making.
- **Comprehensive Traceability:** the data ensures full traceability of all journeys, eliminating the common issue of underrepresented trips found in household surveys and providing a complete view of population movement.

The use of MND is also contemplated by official transport modelling standards and guidelines, such as the Transport Analysis Guidance (TAG) framework developed by the UK's Department for Transport [8] and other public and private authorities around the world for characterizing travel behaviour and feeding transport models (e.g., Spanish Ministry of Transport initiative "Open Data Movilidad" [9]). MND is also increasingly popular among transport practitioners in the LAC region, as shown by the IADB 2019 report on the subject [10] and the World Bank Group's several initiatives in the region [11].

Under these circumstances, the Municipal Institute of Transport of Saltillo commissioned a mobility study. Conducted by Red Planners with Nommon's assistance, the study's core was an MND-based OD matrix obtained with mobile network data from Telcel. Telcel is the main MNO for the Mexican market, with a market share of 55% [12].

The MND-based OD matrix meticulously measures and maps mobility patterns, revealing how people move around and where they are travelling from and to. This data empowers public authorities to:

- Accurately identify mobility needs to inform the location and design of new transport infrastructure.
- Enhance public transport and promote sustainable alternatives such as cycling and walking.
- Reduce reliance on private transport.

Furthermore, the MND-based OD matrix is a key input for the city's ongoing public transport route restructuring project. By providing a detailed vision of travel patterns, it will help identify critical issues and form the basis for transport models. This, in turn, will allow for the design and prioritisation of strategic actions that improve urban mobility across the city.

III. Methodology

A. Region of Study

Saltillo is the capital of the Mexican state of Coahuila, located in the northeast of the country, near the border with the United States. Founded in 1577, its development is rooted in the colonial era, and it has since grown into a significant industrial centre [13]. The local economy is heavily reliant on industrial activities, particularly the manufacture of automobiles, machinery and steel products. This is evidenced by the fact that Saltillo has more than 40 industrial parks located throughout the city. The rapid industrialisation is reflected in a substantial annual growth rate of 2.6% [14], positioning Saltillo as one of Mexico's fastest-growing urban areas.

This urban expansion has extended to the neighbouring municipalities of Arteaga and Ramos Arizpe, which collectively form the Saltillo Metropolitan Area (SMA). According to the National Institute of Geography and Statistics Information (INEGI) in 2020, the SMA had a population of 1,093,779 inhabitants [15]. The distribution of this population shows that 85% reside in Saltillo, 12% in Ramos Arizpe, and the remaining 3% in Arteaga.

As in many other Mexican cities, the city's urban and transport infrastructure has expanded rapidly to accommodate this intense development. Unfortunately, this process has led to a vicious circle in which the expansion of infrastructure stimulates urban growth towards the periphery, increasing car dependency, which requires additional infrastructure development [16].

To address this challenge, the municipal administration has focused on the creation of a comprehensive transport system, focusing on reorganising its routes for a more efficient service. The development of an updated OD matrix is considered the starting point for this initiative.

B. Mobility Insights

To gain a deeper understanding of Saltillo's mobility patterns, the project utilised Nommon's Mobility Insights[1] solution. This tool integrates anonymised mobile network data with land use sociodemographic statistics, transport network and transport supply information to generate MND-based OD matrices and other vital mobility indicators. The methodology is detailed in the following section.

Through a commercial agreement with Telcel, we accessed high-resolution, spatiotemporal mobile data. This information enabled us to reconstruct users' daily activities and time spent in various locations, helping us identify mobility patterns with greater precision.

Each record includes an ID, a timestamp and the antenna the device connected to. In addition to this, the MNO provides basic sociodemographic information for each anonymous user, such as age and gender.

The initial step involves the aggregation and cleaning of raw data. This refinement stage includes rectifying potential inaccuracies, such as antenna geolocation errors, ensuring all records accurately correspond to the designated study area.

Following data normalisation, the study proceeds to user selection. This involves identifying users whose records provide sufficient information to accurately infer daily activities and trips. Users exhibiting significant gaps in their daily activity logs are discarded; however, an exception is made for foreign visitors, for whom intermittent signal patterns are anticipated.

The core of the technical solution lies in transforming the validated mobile records into meaningful mobility data by generating daily activity and stay diaries. A stay is considered an action of an individual staying in a certain place for a certain time. It can correspond to an activity or to an intermediate stop

[1] https://www.nommon.es/products/mobility-insights/

between two consecutive legs of a trip. An activity is defined as a stay originated by an interaction or set of interactions with the environment that motivates the individual to travel there. A trip is formally defined as the sequence of stages between two consecutive activities. Proprietary algorithms combine criteria based on stay times, displacement itineraries, and observed patterns across the study period to filter and identify intermediate stays. This comprehensive, longitudinal analysis allows for the inference of the user's place of residence, the identification of trip purpose considering four activity types - home, full-time work or study, frequent activities, and other non-frequent activities - as well as the frequency of the trip.

By analysing users' activity and travel patterns from several weeks of data, the algorithm also identifies professional drivers (e.g., truck drivers, taxi drivers, bus drivers, delivery riders, etc.). This identification is based on the analysis of metrics such as the number of trips performed, the distance travelled, the recurrent appearance at certain places (e.g., logistic hubs).

Once the associated trip information—including origin, destination, purpose at origin and at the destination, and start and end times—is complete, the sample is expanded to represent the total population. This expansion utilises standard, well-established procedures analogous to those employed in traditional household surveys. For the expansion of Mexican residents, the Population and Housing Census (2020) served as the sampling frame, with the expansion factors derived from the place of residence. Conversely, the expansion for foreign visitors was achieved through the calculation of expansion factors based on the visitor's nationality and their point of entry. The sampling frame comprised the fusion of two sources: the International Tourism Survey (ETI) and air entries of foreign tourists by country of nationality (Datatur).

The final step is to aggregate the data from the individual activity-travel diaries to generate the required trip matrices and additional demand indicators. The spatial aggregation process allocates trip ends to origin-destination zones based on trip end coordinates and the user's specified zoning system. The temporal aggregation criterion can be based on (i) trip start and end times, and (ii) the time a trip passes by a specific point, according to the information of the intermediate positions along the trip. The latter can be used for long-distance trips entering or passing through the study area.

IV. Results

For the analysis, we examined data from three typical working days from February 2025 to create an average daily mobility profile, broken down into 24 time slots. The project's zoning system considered a total of 212 zones covering the entire SMA. The definition of these zones was based on the delineation of the AGEBs (Basic Geostatistical Areas, as abbreviated in Spanish), which were grouped according to the density of antennas in the region. Additionally, leveraging the benefits of utilising mobile data for matrix generation, the zoning incorporated a special zone to identify trips originating and/or destined for the Monterrey Metropolitan Area.

The effective sample comprised the local population (the customers of Telcel), as well as foreign visitors (roaming-in users), covering 55% of the population. The segmentations identified for each set of trips were: start time, origin, destination, purpose at the origin, purpose at the destination, place of residence, income level, gender, age, along with an indicator expressing whether the trip is considered a professional mobility trip.

This approach allowed us to identify the trips generated and attracted by each zone, regardless of the mode of transport, quantify the total number of journeys, and pinpoint their spatial and temporal patterns.

The results showed a total of 3.46 million trips, a 112.5 percentage point increase compared to previous estimates [16] on a regular working day, highlighting the extensive daily mobility within Saltillo. The Municipality of Saltillo accounts for the majority of these, with over 2.59 million trips, followed by Ramos Arizpe (534,000), Arteaga (85,000), and Derramadero (75,000). Additionally, we recorded approximately 177,000 external trips, with over 25,000 of them destined for Monterrey. This finding underscores the strong connection between these two major cities in the region.

While a high volume of trips occurs within the same zones, especially in industrial areas, the research highlighted the need for improved connections between different municipalities and service areas along the main transport corridors. The high concentration of internal trips reveals a strong presence of short-range movements, many of which could be addressed using non-motorised modes, such as walking or cycling. This is most evident in residential areas characterised by dispersed, local commercial provision, but also holds true for large industrial estates, where a substantial portion of daily movements relate to internal logistics activities or transportation between nearby facilities. This pattern suggests that a considerable segment of mobility needs does not require long-range motorised solutions, but rather improvements in local accessibility, street-level connectivity, and last-mile infrastructure.

The analysis confirmed the historical significance of the city centre as a pivotal activity hub, serving as a primary generator and attractor of daily trips. Crucially, however, the study also revealed the simultaneous emergence of several new, highly active mobility centres situated in the southern, eastern, and western sectors of the city. Beyond mere population growth, these zones have undergone a significant expansion of commercial, service and mixed-use developments, resulting in areas with their own OD dynamics. This commercial consolidation, coupled with the higher densities anticipated in the Municipal Development Plan, has reduced reliance on the

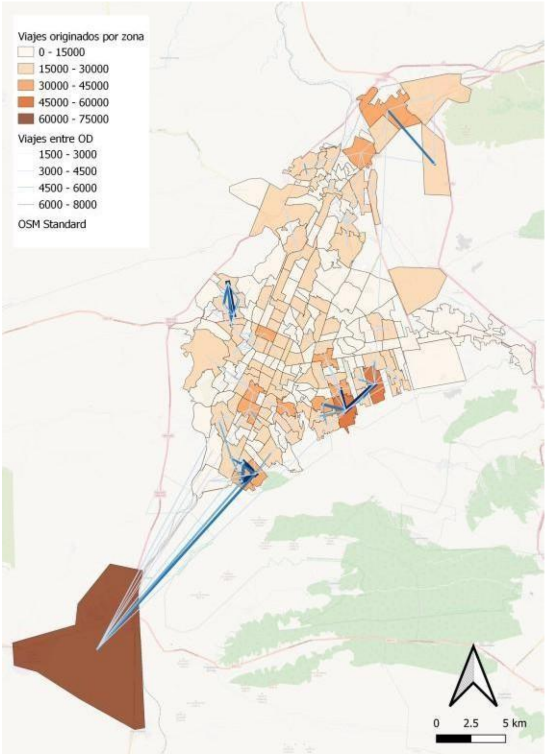

Figure 1. Major Flow Lines

historic centre for shopping, accessing services, or commuting. Consequently, these new centralities absorb a growing share of local demand and generate a trip volume comparable to that of the traditional city centre. Quantitatively, the analysis revealed that these peripheral centres collectively account for 30% of the city's total daily trips, indicating a significant decentralisation of travel demand across the SMA. The outcome is an increasingly polycentric urban structure, where various sub-centres are emerging as key players in shaping mobility patterns.

This finding is crucial as it marks a shift in the region's historical mobility patterns and underscores the need for a new transport planning strategy. Specifically, the results show that developing new cross-city corridors and direct routes is essential. These new connections will link the emerging hubs and ensure a more efficient transport system that is better suited to Saltillo's evolving mobility dynamics.

V. Discussion

When compared to other big data sources, MNDs are particularly appropriate for the analysis of travel demand. This is thanks to their ability to capture door-to-door trips and the possibility of obtaining very large samples of geopositioned data with good temporal and spatial resolution for most population segments. Consequently, MND-based Origin-Destination (OD) matrices usually have a more accurate trip distribution than those derived from other data sources, enabling the construction of transport models that provide a better representation of demand patterns and, thus, greater predictive power.

The passive nature of data collection from MNOs also allows information to be obtained on trips that are typically underrepresented in other types of surveys, such as those made during the lunch hour or those classified as care trips. Furthermore, evidence demonstrates differentiated mobility patterns between men and women; consequently, an adequate understanding of mobility requires data that facilitates the identification of these gender differences [18]. This capability also opens the possibility of studying multi-day, long-distance journeys, such as those undertaken by freight transporters.

Nevertheless, it is essential to acknowledge that no singular data source offers a wholly comprehensive representation of urban mobility. While MND provides large, spatially well-distributed samples that cover most population segments, enabling a detailed characterisation of the study area, it inherently suffers from limitations regarding the granularity of data related to modal choice and precise trip purpose. Conversely, traditional travel surveys can provide vital qualitative information, such as motivation and detailed mode splits. However, the infrequent update cycle of these surveys fundamentally undermines their ability to provide current, time-relevant data for effective planning and reorganisation. Therefore, the most robust approach relies on the strategic integration of both MND and survey data.

Due to the data's origin, the information is geolocated at the cell level, meaning the position is known at the level of the coverage area of each antenna. This resolution varies geographically depending on cell density, ranging from 250 and 500 meters in the urban areas of the SMA to 1 or 2 kilometres in rural areas. To estimate the exact user location Nommon's solution relies on supporting inputs, including land use data, sociodemographic statistics (e.g. population density in each administrative unit), and information on the type of activity/stop carried out by the user. For instance, the exact location of the user 's home location is probabilistically assigned using information on residential land uses and population distribution. The spatio-temporal resolution of MND also impacts temporal attributes. The frequency of records depends on the MNO's technology and the user's mobile device usage, which must be considered during the sampling process. This low temporal granularity—typically a register every 15–30 minutes—directly impacts the accuracy of trip duration indicators.

Finally, regarding modal splits, the use of map-matching techniques enables the identification of the transport mode for most medium- and long-distance trips, distinguishing between road and rail. This is achieved by analysing the overlap among three key elements: (i) the spatio-temporal trajectory observed in the MND; (ii) the transport network (road network, bus network, location of transport hubs, etc.); and (iii) the travel times for different modes. However, the applicability of this approach is limited by the spatio-temporal resolution of the MND. While map-matching is very reliable for interurban travel, mode identification is often not possible for short trips. This is particularly problematic in urban and metropolitan areas because, due to the high density of the transport network and the coexistence of multiple transport services, the travel times and user trajectories for different modes are frequently very similar.

To overcome this limitation, the solution can fuse complementary data from other mobility surveys or smart ticketing information to calibrate a machine learning model that classifies trips by transport mode. This solution offers reliable results; however, it is dependent on the availability of such complementary data. Within the Mexican context, where survey data is usually not available and there are significant disparities in public transport digitalisation levels, with some cities having implemented ticketing and smart cards for several years, while many others still rely on cash payments [19].

VI. Conclusions

The arrival of the new passenger train presents a significant opportunity for Saltillo to transition towards a new urban planning approach focused on public transport, allowing the city to adapt to its rapid expansion. The origin-destination matrices developed by Nommon using mobile network data are not merely diagnostic tools; they serve as an objective planning instrument essential for the strategic reorganisation of the public transport system. This study has underscored the need for reliable data that facilitates the deepening of diagnostic insights and the comprehension of urban and user mobility representations. In this context, data derived from mobile phone networks represent a compelling and viable alternative for generating these essential diagnostics.

A critical challenge facing transport planning and operations in Mexico is financial vulnerability. Business models governing public transport systems across the country are typically characterised by a high degree of vulnerability to variations in passenger demand [20]. This financial fragility arises because fare revenue often constitutes the primary source of income, meaning that unpredictable or uneven demand directly compromises operational feasibility and long-term investment planning.

Consequently, the precise, data-driven analytical insights derived from this study, specifically the Origin-Destination (OD) matrices, provide the municipal authorities in Saltillo with the necessary evidence base. This enables the development of a structurally sound and financially sustainable public transport system, allowing the local government to strategically plan routes and schedules, optimise resource allocation, and ensure greater long-term cost recovery, thereby effectively meeting the city's rapidly evolving mobility requirements.

An improved public transport system would efficiently connect the city's various activity hubs –from industrial parks to commercial zones, making it easier for people to reach their destinations. This strategy would make Saltillo more attractive for investment, boosting its competitiveness and establishing it as a role model for other Mexican cities facing similar challenges.

Lastly, these matrices offer utility far beyond initial planning or a snapshot of the current situation. They serve as a baseline for setting future goals and measuring the impact of new projects. This supports a process of continuous, data-driven improvement in urban mobility, ensuring its position as the leading city in Mexico for Urban Competitiveness.

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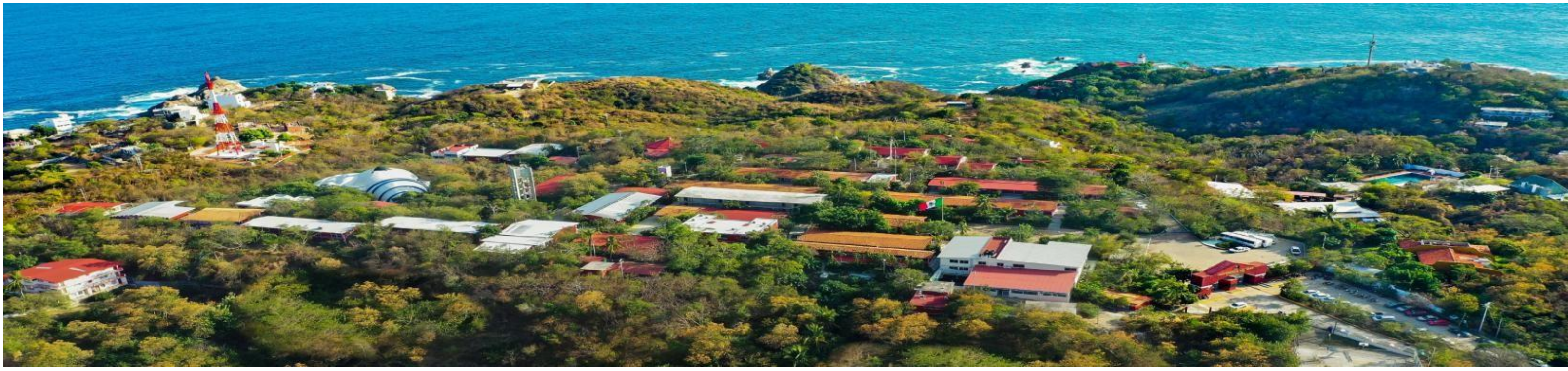

2- Optimization of Logistics and Manufacturing Processes (AGVs)

1- **Balancing throughput, utilization, and total idle time cost in AGV fleets**
- Salvador Hernández González
- Idalia Flores De La Mota
- Quetzalli Atlatenco Ibarra

2- **Optimizing Material Flow with AGVs in a Closed System Using Metamodels**
- Ana Valeria Monzón Cabrera
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Balancing throughput, utilization, and total idle time cost in AGV fleets

A metamodel-based approach

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***Abstract*— Determining the number of AGVs for material handling is a design problem that requires defining several parameters. Most published articles have focused on solving very specific problems, neglecting to understand the general behavior of performance indicators such as production rate, equipment utilization, or waiting cost as a function of design variables. The analysis is further complicated because there are no direct analytical functions due to the stochastic nature of several of these factors. This article analyzes the behavior of a manufacturing system with AGVs as a means of material transport. Metamodels are used for production rate, equipment utilization, and idle time costs. Since these indicators have contradictory objectives, a multi-objective approach is used to determine the best operating conditions. The multi-objective analysis reveals that there are balanced operating conditions where the output rate and utilization are acceptable and there is a minimum total idle time cost where 52% corresponds to underutilization of the AGV fleet and 47% corresponds to waiting for material to be transported. Other operating conditions generate a higher and unbalanced total idle time cost. The analysis method is flexible, can be extended to more complex contexts, and can be used in the initial design phases**

Keywords: AGV, fleet size problem, metamodeling, design, multi-objective optimization

I. Introduction

AGVs are crucial for streamlining modern industrial processes but are no longer confined to factories and manufacturing environments. In recent years, diverse sectors, including port authorities [1], airport administrations [2], and hospitals [3], have embraced this technology. These organizations leverage the flexibility and enhanced capabilities of the Internet of Things (IoT) to optimize their logistics operations. However, designing systems that incorporate AGVs presents several challenges[4]: Material flow in the network, Locating loading and unloading points, Number of vehicles, Scheduling the loading and unloading activities, Route design, Traffic conflict resolution strategies.

Key performance indicators (KPIs) for AGV systems include material transport rate, cycle time, work-in-process inventory, and vehicle utilization [5]. AGV implementation represents a significant capital investment, and determining the fleet size is a complex design challenge. This optimization process must account for the interdependence among numerous dynamic parameters, many of which are influenced by unpredictable external events [6,7]. This optimization problem is commonly known as the AGV Fleet Size Problem [8]. Determining the appropriate AGV fleet size for a manufacturing cell requires careful consideration of several factors, including transport demand, vehicle speed, loading/unloading times, and potential downtime.

II. Previous work

The AGV fleet size problem involves finding the Optimal Number of AGV [9,10] which must be able to handle situations like unexpected demands, ensuring efficient workshop operations and the desired output [11,12,13] .

Despite the availability of general methods for estimating the number of AGVs, these are approximate values obtained in the initial design stage; however, they require validation using complementary methodologies.

Common validation approaches include queuing theory, simulation modeling, and metamodel construction, often integrated with mathematical programming techniques, some of which are detailed in subsequent articles.

Automated guided vehicles often serve a network of workstations, facilitating the transfer of entities (components or clients) between processing phases or the conveyance of materials from a storage facility [14] ; assuming loading and unloading points operate as M/M/c queuing systems and transit routes as M/M/∞ queuing systems, the overall process can be modeled as an open queuing network [15], and its analysis facilitated through decomposition methodologies. In cases where the system is modeled as a closed queuing network, with a constant population of AGVs circulating within it [16], the primary solution methodologies involve Mean Value Analysis (MVA) [17] or the Convolution Algorithm [14].

A further analytical perspective involves treating the system as a semi-open queuing network. This approach considers a demand for the transportation of items (components or clients) via AGVs, utilizing containers or pallets, through a sequence of workstations (the closed subsystem). Upon completion, the entities (components or clients) exit the system as finished goods (the open subsystem), and the transport unit (container or vehicle) is then available for subsequent material handling operations [18].

The inherent complexity of the problem is amplified by the necessity to consider supplementary factors, and therefore a simulation model is suitable to include and study such factors. Consequently, Gobal & Kasilingam [19] tackled this by employing station and machine idle time, along with accumulated pieces, as performance metrics, conducting their search through vehicle quantity enumeration. Furthermore, Asef-Vaziri, Khoshnevis & Rahimi [20], in a seaport case study, utilized the product transport rate and AGV utilization as key performance indicators. Prombanpong, Kiattiphatthananukul, Songsanan & Sukin[21] account for product mix and utilize a simulation model, employing enumeration to determine the optimal vehicle fleet size.

Other situations have also been considered in simulation models, such as recharging periods and energy consumption [22,23,24], route design [25,26,27]or the presence of obstacles [28,29] .

Recent research has also applied metamodeling to elucidate the relationships between design variables in manufacturing systems utilizing AGVs for material handling. A metamodel, an approximate mathematical representation, captures the connections between simulation inputs and outputs [30,31] Metamodels are valuable when performance measures depend on numerous stochastic parameters or lack a suitable closed-loop expression, when direct process optimization is impractical due to cost, or during the design phase. Typically, an experimental design dictates the combination of simulation factors, a statistical analysis is performed, and the resulting model, valid within the experimental scope, is used to explain, predict, or optimize the system [32].

Tshibangu & Tshibangu [33] conducted an analysis of a manufacturing cell, incorporating control failures and AGV operational rules, to formulate metamodels for cycle time and output rate. Subsequently, they utilized mathematical programming to ascertain the optimal number of vehicles. Fu et al. [34] developed metamodels for AGV utilization and cycle time, considering factors such as vehicle quantity, loading/unloading duration, and speed, and subsequently proposed a multi-objective model solved via genetic algorithms. Chen, Chen & Teng [35] employed a comparable metamodeling methodology to determine the optimal vehicle fleet size under diverse charging protocols. Molina – Concha et al (36) propose a Bayesian optimization method to determine the number of exploration robots and test their strategy using simulation models, Mesut – Senaras Et al [37] compare Response Surface Method(RSM), Neural Networks and multivariate regression to obtain the number of vehicles. Although the neural networks have a lower error with respect to simulation, they are a "black box" that does not allow us to understand how the variables relate to each other. Wang et al [38] solve the problem in a container handling system using multi-agent simulation and an experimental design, given the high complexity of the system they limit the number of variables studied to the number of cranes, loading speed, and number of batteries to recharge, although they do not generate a metamodel, at least they perform a statistical analysis to identify the significant variables.

III. Experimental procedure

Quantifying the performance of production systems that use AGVs requires the consideration of various metrics, including, but not limited to, throughput, cycle time, vehicle capacity and utilization, and investment costs. Maximizing throughput does not necessarily correlate with minimizing cycle time, capacity utilization, or work-in-process. Therefore, a multi-objective optimization approach, utilizing multiple context-dependent performance measures, is recommended to facilitate robust decision-making. For this study, a generic manufacturing cell model based on Kelton, Sadowsky & Zupick [39] is employed. The manufacturing cell consists of four workstations and processes three distinct products. The production routes, arrival rates (Table 1), and service times (Table 2) are presented below.

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TABLE I. PART TYPE, ROUTES AND ARRIVAL RATE

i	Route	Demand (pz/hr)
A	1-2-3-4	0.7326
B	1-2-4-2-3	0.2664
C	2-1-3	1.221

TABLE II. SERVICE TIMES

i	1	2	3	4
A	8	8	20	12
B	13	6	33	18
C	10	9	23	

Service times are stochastic and follow an exponential probability distribution, also time between arrivals are stochastic and follows an exponential probability distribution.

Following the completion of a processing operation at a machine, a material transfer request is initiated, with the AGV dispatched according to the nearest neighbor's rule. The AGV loads the processed material at the station and transports it to the subsequent processing phase. The system's material inventory is constrained to a maximum of six units. It is assumed that the AGVs' acceleration and deceleration periods are sufficiently brief to be disregarded. The experimental design incorporated four key variables: the number of AGVs, loading time, unloading time, and AGV speed. Each variable was evaluated at three levels, representing typical design factors for this type of system (Table 3).

TABLE III. VARIABLES AND LEVELS

Variable	Levels
x1: # AGVs	2,3,4
x2: Loading time (seconds)	5, 10, 15
x3: Unloading time (seconds)	5, 10, 15
x4: Speed AGV(m/min)	10, 15, 20

The unidirectional AGVs facilitated material transport between workstations, as well as from the entry bay to workstations and from workstations to the output bay (Fig. 1).

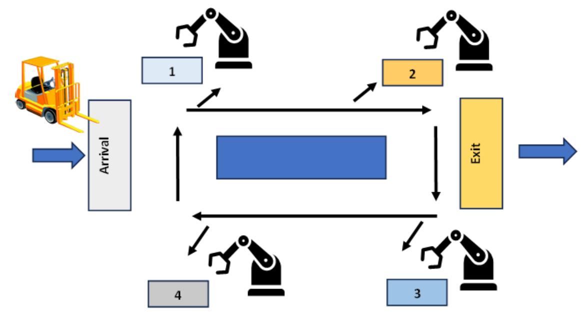


Figure 1. Manufacturing cell representation.

This paper uses the throughput $Th\ (x1,\ x2\ldots)$, the fraction of capacity usage of stations $U\ (x1\ldots)$ and the cost of idle time of the AGV as performance measures.

Building upon the function proposed by Gobal and Kasilingam [19], which relates the cost of AGV idle time exclusively to the number of vehicles, we present a modified version of the cost of idle time or Idle Time Cost Factor (ITCF). This new version introduces additional variables, and its equation is:

ITCF(x1,…)ITP(x1,…)+ITAGV(x1, …) (1)

Where:

ITCF: Idle Time Cost Factor

ITP: Part Idle Time

ITAGV: AGV Idle Time

Since equation (1), Th, and U do not have a direct analytical expression, approximations are employed to evaluate these performance measures. This need for approximation arises from the random nature of the required parameters: for example, service time or failures. For this study, metamodels of Th, U, and ITCF are generated using the following variables:

x1: number of AGVs; x2: Loading time (seconds); x3: Unloading time (seconds); x4: AGV speed

Building upon prior research demonstrating a concave relationship for output rate [30] and quasi-convex relationships for capacity usage and ITCF [5,19], this study employs quadratic models to approximate these functions. In this case, a metamodel is required that ensures low uncertainty in the predictions; a 25-run I-optimal experimental design was developed using Design Expert 23 software, as detailed in Table 4; I-optimal designs reduce the average variance in the experimental region in pursuit of reliable predictions [40], there was one run per experiment. The simulation model was built in ARENA R16 software, each simulation run lasting 2,880 hours: the WIP was used to monitoring the evolution of the process and observed that the process reach the stabilization phase after 50-hours[39]; the next 2330 hours were used for collecting data and represent approximately 97 labor days of continuous operation.

IV. Results and discussion

A. Development of metamodels

Table 4 gives the results of the experimental runs, followed by the running of the Analysis of Variance and construction of the Th metamodels, capacity usage and ITCF. All calculations were performed using Design Expert 23 software. Determining the best operating conditions from Table 4 necessitates a multi-criteria decision approach, given the conflicting performance measures and numerous viable options. Consider the objective of maximizing throughput (Th). While Experiment 6 (4 AGVs, 5s load/unload, 20 m/min) and Experiment 11 (3 AGVs, 15s load/unload, 20 m/min) both achieve Th = 2, they exhibit significant differences in Utilization (U: 0.2401 vs. 0.3574) and ITCF (3.0417 vs. 1.9605).

To facilitate systematic evaluation and selection, the metamodels will be developed for subsequent integration into a mathematical programming model.

ANOVA results (Tables 5-7) revealed that vehicle count and traveling speed significantly influenced all performance measures, while loading and unloading times did not show significant effects. The sum of squares analysis indicated vehicle speed (x4) had the greatest impact on Th (Table 5), and vehicle count (x1) on U (Table 6) and ITCF (Table 7).

TABLE IV. Experimental results

Run	*Th*	Utilization	IT AGV	IT part	*ITCF**
1	1.772	0.6513	1.0461	0.2592	1.3053
2	1.8301	0.7157	0.5686	0.5473	1.1159
3	1.9515	0.5614	0.8772	0.2447	1.1219
4	1.5789	0.8942	0.2116	1.205	1.4166
5	1.9644	0.3119	2.7524	0.0073	2.7597
6	2	0.2401	3.0396	0.0021	3.0417
7	1.9614	0.58	0.84	0.2621	1.1021
8	1.99	0.3575	1.9275	0.03186	1.9593
9	1.9713	0.316	2.736	0.007	2.743
10	1.7731	0.6508	1.0476	0.2706	1.3182
11	2	0.3574	1.9278	0.0327	1.9605
12	1.8427	0.4625	2.15	0.0383	2.1883
13	1.978	0.33	2.01	0.02724	2.0372
14	1.763	0.6495	1.0515	0.2717	1.3232
15	1.93	0.4577	1.6269	0.0779	1.7048
16	1.9514	0.3133	2.7468	0.0072	2.754
17	2	0.23	3.08	0.002	3.082
18	1.948	0.5561	0.8878	0.2358	1.1236
19	1.9365	0.4587	1.6239	0.0766	1.7005
20	1.5782	0.899	0.202	1.2177	1.4197
21	1.5845	0.889	0.222	1.1825	1.4045
22	1.975	0.31667	2.73332	0.0071	2.7404
23	1.77	0.6531	1.0407	0.2673	1.308
24	1.8605	0.454	2.184	0.0347	2.2187
25	1.9565	0.5649	0.8702	0.2522	1.1224

TABLE V. ANOVA OF THE THROUGHPUT

Source	SS	df	MS	F-value	p-value	
Model	0.4409	5	0.0882	557.68	< 0.001	significant
x1	0.0809	1	0.0809	511.54	< 0.001	
x4	0.2538	1	0.2538	1605.05	< 0.001	
x1x4	0.0355	1	0.0355	224.47	< 0.001	
$x1^2$	0.0074	1	0.0074	46.92	< 0.001	
$x4^2$	0.0104	1	0.0104	65.63	< 0.001	
Resid.	0.003	19	0.0002			
L. of Fit	0.0026	14	0.0002	2.34	0.1775	Not significant
Pure Error	0.0004	5	0.0001			
Cor Total	0.4439	24				

TABLE VI. ANOVA OF THE CAPACITY USAGE

Source	SS	df	MS	F-value	p-value	
Model	0.9684	5	0.1937	1702.46	< 0.001	significant
x1	0.5252	1	0.5252	4616.03	< 0.001	

x4	0.3506	1	0.3506	3081.82	< 0.001	
x1x4	0.0065	1	0.0065	57.26	< 0.001	
x1²	0.0095	1	0.0095	83.93	< 0.001	
x4²	0.0047	1	0.0047	40.91	< 0.001	
Residual	0.0022	19	0.0001			
L. of Fit	0.0021	14	0.0002	59.14	0.001	significant
Pure Error	0	5	2.60E-06			
Cor Total	0.9706	24				

TABLE VII. ANOVA OF THE ITCF

Source	**SS**	**df**	**MS**	**F-value**	**p-value**	
Model	10.72	4	2.68	249.96	< 0.001	significant
x1	8.37	1	8.37	780.53	< 0.001	
x4	0.8323	1	0.8323	77.66	< 0.001	
x1x4	0.9889	1	0.9889	92.27	< 0.001	
x1²	0.5706	1	0.5706	53.24	< 0.001	
Residual	0.2144	20	0.0107			
Lack of Fit	0.2141	15	0.0143	235.18	< 0.001	significant
Pure Error	0.0003	5	0.0001			
Cor Total	10.93	24				

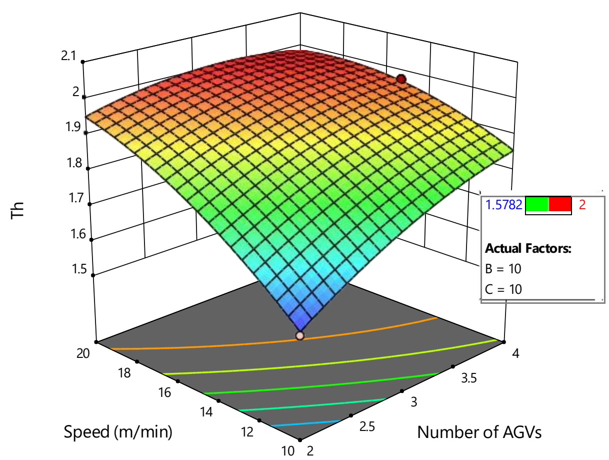
The interaction of x1 and x4 implies that performance indicators are derived from the synergistic effect of vehicle count and speed, indicating that isolated consideration of these variables is insufficient. As a result, the application of metamodels is expected to yield significant benefits in solving this problem, by providing efficient surrogate models. Subsequently, quadratic models for Th, U, and ITCF were derived through linear regression, incorporating only significant uncoded variables. The resulting models are presented below.

$$Th= 0.04903 +0.4684x1 + 0.1175x4 - 0.01168x1x4 + 0.0362x1^2+0.001936x4^2 \quad (2)$$

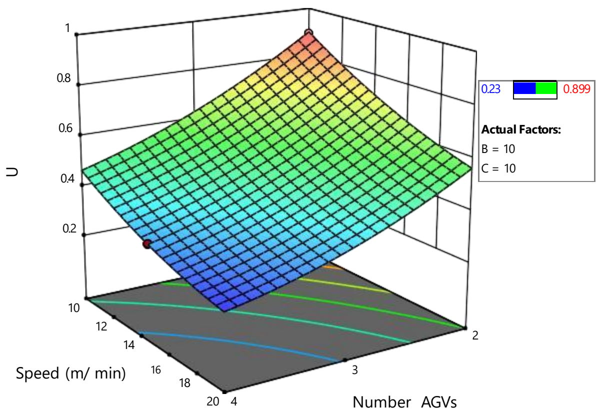
$$U=2.36-0.5148x1 - 0.0826x4 + 0.005x1x4 +0.041x1^2 + 0.0012x4^2 \quad (3)$$

$$ITCF=4.428 - 2.097x1 - 0.1406x4 + 0.06164x1x4 + 0.3163x1^2 \quad (4)$$

Equation (2) reveals a positive correlation between Th and both the number of AGVs and speed. Specifically, Th increases by 0.4684 units per additional AGV and by 0.1175 units per unit increase in speed. Furthermore, the negative coefficients of the quadratic terms suggest the existence of a maximum value for Th.(Figure 2a) Conversely, Equation (3) reveals an inverse relationship between U and both the number of AGVs and speed. Specifically, U decreases by 0.5148 units per additional AGV and by 0.0826 units per unit increase in speed. The positive coefficients of the quadratic terms suggest the existence of a minimum value for U.(Figure 2b) Finally, Equation (4) demonstrates an inverse relationship between ITCF and both the number of AGVs and speed. Specifically, ITCF decreases by 2.097 units per additional AGV and by 0.1406 units per unit increase in speed. The positive coefficients of the quadratic terms indicate the presence of a minimum for ITCF.(Figure 2c)



a



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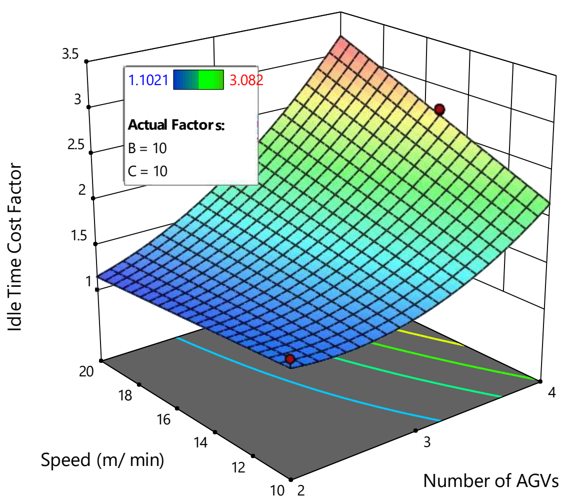

c

Figure 2. Response Surface: a) Th; b) U; c) ITCF

The calculated % error for all three models was below 10%, deemed acceptable for predictive accuracy. Table 8 presents the results of Equation (5), where RM is the metamodel prediction and RS is the simulation response.

$$\%Error = ((R_M - R_S))/R_S \times 10 \quad (5)$$

Additionally, the close correspondence between Pred. R^2 and R^2 values in Table 8 indicates the reliability of the adjusted model predictions. The percentage error is calculated as follows:

TABLE VIII. % OF RELATIVE ERRORS, COEFFICIENT OF DETERMINATION R2 AND PRED. R2

	Th	*U*	*ITCF*
Error	0.14%	-6.79%	0.55%
R^2	0.9936	0.9985	0.9984
Pred. R^2	0.9878	0.996	0.9676

B. Multi-objective approach for the optimal fleet size and operating conditions

To establish optimal operating conditions for the process, it is essential to consider the following three objectives: maximizing output rate, maximizing capacity usage, and minimizing ITCF. Consequently, the problem can be modeled as a multi-objective optimization problem [41]:

Minimize

$$P = W_{Th}F_{Th} + W_U F_U + W_{ITCF}F_{ITCF} \quad (6)$$

Subject to:

$$2 \le x1 \le 4 \text{ integer} \quad (7)$$

$$10 \le x4 \le 15 \quad (8)$$

Where [36]:

$$F_{Th} = f_{Th}^{Id} - Th/ f_{Th}^{Id} \quad (9)$$

$$F_U = f_U^{Id} - U/f_U^{Id} \quad (10)$$

$$F_{ITCF} = f_{ITCF}^{Id} - ITCF/f_{ITCF}^{Id} \quad (11)$$

Where F_{Th}, F_U and F_{ITCF} are non-dimensional objective functions with an upper limit of one; f^{Id} is known as the ideal value of the performance measure and in our case, it was obtained by maximizing separately Th and U and minimizing ITCF; Th, U and ITCF are the metamodels (2), (3) and (4). The solutions to the multi-objective problem were obtained by assigning values to WTh in Eq (6) in the range 0.05 - 0.95 and distributing the remaining weights to WU and WITCF equally. The decision variables were x1 and x4 and have and are bounded on both sides, variable x4 upper bound was in conformity with the safety speed used in factories (Eqs 7 and 8). LINGO 13 software was utilized for the optimization calculations. Although metaheuristic approaches, such as Genetic Algorithms, are frequently cited in the literature [34], the computational efficiency of LINGO 13 in this specific case rendered their use redundant.

The optimization results presented in Fig. 3 show that maximizing output rate (WTh=0.90, 0.95) demands a larger fleet of vehicles. This increased vehicle count leads to a lower capacity utilization (U, Fig. 4), indicating more vehicle idle time or empty trips. As a result, the ITCF (Fig. 5) increases, highlighting the need to increase vehicle speed to 15 m/min to improve overall system efficiency.

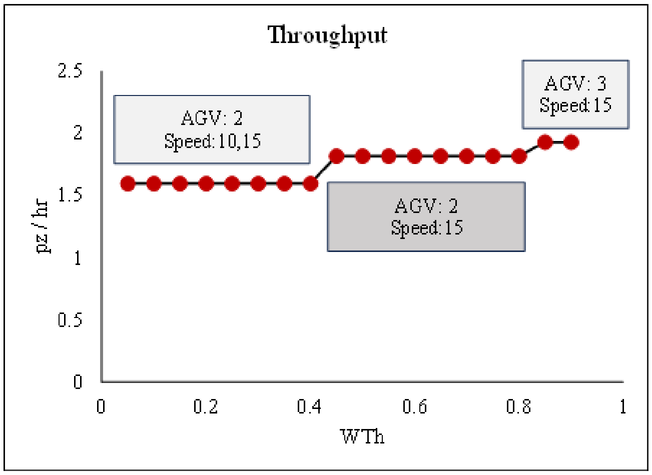

Figure 3. Th vs WTh

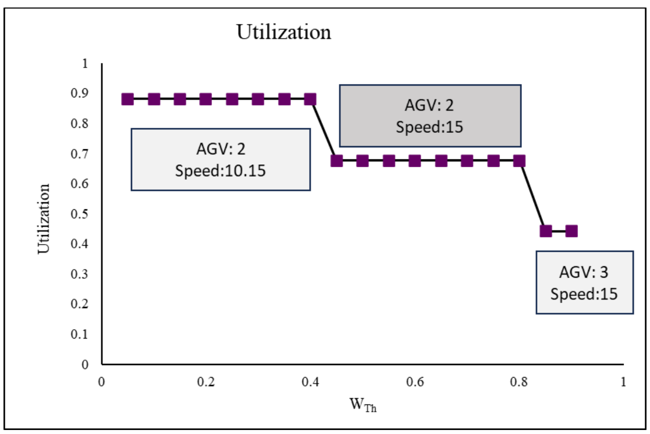

Figure 4. U vs WTh

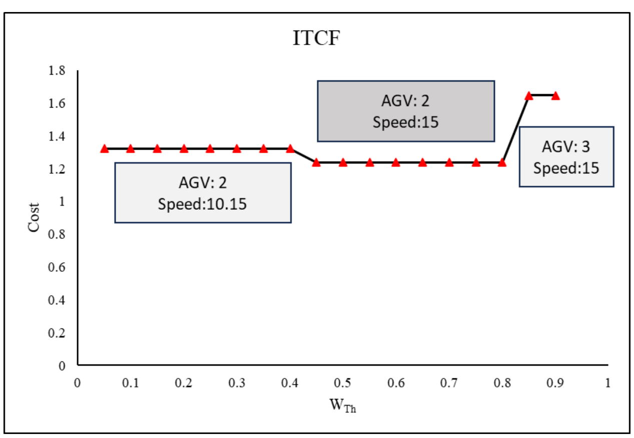

Figure 5. U vs W_{TH}

Conversely, when production weights are minimized (WTh = 0.05-0.4), the optimization results indicate that only two AGVs are necessary, and they operate at the lowest speeds (10-15 m/min). This configuration leads to increased capacity utilization and a corresponding reduction in ITCF, attributable to a decrease in vehicle idle time and empty journeys.

The solution set within the WTh = 0.45-0.8 range yields the minimum ITCF. This optimal result is achieved by utilizing two vehicles operating at 15 m/min, balancing output rate and capacity utilization at intermediate levels. This ITCF behavior aligns with previous observations: an increased vehicle counts leads to longer idle times and more empty journeys, contributing up to 95% of the ITCF.

The multi-objective model yielded three solutions, summarized in Table 9.

Solution 1 highlights the limitation of capacity utilization (U) as a sole indicator of material transfer efficiency. Despite a high U of 0.879, it fails to achieve a balanced cost structure. In contrast, Solution 3 prioritizes throughput (Th = 1.94), leading to low workstation utilization and higher costs associated with idle AGVs.Solution 2 demonstrates a trade-off, achieving intermediate values for both Th and U, and a more balanced distribution of ITCF components. This trade-off analysis suggests Solution 2 as a potentially favorable compromise, balancing efficiency and cost.

TABLE IX. SIMULATED RESULT OF THE MULTI-OBJECTIVE MODEL (LOADING AND UNLOADING TIMES WERE SET AT 10 SEC.)

Solution	**AGV**	**Speed**	***Th***	***U***	***IT of AGV***	***IT part***	***ITCF***
1	2	10.5	1.61	0.879	0.2418	1.12	1.3618
2	2	15	1.82	0.709	0.5816	0.531	1.1126
3	3	15	1.94	0.460	1.6182	0.0797	1.6979

V. CONCLUSIONS

Driven by increasing automation, industries require structured methodologies for optimizing operational parameters. Unlike studies that address specific cases with greater operational complexity, this paper presents a generic method for designing and analyzing manufacturing systems utilizing automated guided vehicles (AGVs). Employing simulation and I-optimal experimental designs, analytical approximations are obtained, prioritizing the reliability of predictions. Informed decision-making is supported throughout the process, using the principles of queuing theory as a guide for selecting appropriate regression models.

Recognizing the multi-objective nature of manufacturing cell design, as demonstrated by recent literature, this study considers performance measures with conflicting objectives (maximizing throughput or minimizing idle time) to ensure efficient operation and align with decision-makers' goals.

Our findings illustrate a trade-off: maximizing throughput necessitates increased AGV deployment, resulting in higher idle time costs to maintain material availability at workstations. Conversely, under the specific operating conditions examined, the experimental results demonstrate that material loading and unloading times do not significantly impact the chosen performance measures.

The multi-objective analysis revealed a balanced operational regime, simultaneously optimizing output rate, utilization, and idle time cost. This equilibrium is not discernible when focusing solely on output rate and is particularly useful when companies apply approaches such as Lean Manufacturing or the Theory of Constraints for decision – making. Specifically, a minimum idle time cost was observed within a defined operational interval. However, increasing the weighting of output rate (WTh) in the objective function led to a corresponding increase in idle time cost.

Future research should incorporate inventory costs, as well as downtime related to equipment recharging, failures, and maintenance. Additionally, overall equipment efficiency (OEE) should be considered as an additional performance metric to provide a more comprehensive evaluation of system performance.

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Optimizing Material Flow with AGVs in a Closed System Using Metamodels

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***Abstract*— The use of AGVs (autonomous guided vehicles) is becoming more and more frequent within the industrial automation strategy. The objective is to integrate industry 4.0, achieving faster and safer means of transporting raw materials, facilitating fleet management through tools that increase efficiency while being safe for the personnel in charge. All this with a primary purpose: to increase competitiveness. It should be emphasized that the use of VFA entails a large investment, so it is necessary to carry out a quantitative analysis. In this work we analyze a real case in which an AGV is used that moves from 7 to 1 dolly as a transport system, for the distribution of assembly parts, it also has 2 buffers for the reception of parts. The closed system has 5 workstations where the AGV pauses so that manually the operators take the necessary parts, it is worth mentioning that the AGV does not leave the system, it recirculates and at station 5 it only pauses to rejoin the system again. This system is simulated using the Arena software and a complete factorial DOE (design of experiments) 26 is created with a central point, which allows better control in the distribution of dollies in the workstations, avoiding crowds in the system and generating a good supply of material through the AGV. Once the simulation and the DOE have been generated, the metamodel is carried out to find the optimal number of dollys that maximize the output rate of the parts (th).**

Keywords-; AGV (Autonomous Guided Vehicle); optimisation; metamodel; simulation; throughput.

1. Introduction

In recent years, numerous manufacturing industries have been modernizing and this has been reflected not only in technological acquisition, but also in the ability to take the entire volume of information generated in the processes to the management systems, allowing the status of the plant to be consulted at all times, and consequently, enabling all the machinery for the exchange of information between them. thus achieving the migration of an entire process towards what is now known as Industry 4.0[23].

Nowadays, automation 4.0 has been of great relevance for production systems, as it allows companies to improve their efficiency, productivity and be competent in demands. The implementation of automation allows companies to optimize their production processes, mainly by reducing cycle time and increasing the production rate, avoiding blockages within the line. Production systems are given by a set of interconnected workstations (in series or network), which require a processing time. The objective is to integrate industry 4.0, achieving faster and safer means of transporting raw materials, facilitating fleet management through tools that increase efficiency while being safe for the personnel in charge. All this with a primary purpose: to increase competitiveness.

1. BACKGROUND

Recently, an AGV (Autonomous Guided Vehicle) transport system can be considered useful to be implemented in the automation and distribution of raw materials, such as a transport [15]. In the network of a closed system, the number of agents is constant since agents can neither arrive nor leave the system, but circulate repeatedly through the various stations at all times. Thus, a closed queuing network, which includes N queues, i.e., a series of N tails cyclically arranged in such a way that agents advance sequentially through the cycle, returning to the first station after beingserved at station N, is called a closed system. [16]

The number of AGVs can be obtained by quantitative calculationand/or simulation. However, appropriate criteria are used to make the decision. Therefore, an AGV is designed to transport a set of workpieces from storage to stations and back to storage. Thus, the autonomous guided vehiclewill serve only one station at a time. [31]

The problem is to increase the rate of production of the production system. Previously, the system had agglomeration at workstations and therefore blockages, so examining routing in AGV and location traffic problems from a network optimization perspective where manufacturing facilities are modeled as closed finite queue networks will avoid reducing this problem. Carry out a simulationmodel that allowsknowing and analyzing the process and the results of line improvement and consequently achieve greater performance to be able to absorb the appropriate production in a standardized cycle time and with the necessary material, avoiding waste and executing deliveries on time

1. Tools and methods

This section presents the tools that were used for the analysis of the closed production system where performance (Th) is maximized.

Work is carried out under the following restrictions:

$$Max\ Th\ (b_1, b_2, b_3, b_n \ldots\ldots) \quad (1)$$

$$Subject\ to: \quad 1 \leq b_n \leq 7 \quad (2)$$

$$b_n = whole$$

The maximization objective function represents the maximum number of dollies that can arrive at the station transported by the AGV. The bn condition represents the number of dollys carried by the AGv within the closed system. Integers are worked since thereare no transporters or dollys in fraction, only integer artifacts.

It is a closed system with a series arrangement where the AGV makes the journey carrying 7 dollys which carry a certain load of artifacts. Below is a sketch of the route taken by the AGV (Figure 1):

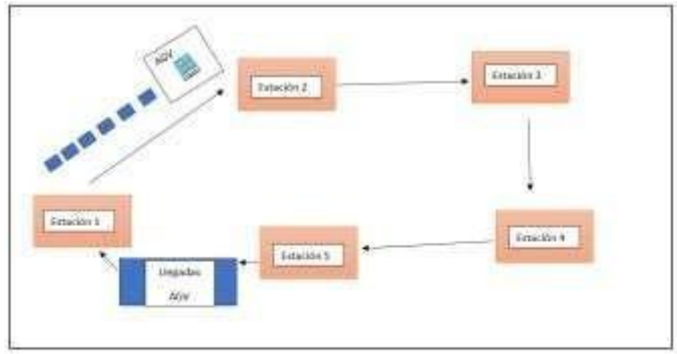


Figure 1. Diagram of the AGV journey in the Closed System.

A simulation model is used to analyze the process, as performance measures the throughput rate is used.

To make the analysis, the following considerations were made:

1. AGV speed is constant
2. Acceleration is already contemplated in the transfer of the AGV from one station to another
3. The AGV has the capacity to move 7 dollys
4. AGV monitoring is performed only on the circuit
   - The travel time already includes the load that the AGV has from station to station.

The method used is as follows:

1) A complete factorial experimental design 25 is constructed since 4 possible workstations are simulated where spaces can be generated for the arrival of the dollies and the number of dollies transported by the AGV. For this reason, it is not possible to work with a fractional design. For each combination, 2 replications were made; in total, 64 runs were obtained within the experiment, the results obtained are analyzed through the ANOVA.

2) The ANOVA is obtained in order to explain the behavior of a system based on a set of proposed variables, identify interactions between variables, quantify their importance and their effect on a response; where the analysis criterion is p value < 0.05, the results are expressed through a regression model.

3) The regression model is analyzed using the adjusted R2 criterion to draw a conclusion about the validity of the metamodel, which helps to verify whether the data obtained in *the simulator are correct as presented in the process diagram (Figure 2).*

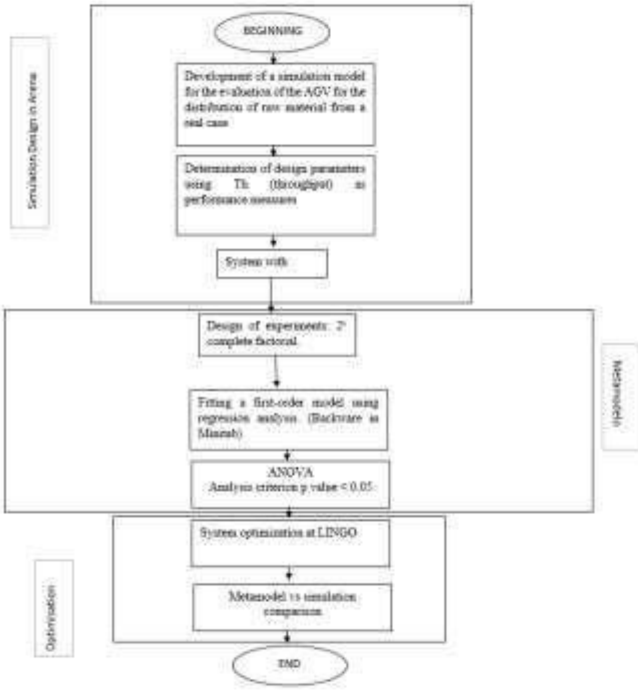
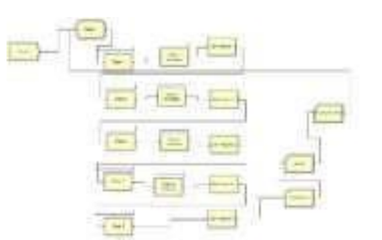


Figure 2. Process diagram

1. SIMULATION DESIGN

Discrete event simulation is often used in performance analysis due to its simplicity in terms of flow in line modeling. For this research, the Arena software was used where the simulation of the system was carried out as shown in the following figure (Figure 3) is only shown as an illustrative effect.

Figure 3 Simulator in Sand



The simulation was carried out under the following conditions:

The following are constants:

- Service Time = 1.125 betahours and 0.444 alpha hours with a Gamma distribution
- Time between arrivals = 0.25 hours with exponential distribution
- Simulation Time = 17 hours
- Number of replications= 3
- Number of servers = 5

These conditions are generated from the manufacturing parameters that are presented in the company, where it works with two shifts. The simulation time is the time covered by the 2 shifts but not the time of system stability. In this way, the values of th are found by means of simulation.

1. RESULTS

Table 1 presents the levels of the factors with which the design of experiments is obtained:

Table 1. Factor levels

Factors	Meaning	High Level	Low Level
A	Station 1 (Spaces)	1	7
B	Station 2 (Spaces)	1	7
C	Station 3 (Spaces)	1	7
D	Station 4 (Spaces)	1	7
E	Dollys	1	7
F	Availability	0.1	0.99

The results of ANOVA are presented in Table 2 for Th. In which the iterations of the terms can be observed, it should be noted that all the behavior is linear.

Table 2. ANNOVA for the Th

Fountain	GL	SC Ajust.	MC Ajust.	Valor F	Valor p
Model	19	89637.6	4717.8	27.00	0.000
Lineal	6	78935.7	13156.0	75.30	0.000
Station 1	1	19.8	19.8	0.11	0.738
Station 2	1	0.4	0.4	0.00	0.962
Station 3	1	9.4	9.4	0.05	0.818
Station 4	1	8.7	8.7	0.05	0.824

dollys	1	45295.7	45295.7	259.27	0.000
availability	1	33601.7	33601.7	192.33	0.000
2-term interactions	10	9134.3	913.4	5.23	0.000
station 1* station 3	1	525.1	525.1	3.01	0.090
station 1*availability	1	11.1	11.1	0.06	0.802
Station 2*Station 3	1	310.3	310.3	1.78	0.189
Station 2*Station 4	1	558.8	558.8	3.20	0.081
2*dollys station	1	18.3	18.3	0.10	0.748
Station 2*Availability	1	10.5	10.5	0.06	0.808
3*dollys station	1	3.4	3.4	0.02	0.889
3*Availability	1	4.0	4.0	0.02	0.881
Station 4*Availability	1	8.2	8.2	0.05	0.830
dollys*availability	1	7684.7	7684.7	43.99	0.000
3-term interactions	3	1567.5	522.5	2.99	0.041
Station 1*Station 3*Availability	1	520.7	520.7	2.98	0.091
2*Station 3*Dollys Station	1	507.5	507.5	2.90	0.095
Station 2*Station 4*Availability	1	539.3	539.3	3.09	0.086
Error	44	7687.0	174.7		
Total	63	97324.6			

According to the criteria that were set out above, adjusted R2 is consideredas a response factor, since R2 can become confusing because it can cover a large amount of data, which would bring it closer to 1. On the other hand, adjusted R2 only covers the data that is close to the adjustment line, therefore, its value becomes more accurate.

Table 3. Coefficient of determination

Model Overview				
	S	**R-cuad.**	**R-cuad. (ajustado)**	**R-cuad. (pred)**
Th	13.3807	88.96%	88.41%	87.44%

A step-by-step regression is used for the fit, as it is used in the exploratory stages of model construction to identify a useful subset of predictors. The process systematically adds the most significant variable or removes the least significant variable during each step. Obtaining the following equation:

$$Th = -32.87 - 0.48*B1 - 1.21*B2 + 1.16*B3 + 0.52*B4 - 17.00*D + 58.91*F + 0.169*B1*B2 + 0.480*B1*D + 0.482*B2*B4 + 1.214*B2*D - 0.405*B3*B4 - 1.160*B3*D - 0.90*B3*D - 0.524*B4*D - 0.91*B4*D + 27.78*D*F - 0.169*B1*B2*D - 0.482*B2*B4*D + 0.405*B3*B4*D + 0.902*B3*D*F + 0.906*B4*D*F \quad (3)$$

1. Th Optimization

To perform the optimization, equation (3) is used where you work with the lingo software to find the appropriate space assignments and avoid blockages in the production system. For this purpose, table (4) is shown for the Th. Where each of the numbers represents the number of Dollys that can reach the station. The 5 runs were taken from the design of experiments, since they have the mismos parametros de comportamiento que the optimal run, this to be able to compare the available spaces in each station vs. the optimal run and thus avoid crowds and blockages on the line.

Table 4. Assignment for Th in the Closed System

Race	A	B	C	D
1	2	1	2	1
2	1	1	2	2
3	1	1	1	2
4	1	2	2	1
5	2	1	1	1
Optimal	2	2	1	1

1. PROBLEM OPTIMIZATION SOLUTION

The optimization adjustment that was made vs. the simulation of the closed system is presented, it is observed that the distribution of the spaces that can be had for the arrival of the Dollys are adequate and avoid agglomeration during the AGV circuit allowing the transit of parts. It is triggered in this way by calculating the average error with equations 4 and 5, obtaining the comparison in table 5.

$$Error = \frac{adjustment\ data - adjustment\ simulation}{adjustment\ simulation} \quad (4)$$

$$\sum \frac{error}{number\ of\ total\ errors} * 100 \quad (5)$$

Table 7. Comparison of Th adjustment vs Th simulation

Reply	Adjustment	Simualtion	Difference	absolute	Error
1.00	111.10	110.45	0.65	0.65	0.59
2.00	111.82	112.47	-0.65	0.65	0.58
3.00	111.49	110.84	0.65	0.65	0.59
4.00	113.42	113.42	0.00	0.00	0.00
5.00	110.77	111.42	-0.65	0.65	0.58
optimo	112.90	112.90	0.00	0.00	0.00
				Average error	2.33%

1. Conclusions

According to the results presented, metamodels are tools that help identify the relationships between the set of variables with which a production process is analyzed. In this case, it was applied to know the interactions that exist between the spaces within the workstations with the dollies carried by the AGV within a closed production system with some failures within it.

It can be observed through the optimization of the assignments that each of the stations has for the dollies to arrive and supply the operators with artifacts, highlighting that for the Th the stations with less space are the last. This allows the AGV to circulate constantly without crowds within the system.

In addition, we are open to analyze a second facet in the research, where the OEE (global efficiency) measurement parameter can be added to compare whether it affects arrivals to the system, as well as its behavior.

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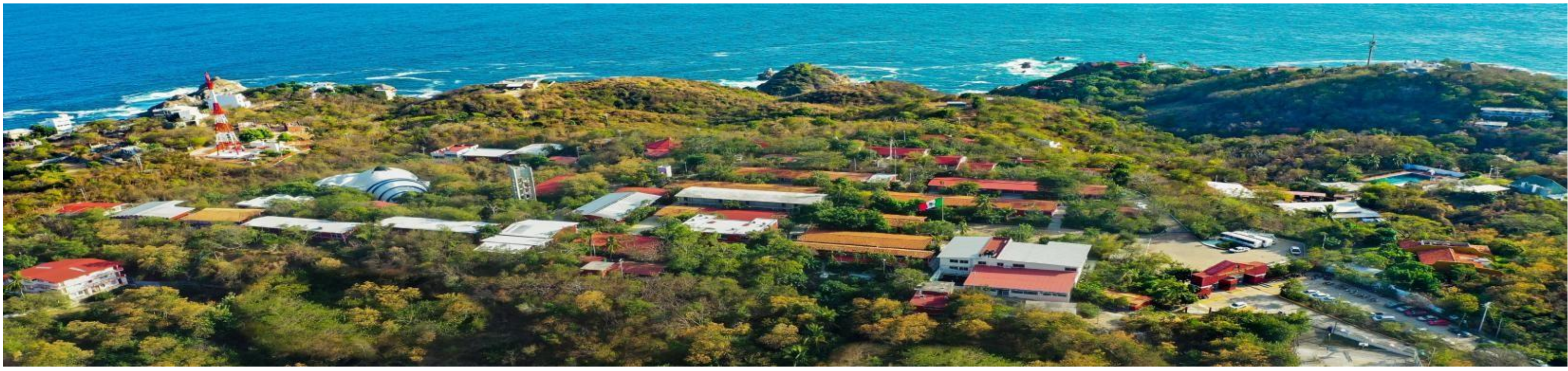

3- Maritime Logistics and International Trade Systems.

1- **Digitalización aduanera y comercio transfronterizo inteligente: retos y oportunidades para la facilitación del comercio en América Latina**
   - Jessica Margarita García Hernández

2- **Simulation-Based Analysis of Port Operations in Manzanillo**
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   - Idalia Flores

3- **Analysis of the Port Community System implementation process on the example of the Port of Szczecin**
   - Kateryna Dikhtiarenko, MSc
   - Bogusz Wiśnicki, PhD Eng

Simulation-Based Analysis of Port Operations in Manzanillo

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***Abstract*—The port of Manzanillo is a vital hub for international trade, but its complex operations can be difficult to manage and optimize. A simulation of the port's operations can provide valuable insights into its systems and processes, offering a powerful tool for improving efficiency and decision-making. This simulation creates a virtual model of the port, allowing us to replicate real-world scenarios and test changes in a risk-free environment. By simulating the movement of vessels, containers, and cargo, it is possible to identify bottlenecks, optimize resource allocation, test new strategies that means valuate the impact of proposed changes, such as a new terminal layout or an updated scheduling system, before implementing them in the real world. And predict future performance: Forecast how the port will handle increased trade volumes or unexpected disruptions.**

Keywords: simulation, operations, queue theory, decision-making, supply chain

I. Introduction

Maritime seaports are logistical hubs that vary in their levels of modernization, openness, connectivity, innovation, and national relevance, both in terms of international trade and domestic importance. As productive sectors that occupy territory and facilitate commercial activities, their significance is also shaped by their size, location, and management [1]. The quality of service provided by a port has a direct impact on the final price of goods. When these logistical and supply centers are integrated, the characteristics of new tasks and adaptive processes can enable a rapid response to various changes.

II. Literature Review: The Pivotal Role of Simulation in Container Terminal Operations Management

Container terminals are critical nodes in global supply chains, connecting maritime and land transport within complex intermodal networks. The increasing scale of containerization, coupled with technological advancements and rising demand, necessitates continuous adaptation and optimization of terminal operations. Simulation modeling has emerged as a fundamental prerequisite and instrumental tool for strategic decision-making in managing these complex, dynamic, and uncertain environments. This review emphasizes the pervasive and diverse application of simulation across various facets of container terminal and logistics operations, drawing from the provided literature.

The Foundation of Simulation in Port Development

The comprehensive review by Dragovic, Tzannatos [2] establishes the foundational role of simulation modeling in port development and project planning. Their analysis, spanning over 50 years (1961–2015), indicates an increasing favor for simulation, particularly in container terminals. The literature overwhelmingly addresses operational issues, with a high concentration in the field of operations research. The observed trend toward using simulation tools that yield the most realistic results underscores the commitment to developing tangible solutions for the maritime and transport industry, promoting sustainable ship-port interfaces and freight transport chains. The need for integrated solutions is also noted, pushing the dissemination of relevant literature into sector-specific fields like transport and maritime.

Discrete-Event and Agent-Based Simulation for Terminal Optimization
Simulation is applied across various functional areas of a container terminal, using distinct methodologies:

Operational Management and Configuration Analysis

- Carvalho [3] leverage Discrete Event Simulation (DES), developed in FlexSim, to create a simulation-based decision support tool for analyzing different container terminal configurations. A key focus is on automation and sustainable practices, particularly on reducing energy consumption. Preliminary results highlight the critical influence of sizing and planning the fleets of Automated Guided Vehicles (AGV) on total operating time, energy consumed, and battery charging costs. The work aims to test and validate the model at the Port of Sines in Portugal.
- Then, Gil Pereira [4] also employs a DES model (using Anylogic software) to dynamically analyze and forecast the behavior of a new Smart Pre-Gate at the Sines Container Terminal. By varying processing time and the number of active lanes, the simulation forecasts potential problems, predicts pre-gate behavior, and provides insights into preventing congestion. The goal is the development of a reliable digital twin.

Berth Allocation and Vessel Priority: Yıldırım, Aydın, and Gökkuş [5] address the non-trivial Berth Allocation Problem (BAP) using a decision support system coupled with a simulation optimization module based on the Artificial Bee Colony algorithm. By testing various scenarios, including single-queue (SQM) and multiple-queue (MQM) models with different vessel priority rules (First Come First Served (FCFS) and a proposed Hybrid Queue Priority (HQP)), the study shows that HQP with SQM further minimizes average vessel waiting times and increases berth utilization and port throughput at the Izmir port, demonstrating the value of simulation-optimization for resource-constrained problems.

Impact of Call Size and Uncertainty: The work by Veenstra and de Waal [6] uses standard container terminal simulation software to analyze the operational impact of large container ship call sizes on terminal efficiency and hinterland modes of transport. By incorporating dynamic crane productivity and arrival time uncertainty, the experiments reveal that large call sizes create operational peaks in subsystems like quay cranes and gates. Crucially, they find that higher uncertainty in arrival times deteriorates performance and that the impact on hinterland modes of transport (barges and feeders) is greater than on the deep-sea vessels. They also offer the first simulation-based insight into the impact of split call size.

Simulation for Intermodal and Supply Chain Connectivity
Simulation extends beyond the terminal gates to assess broader logistical and intermodal networks:

1. Inland Terminal and Waterway Integration: Benedecti, Silva, and da Costa [7] focus on enhancing maritime supply chain connectivity between the city of Joinville and Itapoá Port in Brazil. Their primary contribution is the evaluation of a proposed inland container terminal and waterway service using an Agent-Based Simulation Model. The results demonstrate operational, economic, and environmental viability, showing a 65% reduction in truck dwell time, a 65% decrease in greenhouse gas emissions, and a 2% reduction in costs for end customers compared to the current truck-centric scenario.
2. Optimized Allocation across Supply Chains: Richter, Martins-Turnera, and Nagel [8] present an extension of an agent-based logistics simulation to consider freight delivery across multiple possible logistics chains. This addresses a key limitation of previous studies and allows for the iterative optimization of assigning freight requests to different logistics chains (composed of depots, hubs, and carriers). The work develops and presents appropriate assignment methods and rescheduling strategies, highlighting the advantages of simulating the use of multiple logistics chains in constructed and real-world scenarios.

Relevant publications, ranging from methodological approaches to the application of various simulations, have been documented in the aerospace sector. For example, addressing port congestion problems by exchanging abstraction levels across different studies [9]; improving cargo handling prediction to better manage port capacity [10]; or quantifying compliance costs in port operations [11]. These works provide an important foundation for establishing the initial simulations for the Port of Manzanillo, following the classical theoretical simulation methodology [12].

III. MANZANILLO SEAPORT FRAMEWORK

A. Structural layout and Operational framework

Manzanillo seaport plays a key role in foreign trade, handling a wide range of goods in compliance with transaction regulations. Conceptualized as a system, the Secretariat of the Navy designated Manzanillo as a Smart and Secure Port (Puerto Inteligente y Seguro, PIS) in 2022. This designation involves the digitalization of administrative and operational processes to enhance management and efficiency. It is essential to consider the port's level of automation, which helps minimize undesired events and facilitates interaction with stakeholders to respond swiftly to potential risks. Currently, the system includes registered clients, employees, companies, vehicles, operations, permits, and financial tracking. Additionally, Manzanillo Port holds a Clean Port certification, which reflects its effective management of emissions across its infrastructure and operations. This "zero-emission" infrastructure encompasses vehicles, cranes, locomotives, and vessels, as well as the utilization of LNG-powered ships for maritime transportation. Some of the principal activities include transit, transportation, logistics, and distribution. These can be categorized as part of a supply network encompassing the following areas, based on [1]:

1. Cargo handling, operation, and transfer
2. Storage: tanks, silos, and warehouses
3. Management of loose and consolidated goods
4. Cargo management
5. Distribution of information and materials
6. Customs and phytosanitary processing

In addition, the most relevant internal processes carried out at the port include:

1. Receiving and storing goods for production
2. Order picking and preparation
3. Assembly
4. Delivery of goods
5. Consolidation and deconsolidation
6. Direct transshipment
7. Inventory management: transition and distribution

To provide a general representation of the operations within the seaport, the activities that add value to the internal flow of materials are systematically organized. The process mapping is presented in Figure 1.

The physical size of the seaport is framed by describing its known storage capacities and the layout that currently supports port operations. Figure 2 displays the official and operational layout of the Manzanillo seaport. In terms of physical size, the Manzanillo seaport occupies a total area of 437 hectares, including water zones, docks, and storage facilities; 19 berthing positions: 14 for commercial use, 3 for hydrocarbons, and 2 for cruise ships. Polygon 2 is the most developed area, covering a road infrastructure of 6.2 km of internal roads for cargo movement and 24.70 km of railway tracks. Manzanillo seaport is operated by 14 companies, both private and national, and both national and foreign. A description of storage capacity, the seaport considers 60,000 tons for gypsum; 3,5000 tons for storage frozen seafood, 3 silos with a capacity of 7,000 tons each for bulk installation; 13,900 m³ for palm oil and fish oil as liquid bulk container, and capacity to store between 25,000 and 50,000 tons of cement.

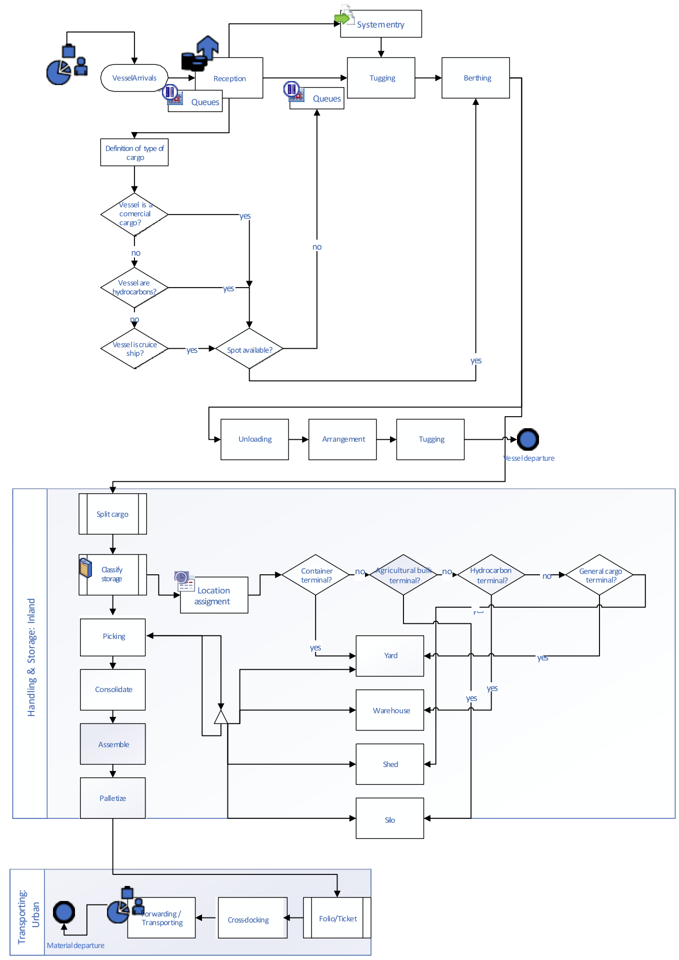

Figure 1. Process flowchart of operations at the Manzanillo seaport.

B. *Risk and Vulnerability factors of Manzanillo seaport*

According to CENAPRED's risk classifications, the Manzanillo seaport is exposed to multiple natural disasters documented by the Government of Mexico. Using the publicly available mapping platform, we delineated the Manzanillo seaport zone and selected layers corresponding to officially defined natural disaster categories. Figure 3 presents the relevant geospatial data.

By leveraging the public data set, it is possible to assess municipal vulnerability in relation to the seaport (see Figure 3, part a). Specifically, when applying the tsunami risk layer to the Manzanillo seaport zone, the results indicate the presence of potential local tsunami events, represented by the yellow line

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(see Figure 3, part b). Furthermore, analysis of the cyclone hazard layer shows that Manzanillo ranks among the highest-risk areas within the Pacific region (see Figure 3, part c). Similarly, the flood vulnerability layer reveals that the region exhibits high susceptibility to flooding, reinforcing the critical need for disaster preparedness (see Figure 3, part d).

Figure 2. Layout of Manzanillo seaport.

This is further supported by the flood hazard indicator shown in part e. Finally, when applying the hurricane category layer, the analysis suggests that Category 1 hurricanes are the most likely to affect the Manzanillo seaport (see Figure 3, part f).

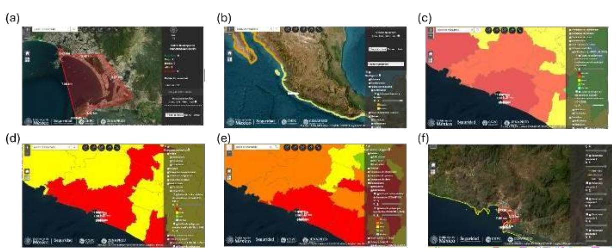

Figure 3. Identification of hazard types affecting the Manzanillo seaport. Source: Official data from Government of Mexico.

The potential risks associated with port operations and services stem from market globalization, product life cycles, and the rise of outsourcing. To address these risks, this study analyzes the costs, time, and quality factors that contribute to disruptions within the maritime port as a productive system. Some of the principal risk categories include *disruptions, delays, systems: operation and organization, forecasting, procurement, capacity, inventory, and accounts receivable.*

Port operations face various risks due to environmental changes, natural hazards, extreme weather events, human activities, and the need for sustainable post-event management. And some of its infrastructure challenges are port structure, port scaling, the absence of a coastal buffer zone, which increases both risk and operational costs, and risk response strategies. In terms of impact dimensions, the occurrence of an undesired event is generally characterized by Physical, oceanographic, economic (Contingency amount = economic + operational), social, and cultural impact. Similarly, the vulnerabilities factors identified so far can be generally categorized as: human activities, cruise operations, manual labor, and centralized decision-making. Key natural disasters to be considered in the port's undesired event profiles include tsunamis, flooding, cyclones or typhoons, and Earthquakes.

To derive the corresponding simulations, as well as the data collection and definition of the simulation models, the Manzanillo Risk Atlas for 2024 [13] has been taken as part of the inputs. As baseline information, the disaster analysis has been important to identify the natural hazards applicable to the port area of Manzanillo. For example, it is known that the port is in a zone prone to tsunamis, earthquakes, hurricanes, pluvial, fluvial, and coastal floods, and storms; without excluding landslides, fires, and compound accidents. In fact, the last earthquake reported according to the 2024 atlas occurred in 2022. Currently, the atlases focus on risk analysis for housing, since the operation of the port of Manzanillo is safeguarded by the national Navy, and consequently is not public openly available. Nevertheless, the reports issued by the Mexican government serve to associate the risk taxonomy with what is applicable (in the first instance) to the port of Manzanillo.

The nature of port operations requires the inclusion of risks taxonomies and categories, as detailed in Tables 1 and 2 [14]. While Table I presents the general description to every risk category, Table II determines a general taxonomy for seaports and the potential domain. Additionally, for tables I and II we establish the occurrence possibilities for each risk category represented as follows: 🟢confirmed, 🔴 not applicable, and 🟡 uncertain. The *a priori* classification is proposed based on the Disaster Risk Atlas published by the Mexican government in 2024.

TABLE I. RISK CATEGORIES BY OPERATIONAL IMPACT.

Category	Description	Ocurrence at the Port of Manzanillo
Disruption	Natural disasters, labor disruptions, supplier bankruptcy, war or terrorism, and reliance on a single supply source	🟢
Delays	High utilization at loading points, inflexible sourcing, poor supplier performance, excessive border handling or mode changes	🟢

Systems	Information infrastructure failure, system integration, extensive e-commerce	🟡
Forecasting	Inaccurate forecasts due to short lead times, seasonality, product variety, short life cycles, small customer base, bullwhip effect	🟡
Procurement	Exchange rate risks, single-source component risks, full capacity utilization, long vs short-term contracts	🟡
Accounts Receivable	Number of clients, financial strength of clients	🟡
Inventory	Product obsolescence rate, inventory holding costs, product value, demand/supply uncertainty	🟡
Capacity	Capacity cost, flexibility in capacity	🟡

TABLE II. GENERAL RISK TAXONOMY FOR MARITIME PORTS.

Category	Description	Domain	Ocurrence
Human	Caused by workers' lack of planning adherence	Land	🟡
Natural	Atmospheric, hydrological (e.g., tsunamis), and geological hazards	Sea – Land – Urban	🟢
Technological	Inadequate or insufficient information, outdated equipment	Land	🔴
Environmental	Uncontrollable: floods, natural disasters Controllable: broken roads, blackouts, cargo spills, noise	Mixed	🟢
Security	Illegal imports, terrorism, piracy, ship attacks, kidnapping, arson	Mixed	🔴
Economic	Inflation and interest rates, deferred payments, contractor financial issues	Land	🟡
Operational	Equipment and machinery failures, unloading accidents, grounded vessels, cargo spills	Sea – Land	🟡
Legal	Changes in laws and regulations	Land	🔴
Organizational	Inefficient basic communication, structural limitations, security blockages	Land	🔴
Pollution	Noise, waste, dust, dredging, air pollution, congestion, traffic, wastewater	Mixed	🟢
Machinery	Damage to machines, engines, equipment, and electrical errors	Land	🟡
Political	Government policy changes, lack of transparency, contract disputes, war	Land	🔴
Financial	Profitability (NPV, ROI, utility, benefit)	Land	🔴
Fire	Caused by mechanical or electrical energy converting to heat, flames, sparks	Land	🟡
Weather	Wind, rain, thunder, fog, flooding	Sea – Land	🟢

Despite all the information found in public and academic sources, it is not currently possible to establish a quantitative value for the severity or probability of the different risks. However, it is possible to determine the risk factors related to natural disasters applicable to the port of Manzanillo. In the following sections, the results obtained from the first simulations conducted to generate information are presented.

Based on all the above information published for the port of Manzanillo regarding risks, together with the existing risk taxonomy applicable to seaports, the first simulations are established. These are based on: (1) determining the recurrent loss of tonnage due to the occurrence of natural disasters, and (2) assessing the impact on the unloading cycle times of certain vessels.

C. About costs

To assess the related costs and integrate them into operations using a reductionist approach, the analysis focuses on total cost. This total cost is primarily composed of fixed costs, entry costs, manufacturing costs, transportation costs associated with storage, and market costs [15].

Some strategies to respond and face all risks related to the costs described below can be *Acceptance* understanding as the assumption of economic consequences; *Transfer the consequences,* meaning as sharing risks partially or fully with stakeholders, clients, insurers, among others; *Generate Information* by conducting tests and simulations to anticipate events.

IV. MANZANILLO SEAPORT SIMULATIONS

A. Input-Output Simulation (I-O)

The Input-Output simulation proposed in this paper aims to characterize how tons of materials can be affected during a natural disaster. This approach is enough to map the behavior of material loss affected by tsunamis, big earthquakes, floods, and cyclones. The simulation time was set to 51 weeks to represent one year of material flow at the Manzanillo Seaport.

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We chose Simio as our simulation software because it has the advantage of allowing this model to be reused in future simulations. This simple model approach can be reproduced to achieve the same results. To simulate different natural disasters, we established rates calculated as failure distributions. Then, a repair distribution was programmed to imitate the recovery time for undesirable events. As a first approach, we considered the times shown in Table III.

The capacity programmed for the server that represents the entire seaport was set to 8,600 entities as a fixed quantity, based on the Tons handled by the seaport for one year. Meanwhile, an off-shift rule was programmed to allow already-started work to be completed, simulating queues caused by potential delays identified in the process map. A failure type was then selected to represent situations in which the seaport is disrupted due to a natural disaster. To simulate this behavior, uptime between failures and time-to-repair distributions were programmed for each natural disaster.

For reproducibility of the I-O simulation model, consider the layout shown in Figure 4, which consists of a source, server, and sink. The model simplifies the quantity of Tons the seaport can handle during a year. This initial approach aims to establish the amount of tonnage lost when a natural disaster occurs.

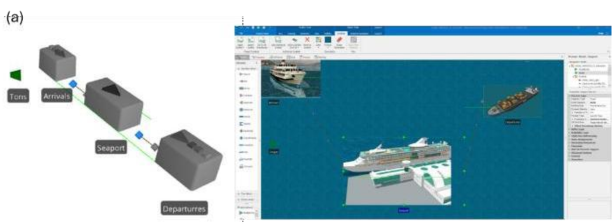

Figure 4: Basic Lay-out for I-O seaport simulation. (a) Basic objects used to simulate the tons handled by the seaport. (b) Basic animation representing the I-O simulation model.

The material handling cost and cost related to the use of consumables were programmed using parameters obtained in public repositories. These costs are a charge reported to every vessel arriving at the Manzanillo Seaport. Based on this, we can estimate and propose a Cost per Ton. The parameter for the material handling cost is 100 USD, while the cost of consumables used is calculated at 10 USD per Ton.

Natural disaster information was collected from public repositories of the Mexican government. As a part of the data collection for the simulation [12], the input data for the simulation models were obtained from public repositories: for earthquakes and tsunamis, the records of the National Seismological Service (SSN) were reviewed; for floods, the data were established based on publications form the National Center for Disaster Prevention (CENAPRED); while for cyclones, the records consulted were those published by the National Water Commission (CONAGUA). Moreover, as a part of the simulation assumptions, the recovery times for the different disasters were estimated based on reports from CENAPRED. However, these recovery times are not officially published by Mexican governmental sources. Table IV presents the corresponding rates for each disaster-related input data.

TABLE III. INPUT PARAMETERS FOR THE SIMULATION

Natural Disaster	Arrival rate (per year)	Recovery Distribution
Tsunami	0.0704	Random.Triangular (10,30,100) days
Big earthquakes	0.09412	Random.Triangular (5,15,30) days
Floods	253.33	Random.Triangular (1,7,15) days
Cyclones	18.19	Random.Triangular (0.5,2,5) days

On the other hand, we recorded information about the tons processed at the Manzanillo seaport, as published by ASIPONA from 2016 to 2024. The data available in the public repository was used to calculate rates per day, week, and month. The following table presents these rates.

TABLE IV. TONNAGE AND PROCESSING RATES BY PERIOD (2016-2024).

Year	Annual (Tons)	Rate: Tons per day	Rate: Tons per week	Rate: Tons per month
2024	31,408,624	86,051	615,855	2,617,385
2023	34,434,270	94,340	675,181	2,869,522
2022	34,434,272	94,340	675,181	2,869,522
2021	35,024,782	95,958	686,760	2,918731
2020	32,504,297	89,052	637,339	2,708,691
2019	29,469,819	80,739	577,839	2,455,818
2018	30,385,784	83,248	595,799	2,532,148
2017	27,980,646	76,659	548,640	2,331,720
2016	26,138,538	71,612	512,520	2,178,211

As a result of the model, two main output variables were measured for each natural disaster per year from 2019 to 2024. The main output variables were:

- Quantity of tons departure without natural disasters, which measures how many tons are generated by the I-O model every year.

- Quantity of tons departure from natural disasters, which measures how many tons are released from the seaport once the disaster occurs and the recovery period has passed.
- Average yearly cost of total losses per ton, which is calculated by aggregating the costs of material handling and consumables usage per ton.

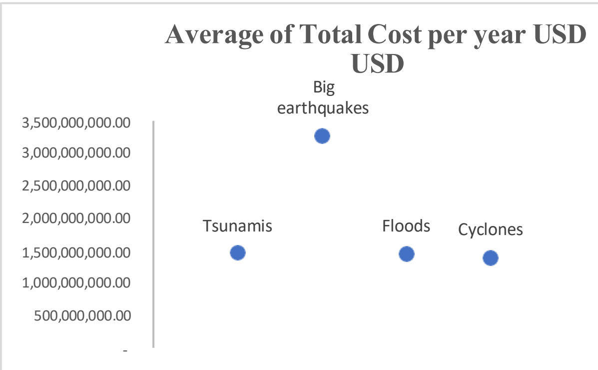

Figure 5. Annual Average of Estimated total costs from natural disasters (simulation results)

Another result that is interesting from the simulation is that floods can disrupt the entire system. The initial simulations described earlier aim to produce preliminary results regarding the financial magnitude of losses, based on the tons handled by the seaport over nine years.

The recovery time from any natural disaster is a critical factor in the model; the results are sensitive to the number of weeks required to restore operational conditions. In the following figure, we show that I-O simulations are significantly disrupted under flood conditions (see Figure 6). In this scenario, many consumables and infrastructure components cannot be quickly recovered, and supplies and goods are completely damaged. Big earthquakes result in substantial economic losses, as they cause damage to goods and often lead to the collapse of critical infrastructure. When comparing these two natural disasters, floods render the Manzanillo seaport inoperative, as recovery requires not only repairs but also waiting for water levels to recede. In terms of time, flooding is the natural disaster that most severely affects port operations. On the other hand, large-scale earthquakes have a greater financial impact due to the destruction of infrastructure, equipment, and goods owned by the port, as well as those being transported through it.

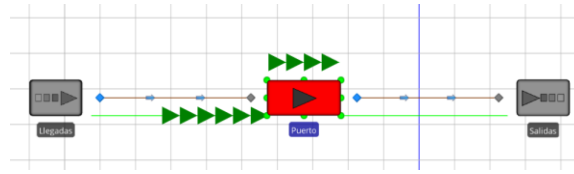

Figure 6. Impact of flood behavior on seaport simulation.

B. *Shipping simulation model*

Ships arrive and wait to be assigned a berth. Once a spot becomes available, a tugboat performs the docking maneuver. Subsequently, cranes are assigned to carry out the loading and unloading of goods. After the operation is completed, another tugboat escorts the ship back to open sea. A simulation model was built using ARENA R16 (Fig. 7), representing a simplified version of port operations. The goal is to visualize and quantify the dynamics of this port and assess the impact of events that interrupt operations—in this case, cyclones.

For input data [12], operational conditions are presented in Table V and were obtained from various sources, such as ASIPONA Manzanillo and the General Coordination of Ports and Merchant Marine, SSA, CENAPRED, and CONAGUA.

TABLE V. OPERATIONAL DATA

Parameter	Value
Time between arrivals (hours)	4
Blocks	15
Number of cranes	10
Loading/unloading time (hours)	38
Tug maneuver time (hours)	0.5

Interruptions due to hurricanes are modeled as random system failures, where both the time to failure and downtime are exponentially distributed random variables.

Performance metrics include average dwell time, ship service rate, and queue length. The analysis was divided into two periods: the hurricane season in the Pacific Ocean, which spans from May 15 to November 30 (198 days), and the off-season from November 31 to May 14, when the likelihood of such events is lower.

TABLE VI. CYCLONE EVENT PARAMETERRS

Element	Nov 31 – May 14	May 15 – Nov 30
Days	167	198
Time between events (days)	90	30
Failure duration (days)	3	3

Specific conditions are shown in Table VI. Since the objective is to quantify the impact of interruptions on ship loading and unloading operations, the time between events is assumed to follow a random pattern, while the failure duration is modeled as an exponentially distributed random variable.

The results indicate that, on average, a ship requires approximately 69.33 hours (or about 2.88 days) to complete the entire process from arrival to departure (Fig. 7).

Specific conditions are shown in Table VI. Since the objective is to quantify the impact of interruptions on ship loading and unloading operations, the time between events is assumed to follow a random pattern, while the failure duration is modeled as an exponentially distributed random variable.

TABLE VII. CYCLONE EVENT PARAMETERRS

Element	Nov 31 – May 14	May 15 – Nov 30
Days	167	198
Time between events (days)	90	30
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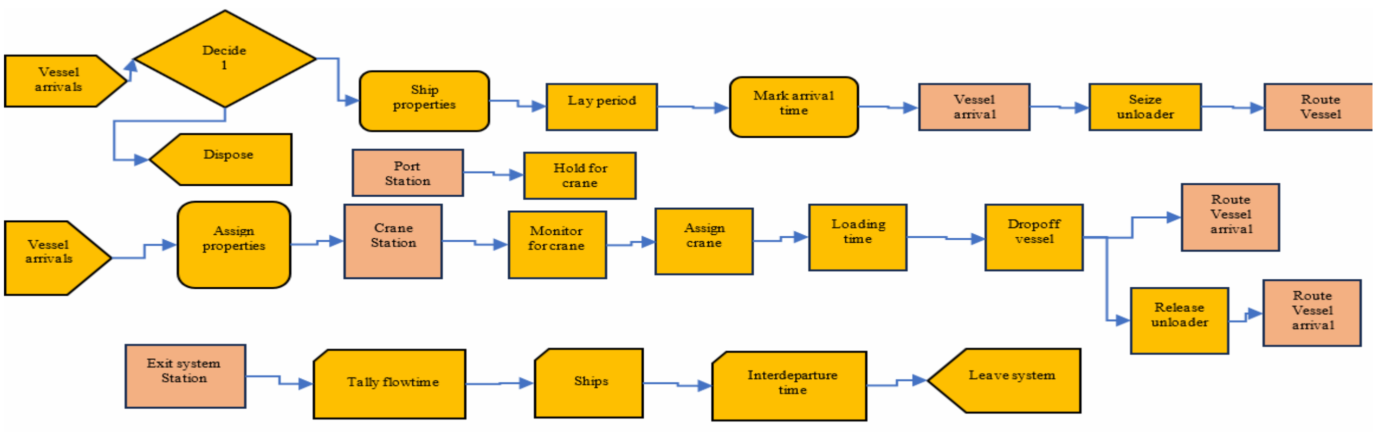

Figure 7. Shipping simulation model in Area

The average time to access a block is 15.19 hours, and the average wait time for crane assignment is 6.86 hours (Table VII).

During the off-season, there is a 3.9% reduction in cycle time, a 20% decrease in block wait time, and a 20.5% increase in crane assignment wait time.

On average, crane utilization is 81.3% during cyclone season and 81.6% during the off-season. Cycle time variability was measured using the coefficient of variation, yielding an average value of 0.6702, indicating moderate variability. In the off-season scenario, variability slightly increased to 0.6842 but remained within the moderate range.

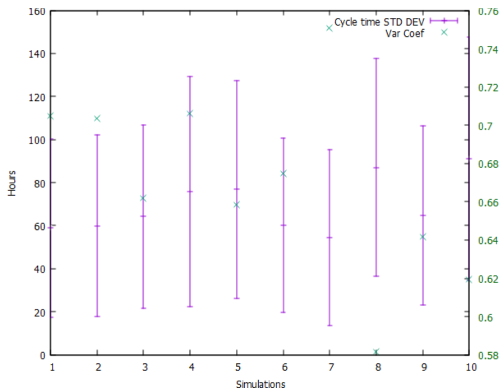

Figure 8. Cycle time of 10 simulations

TABLE VIII. PERFORMANCE METRICS

Metric	Cyclone Season (Mean / Std Dev)	Off-Season (Mean / Std Dev)
Total cycle time (hours)	69.33 / 42.05	66.576 / 45.55
Block waiting time (hours)	15.19 / 32.75	12.167 / 31.04
Crane waiting time (hours)	6.86 / 3.708	8.27 / 8.49
Throughput (ships per day)	5.99/0.16	5.99/0.123

C. V&V process

Validation and Verification (V&V) are essential and distinct processes employed to establish the accuracy and credibility of a simulation model. These procedures are critical for building confidence in the model's results and confirming its fitness for the intended use. In one hand, verification confirms that the computer program and its implementation accurately represent the developer's conceptual description and specifications. This process addresses the question: "Are we building the model, right?", we answer the question by test and methods as code inspection, data flow tracing, and checking for numerical errors.

On the other hand, validation is an external assessment that determines if the model is an accurate representation of the real-world system for its intended use. Its goal is to prove the model's accuracy is satisfactory for the application. A model is only valid for the specific purpose it was built for. The corresponding question addressed is "Are we building the right model?". In particular, we employed approaches such as face validity through expert review, validation of our model's assumptions, and input-output comparison by matching the model's results with data from the actual system.

The following tests were systematically applied to verify and validate the model structure, followed by necessary adjustments. These tests were executed for every simulation run [12, 17, 18, 19]. Table VIII summarizes the entire process, detailing the role of each simulation software used. The V&V process for the model involved two phases of testing conducted for every simulation run:

1. Partial Tests (Verification): Focused on internal components like object connections and parameterization (e.g., failure rates, recovery distributions).

2. Global Tests (Validation): Focused on external performance, specifically comparing simulated entity volume (tons) with the annual tonnage reported by the Manzanillo Seaport and comparing average ship waiting time with the overall Cycle Time.

TABLE IX. V&V TESTS

Model	Test	Verification	Validation
Simio / Arena	**Partial:** Connection between the objects of the model, as sources, servers, sink, paths and connections between them. **Parameters**: Review of the programmed behavior of natural disasters, including failure rates and recovery distributions proposed. **Structural** and behavior tests: verification of the output behaviors: quantities, timing, and scheduled interruptions.	X	
Simio / Arena	**Input-Output comparison:** Between tons (entities) generated by the model under the proposed distributions and the annual tons reported by the Manzanillo Seaport. For Natural Disaster behavior, public data are collected to estimate the annual disaster rates that may affect the port of Manzanillo; at the end of the simulation, this value is		X

	compared with the programmed simulation time. **Outputs:** Comparison between the average time waiting for each ship and the cycle time		

Interpretation of Findings

The key findings derived from the two simulations are summarized as follows:

1. The volume of tonnage passing through the port under various natural disasters, including floods, tsunamis, cyclones, and earthquakes based on the estimated recovery times for each event.

2. The cycle time for unloading different vessels when a natural disaster occurs.

This approach enables a clear integration of the most relevant input variables for subsequent simulations. For instance, the predefined times for the shipping process, the amount of tonnage affected by different risk factors that compromise the Port of Manzanillo, and an initial estimation of expected losses in terms of units and time. The simulations developed for this study were intended to generate information regarding recovery times for each natural disaster, material flow, and shipping times.

The current simulations can be used to estimate forecast situations as scenarios involving an increase in the frequency of cyclones due to global warming. Establishing a plausible recovery time for each type of disaster is essential to ensure port operations from a financial perspective.

Conclusion and Future Directions

The literature strongly affirms that simulation, both Discrete-Event and Agent-Based, is indispensable for modeling, analyzing, and optimizing the multifaceted and complex operations of modern container terminals and their integration into the wider global logistics network. It is crucial for:

- **Strategic Decision-Making:** Evaluating the impact of automation, new terminal configurations, and sustainability practices [3]
- **Operational Enhancement:** Optimizing resource allocation, such as berth scheduling [5] and pre-gate flow management [4].
- **Systemic Analysis:** Understanding the trade-offs of large vessel call sizes and the impact of uncertainty [20]
- **Intermodal Integration:** Assessing the viability and benefits of new logistical structures like inland terminals and multimodal freight allocation [7,8]

Future research, as indicated in the literature, should continue to explore additional operational factors (e.g., storage area reorganization), incorporate advanced optimization techniques for resource allocation, and progress toward developing validated digital twins based on real-world case studies, such as the ongoing work planned for the Port of Sines.

As highlighted during the development of the simulations presented in this study, future research emphasizes the validation of results derived from publicly available related data sources. This step is essential to ensure the robustness and credibility of simulation outcomes as a first approximation. Furthermore, simulation methodologies offer valuable insights into behavioral responses and enable the estimation of potential economic losses in scenarios involving natural disasters or compound risks.

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Digitalización aduanera y comercio transfronterizo inteligente: retos y oportunidades para la facilitación del comercio en América Latina

Hacia un ecosistema Aduanero interoperable y sostenible

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Resumen
La transformación digital está redefiniendo los procesos aduaneros a nivel global, impulsando el concepto de "aduanas inteligentes" mediante el uso de tecnologías emergentes como *blockchain*, inteligencia artificial y análisis de datos. En América Latina, esta transición plantea desafíos estructurales y normativos, pero también oportunidades para fortalecer la competitividad y la transparencia en las cadenas logísticas internacionales. Este trabajo analiza el impacto de la digitalización en la gestión aduanera, tomando como referencia los lineamientos de la Organización Mundial de Aduanas (OMA) y la Agenda de Facilitación del Comercio de la OMC, con especial énfasis en los casos de México, Chile y Colombia. El objetivo es evaluar el grado de avance y los retos, identificando prácticas exitosas y proponiendo un conjunto de recomendaciones concretas, especialmente para México, con el fin de mejorar la **interoperabilidad** y el **control no intrusivo**.

Abstract:
Digital transformation is redefining customs processes globally, driving the concept of "smart customs" through the use of emerging technologies such as blockchain, artificial intelligence, and data analytics. In Latin America, this transition poses structural and normative challenges but also presents opportunities to strengthen competitiveness and transparency in international logistics chains. This paper analyzes the impact of digitalization on customs management, referencing the guidelines of the World Customs Organization (WCO) and the WTO's Trade Facilitation Agenda, with a special focus on the cases of Mexico, Chile, and Colombia. The objective is to evaluate the degree of progress and the challenges, identifying successful practices and proposing a set of concrete recommendations, especially for Mexico, to improve interoperability and non-intrusive control.

Palabras clave
Digitalización aduanera; facilitación del comercio; interoperabilidad; OMA; logística internacional

1. Introducción: El paradigma de las Aduanas inteligentes.

La logística y el comercio internacional están experimentando una disrupción sin precedentes impulsada por la **cuarta revolución industrial**, la cual exige una redefinición completa de los procesos transfronterizos. En este contexto, la función aduanera ha evolucionado de un rol meramente fiscalizador a un facilitador estratégico del comercio global [5], [6]. La función aduanera, históricamente centrada en la recaudación fiscal y el control físico, está experimentando una transformación fundamental impulsada por la **digitalización** y la convergencia de tecnologías emergentes. Este cambio paradigmático posiciona a la aduana como un agente estratégico de la **facilitación del comercio** global [5], [6]. La adopción de sistemas inteligentes (*smart customs*), que integran *blockchain*, la inteligencia artificial (IA) y el análisis de datos masivos, ya no es una opción, sino un requisito para garantizar la competitividad y la seguridad de la cadena de suministro internacional.

A nivel internacional, la **Organización Mundial de Aduanas (OMA)**, a través de su Marco Normativo SAFE [5], y el

Acuerdo sobre Facilitación del Comercio (AFC) de la OMC [6], han definido los pilares para esta modernización: reducir la burocracia, aumentar la transparencia y optimizar la gestión de riesgos. Sin embargo, en América Latina, la implementación de estas directrices enfrenta desafíos estructurales y regulatorios que limitan la plena **interoperabilidad** entre las agencias gubernamentales y los actores privados.

Esta brecha de eficiencia se traduce directamente en sobrecostos y demoras que afectan la competitividad regional, un aspecto clave en la discusión sobre movilidad y logística. Este trabajo se enfoca en el análisis de la madurez digital aduanera en **México, Chile y Colombia**, países estratégicos que han avanzado en la implementación de Ventanillas Únicas de Comercio Exterior (VUCE).

El **objetivo** de esta investigación es evaluar el grado de avance y los retos de la digitalización en las aduanas latinoamericanas, identificando prácticas exitosas y proponiendo un conjunto de recomendaciones concretas, especialmente para México, con el fin de mejorar la interoperabilidad, la trazabilidad documental y la gestión de riesgos. El resto del artículo se organiza de la siguiente manera: La Sección 2 establece el marco metodológico; la Sección 3 presenta los resultados clave y la justificación cuantitativa de la reducción de tiempos; la Sección 4 discute la comparativa regional y las sugerencias específicas para México; y la Sección 5 contiene las conclusiones del estudio.

2. Metodología

Se utiliza un enfoque **descriptivo-comparativo** basado en el análisis documental y la consulta a especialistas.

La metodología se fundamenta en dos pilares:

1. **Análisis Documental:** Revisión de informes y directrices de organismos multilaterales (OMA, OMC, BID, CEPAL) para establecer el marco teórico y normativo de la transformación digital aduanera.

2. **Análisis Comparativo y Empírico:** Se emplean indicadores de eficiencia aduanera y tiempos de despacho provenientes de los **Trade Facilitation Indicators** de la OCDE **[7]** y del **Doing Business** del Banco Mundial **[8]**. La eficiencia se mide principalmente por la **reducción en los tiempos de despacho** y la **mejora en la gestión del riesgo**.
Criterios de Eficiencia: La eficiencia se mide principalmente por la **reducción en los tiempos de despacho** y la **mejora en la gestión del riesgo**. La comparación entre los casos de México, Chile y Colombia se basa en su nivel de adopción de plataformas de Ventanilla Única de Comercio Exterior (VUCE) y el uso de tecnologías de control no intrusivo.

3. Resultados

Los hallazgos sugieren que la adopción de plataformas electrónicas integradas, como la Ventanilla Única de Comercio Exterior (VUCE), y la automatización de procesos resultan en una reducción significativa de los tiempos de liberación de mercancías.

3.1. Justificación del Impacto en Tiempos de Despacho

La digitalización no solo acelera los procesos, sino que también mejora la gestión del riesgo y aumenta la transparencia. Sin embargo, persisten brechas normativas y de infraestructura tecnológica que limitan la plena interoperabilidad entre agencias y operadores, dificultando la materialización del **"30%"** de reducción.

Para sustentar el hallazgo de la reducción de tiempos de despacho en el rango del 20-30%, se presenta una comparativa que contrasta los procesos aduaneros antes y después de la implementación de herramientas digitales clave como la Ventanilla Única de Comercio Exterior (VUCE). El **Cuadro 1** sintetiza el impacto de la digitalización en métricas clave de eficiencia, validando la evidencia empírica regional reportada por organismos como el BID **[1]**.

Cuadro 1: Justificación del Impacto de la Digitalización (Antes vs. Después)

Criterio de Medición	**Antes de la Digitalización (Proceso Manual / Papel)**	**Después de la Digitalización (VUCE / Automatización)**	**Impacto de la Digitalización**
Tiempo de Procesamiento Documental	24 - 48 horas (Promedio regional de trámites interinstitucionales)	4 - 8 horas (Procesamiento electrónico centralizado)	Reducción del **67% al 83%**
Tiempo de Despacho Fronterizo/Portuario	4 - 8 días (Promedio regional de liberación física y documental)	3 - 6 días (Gracias a la gestión de riesgo optimizada)	Reducción en el tiempo total de liberación de mercancías: **20% - 30%** (Según BID y OMC)
Errores y Rechazos Documentales	Alto (Dependencia de la introducción manual de datos)	Bajo (Validación automática por la VUCE)	Mayor transparencia y cumplimiento.
Fuente de Datos	OCDE (*Trade Facilitation Indicators*), Banco Mundial (*Doing Business*).	BID (Estudios de la VUCE en América Latina) **[1]**	**Validación clave del rango 20-30%**

Fuente: Elaboración propia.

Los resultados preliminares indican que la digitalización permite una reducción de los tiempos de liberación en el rango del **20–30%**. Este supuesto se justifica a partir de la evidencia empírica internacional y regional:

- **Fuentes Institucionales (BID):** El Banco Interamericano de Desarrollo (BID) ha documentado que la implementación de plataformas VUCE en países de América Latina ha logrado **reducir los tiempos de procesamiento de trámites en un 25%** en promedio, validando el rango de mejora [1].

- **Experiencias Empíricas (Tecnología):** Adicionalmente, la implementación de tecnologías avanzadas como *blockchain* en la gestión de transacciones transfronterizas ha sido asociada con reducciones de hasta **20%** en los tiempos de despacho [2].

4. Discusión:

La transformación digital aduanera es un proceso continuo que exige un equilibrio estratégico entre la **facilitación comercial** y el **control efectivo**. Los resultados presentados en la Sección 3, que validan una reducción de los tiempos de despacho del 20-30% **[1]**, demuestran el éxito potencial de la digitalización, especialmente a través de la implementación de la Ventanilla Única de Comercio Exterior (VUCE). Sin embargo, para capitalizar plenamente estas ganancias, es fundamental abordar las disparidades y brechas persistentes a nivel regional.

A pesar de que la digitalización es un mandato global, el progreso en América Latina es heterogéneo. Para identificar las lecciones aprendidas y las áreas de mejora específica para México, el **Cuadro 2** presenta una comparativa de la madurez digital aduanera entre México, Chile y Colombia, países líderes en la región en la adopción de medidas de facilitación del comercio. Este análisis comparativo resalta las brechas persistentes en materia de interoperabilidad y la integración de tecnologías de control avanzado.

Cuadro 2: Comparativa Regional de Avances Digitales (México, Chile, Colombia)

Aspecto de la Digitalización	**México**	**Chile**	**Colombia**
Plataforma de Ventanilla Única	**VUCEM (Ventanilla Única de Comercio Exterior Mexicana).** Completa a nivel documental.	**VUCE Chile.** Alto nivel de madurez y alta integración.	**VUCE Colombia.** Alto nivel de avance y enfoque en gestión.
Avance en Interoperabilidad (Gubernamental)	**En desarrollo.** Gran reto en la integración de datos entre ANAM, SAT, y agencias de seguridad (e.g., Complemento Carta Porte) **[3]**.	**Alto.** Sólida integración entre aduanas y agencias sanitarias/fiscales.	**Alto.** Logrado mediante acuerdos interinstitucionales robustos.
Uso de IA y Control No Intrusivo	**Creciente/Potencial.** Amplia red de escáneres (PITA). La IA para gestión de riesgos es el próximo gran reto para optimizar el **20-30% [4]**.	**Avanzado.** Uso de modelos predictivos y *Data Analytics* para el perfilamiento de riesgo en puertos clave.	**Moderado/En Expansión.** Foco en la automatización de la selección de riesgo.
Enfoque Estratégico	Facilitación y **Seguridad Fronteriza** (Foco en el T-MEC).	**Eficiencia Logística** y Control de Calidad.	**Competitividad y Transparencia** (Marco OEA).
Referencia Clave	Ley Aduanera y Disposiciones Fiscales (SAT).	Dirección Nacional de Aduanas (DNA).	Dirección de Impuestos y Aduanas Nacionales (DIAN).

Fuente: Elaboración propia.

El análisis del **Cuadro 2** revela que, si bien México posee una plataforma VUCEM funcional, el principal desafío reside en la **interoperabilidad total de los sistemas** y no solo en la digitalización documental. Países como Chile y Colombia han logrado una integración más fluida entre sus agencias aduaneras, sanitarias y fiscales, lo que reduce la fricción y aumenta la predictibilidad en la cadena logística. Esta brecha es crítica, pues limita el potencial de la gestión de riesgos en tiempo real, un requisito del Marco SAFE de la OMA **[5]**.

El segundo reto fundamental para México es la integración avanzada de la **Inteligencia Artificial (IA)** para el control no intrusivo **[4]**. La mera instalación de escáneres o sistemas de Rayos X no es suficiente; la verdadera eficiencia se logra cuando los *outputs* de estos equipos se conectan a modelos de *Machine Learning* capaces de crear perfiles de riesgo dinámicos y predictivos, un área donde las aduanas mexicanas deben acelerar su inversión y desarrollo para consolidar la visión de aduana inteligente.

Sugerencia de implementación para México

Para acelerar la modernización aduanera en México y cerrar las brechas identificadas, se proponen las siguientes recomendaciones concretas:

1. **Fortalecer la Interoperabilidad entre Agencias:**

    a) Se requiere intensificar la conexión y el intercambio automatizado de datos entre la Aduana Nacional (ANAM) y las agencias estatales de logística, seguridad (e.g., Guardia Nacional, autoridades sanitarias) y fiscales (SAT).

    b) Un eje clave es la total **integración electrónica de la Carta Porte** con el sistema aduanero, garantizando la trazabilidad digital completa de las mercancías desde su origen hasta su destino, lo que permite un control más eficiente y reduce la evasión fiscal [3].

2. **Adopción Masiva de Tecnologías de Control No Intrusivo e IA:**

    a) Expandir la infraestructura de **escáneres inteligentes y sistemas de Rayos X/Gamma** en puertos y fronteras terrestres, conectando sus *outputs* directamente a sistemas centrales de análisis de riesgo.

    b) Integrar la **Inteligencia Artificial (IA)** y el *Machine Learning* para crear **perfiles de riesgo dinámicos y predictivos** que se actualicen en tiempo real. Esta automatización es crucial para optimizar la detección de anomalías y reducir las inspecciones físicas innecesarias [4].

5. Conclusiones

La digitalización aduanera es más que una simple herramienta tecnológica; es una **oportunidad estratégica** para el comercio exterior latinoamericano, vinculada intrínsecamente a los objetivos de movilidad, digitalización y sostenibilidad. La implementación de plataformas electrónicas robustas y sistemas de gestión de riesgo inteligentes ha demostrado ser la medida más efectiva, permitiendo una reducción verificable de los tiempos de liberación de mercancías en el rango del **20-30%**, conforme a los estudios del BID y la OMC.

Sin embargo, para que México y la región alcancen la plena eficacia logística, es imprescindible abordar los desafíos pendientes. El principal reto es la **interoperabilidad total**, la cual requiere políticas públicas coordinadas que garanticen la fluidez de datos entre la Aduana Nacional de Aduanas de México (ANAM) y Servicio de Administración Tributaria (SAT), tal como lo ejemplifica la integración del Complemento Carta Porte **[3]**. Además, el futuro de las "aduanas inteligentes" depende de la **integración masiva de tecnologías de control no intrusivo e Inteligencia Artificial** para optimizar el perfilamiento de riesgo, pasando de una gestión reactiva a una predictiva

La digitalización aduanera representa una oportunidad estratégica para el comercio exterior latinoamericano, como lo demuestran las reducciones documentadas en los tiempos de despacho. Sin embargo, su éxito pleno requiere **políticas públicas coordinadas, marcos regulatorios actualizados y una visión de cooperación regional y nacional.** La implementación de sistemas de Ventanilla Única de Comercio Exterior, la integración de IA para control no intrusivo y el fortalecimiento de la interoperabilidad son los pilares fundamentales para construir un ecosistema aduanero más seguro, eficiente y transparente.

Discusión:

La transformación digital aduanera es un proceso continuo que exige un equilibrio entre la facilitación comercial y el control efectivo. A pesar de los avances regionales en la implementación de VUCEs, la interoperabilidad plena sigue siendo el principal desafío.

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Analysis of the Port Community System implementation process on the example of the Port of Szczecin

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Abstract— This study aims to analyse the implementation process of the Port Community System (PCS) on the example of the Port of Szczecin. To achieve this goal, the following research methods and tools were used: multi-criteria analysis, graph-based modelling, opinion research methods (using direct interviews) and CATWOE analysis. The Port of Szczecin is currently at the initial stage of implementing PCS. The analysis provided insight into the structure and interrelationships within Szczecin's port community. The current method of processing information is complex and congested, and therefore urgently needs to be simplified, organised and integrated. A functional model of the future PCS platform was proposed, which will improve the logistics processes of the port and its surroundings.

Keywords – Port Community System; maritime supply chain; Single Window; port logistics centre

I. INTRODUCTION

Seaports are designed as large logistics nodes where information flows efficiently between all participants in the sea-land transport chain. A seaport is an intersection hub where information is collected, processed and forwarded to other users. In order to ensure effective and efficient exchange of data and information between all port stakeholders, uniformity of information systems and a uniform standard for the exchange of information and data in the intermodal supply chain are applied. The efficiency of information flow in the intermodal supply chain is influenced using various IT tools and systems, of which the most important at the operational level are Transportation Management Systems (TMS) and Terminal Operation Systems (TOS) [1,2]. Since the 1980s, there has been a gradual integration of key tools for managing port transport and logistics processes, with the Port Community System (PCS) IT platform serving as the foundation for this integration [3].

This study aims to analyse the implementation process of the Port Community System (PCS) on the example of the Port of Szczecin. To achieve this goal, the following research methods and tools were used: multi-criteria analysis, graph-based modelling, opinion research methods (using direct interviews) and CATWOE analysis. Multi-criteria analysis allowed for the selection of appropriate entities that were the subject of the analysis from among the port's stakeholders. Subsequently, direct interviews were conducted, which served as a source of data that was analyzed using the CATWOE method and visualized using graph-based modeling.

II. CHARACTERISTICS PORT COMMUNITY SYSTEM (PCS)

Large seaports have begun their digital transformation by implementing a PCS in order to maintain or improve their competitiveness in the transport and logistics market. These IT platforms often have their own names, e.g. PCS Portbase in the Port of Rotterdam, PCS DAKOSY in the Port of Hamburg or PCS Teleport in the Port of Algeciras [4,5,6,7]. The implementation of PCS results in higher quality of sent and received data, reduced formalities, as well as streamlined and simplified operations throughout the supply chain. The PCS platform allows for advanced cooperation and integration between seaport stakeholders thanks to its functionalities [8,9,10,11]:

- orderly, efficient and safe communication between port stakeholders (including importers, exporters, ship agents, customs agencies, sea and land transport carriers, customs and maritime authorities);
- storage, integration and filtering of data and documents passing through the PCS;
- faster and easier access to data and information for PCS users;
- maintain neutrality for PCS users;
- procedures in accordance with the law and standards adopted by the maritime logistics community.

The key task of the PCS platform is to integrate the IT systems of all participants in port and maritime trade [12,13]. In practice, the 'Single Window' service is appropriate, allowing information to be delivered in EDI format - only once and to a single point [14,15,16]. As a result, the processes taking place in the supply chain run more smoothly, efficiently and securely, as the risk of data theft and copying is reduced, which is very important in terms of data security and protection.

PCS on a global scale represent different levels of evolution and can be divided into five phases [16,17]. The first phase provides access to key basic data, such as notifications of the arrival of ships and statistical data. The second phase of PCS development provides users with greater capabilities, such as verifying permits issued by port authorities, customs or phytosanitary services. The third phase of PCS development is called the expansion or regionalisation phase, which means that seaports collect information and data on the entire supply chain. In this phase, sensors are used in accordance with the principles of the Internet of Things (IoT) to enable synchronisation of activities. This allows seaports to better manage the flow of goods and information throughout the supply chain, leading to more efficient and integrated operations. In the fourth phase of PCS, conditions have been created for the emergence of new companies and advanced innovations based on new business models, through, among other things, the development of artificial intelligence applications, robotisation and automation, Big Data and Predictive Analytics [16].

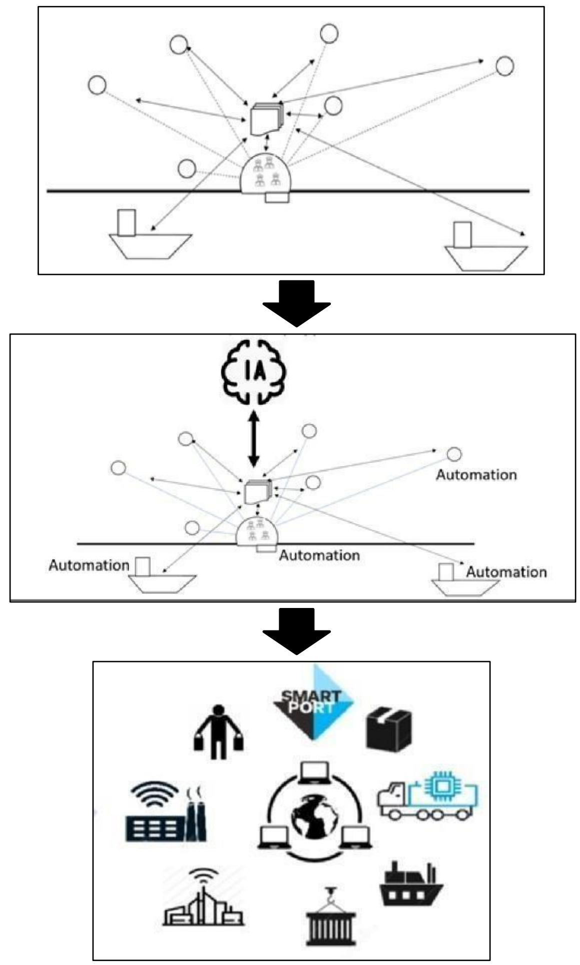

Figure 1. The third, fourth and fifth phase of Port Community System development [16,17].

The fifth and final phase of the PCS development focuses on the international integration and the availability of information worldwide. In this transnational phase, it is possible to fully integrate supply chains, with complete availability of information and data, as well as traceability of goods. In this phase, management decisions can be updated quickly and efficiently using available data and forecasts, enabling effective coordination of flows throughout the supply chain.

Most of the world's seaports PCS are in the first two phases of development [5]. Only some ports are at the beginning of the fourth phase, which is designed to enable entry into the fifth phase.

III. Implementation of the Port Community System in The Port of Szczecin

The Seaport of Szczecin is a major trade and transport hub in the southern Baltic Sea. Its favourable location, extensive infrastructure and investments in modernisation make it an important node in the global supply chain, contributing to the development of the Polish economy and the Baltic Sea region. Szczecin is currently at the initial stage of implementing PCS in the port [18]. Various meetings are being held to present PCS and streamline its implementation in the port environment [19]. The following research is part of this objective, using new source data obtained through targeted interviews with ten potential stakeholders of the PCS platform. The ten entities with which the research was conducted are representative in the context of the seaport and play a key role in the logistics chain. They include shipping companies, customs agencies, the Maritime Office, terminal operators and transport companies.

The collected data in the form of statements by representatives of companies and institutions were analysed using the CATWOE method. This method is used in systems engineering and management to gain a deeper and more accurate understanding of the interactions between the elements (participants) and their impact on the whole system [20]. CATWOE is an acronym for seven areas of system analysis, whose task is to present and understand problems and develop effective solutions. For this study, the identified areas of analysis include [21,22,23]:

C (Customers) – refers to those who participate in the port community or use port services. These are individuals or groups who have a direct benefit or interest in the port system.

A (Actors) – persons or entities involved in activities related to port operations. These may be persons performing specific tasks or entities that influence the functioning of the port system.

T (Transformation process) – a key element that describes the process or mechanism by which the system input (data, information) is transformed into output (result, outcome).

W (Worldview) - refers to the general beliefs, values and perspectives that influence how the port system is perceived and interpreted. Worldview plays a role in determining which aspects of the system are important or valuable.

O (Owners) – is the person or entity responsible for a specific system or process. For example, the owner influences the management, development and objectives of a specific system.

E (Environmental Constraints) – refers to external factors that may affect the functioning of the port system. These may include restrictions, regulations, economic, social or technological conditions.

The analysis provided insight into the structure and interrelationships within Szczecin's port community. In particular, it answered the question of who plays what role, how they operate, what functions they perform, and what goals they pursue in business and social relations (Table 1).

Table 1. CATWOE analysis of stakeholders at the Port of Szczecin.

	Forwarders	Authorities	Terminal operators
C	Business and individual customers interested in freight forwarding and customs services.	Port community, shipowners, port companies.	Carriers, shipowners, export and import companies.
A	Forwarding company employees, customers, transport partners, customs agents	Maritime Authority employees, shipowners, port operators.	Terminal employees, carriers, shipowners, customers.

T	Organisation and supervision of transport in various branches, management of customs and forwarding documentation.	Ensuring navigation safety, environmental protection, supervision of port operations.	Transhipment of various goods, ensuring the smooth running of port operations.
W	Reducing transport time and costs, compliance with customs and shipping regulations.	Maritime traffic safety, minimising environmental impact.	Operational efficiency, striving to minimise delays.
O	Forwarding company owners, Management Board.	State, government institutions.	Terminal owners, management board.
E	Compliance with environmental standards.	Compliance with environmental standards and regulations.	Protection of the environment from pollution.

Interviews with stakeholders allowed to map the flow of information and documents between the port community members. The visualisation shown in Figure 2 depicts key entities in the port area, the relationships between them, and the types of activities correlated with the flow of information between these entities. The diagram illustrates the complex dynamics of the port community, which is dominated by bilateral transactions and a lack of coordination. There are repetitive processes, excessive redundancy, inconsistencies and a lack of adequate information intelligence. Different stakeholders use different information and communication systems to carry out similar operations in the port. The port environment is characterised by a large number of manual activities and fragmentation, especially in the context of information and documentation flow. Customers express concerns about the current manual system because it does not meet their expectations. Port operations are not coordinated, and the whole seems to function in isolation, with a lack of general trust between members of the port community. The current state of the port environment is prone to errors and duplication of processes. The current method of processing information and documents at the Port of Szczecin is complex and congested, and therefore urgently needs to be simplified, organised and integrated.

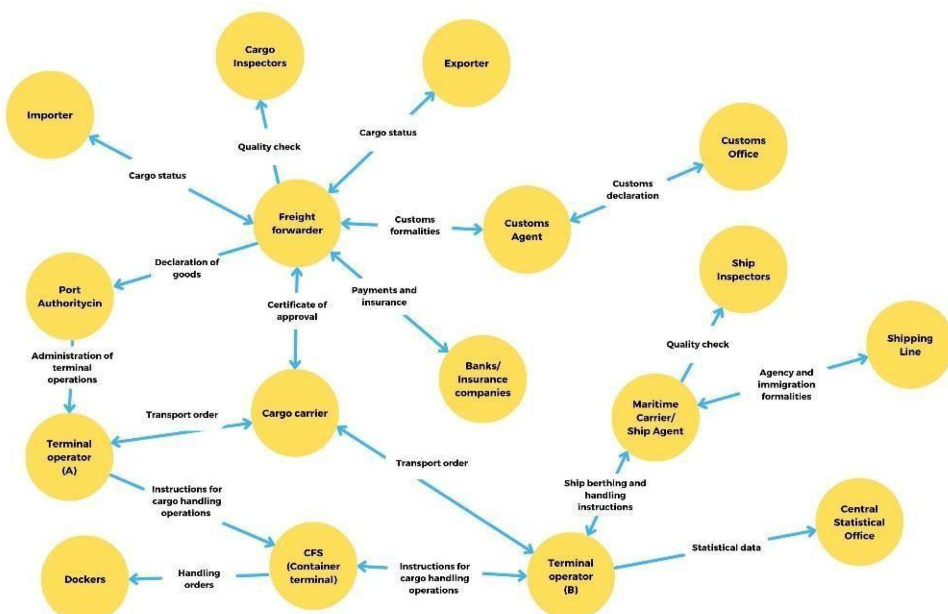

Figure 2. Current state of the information flow between the Port of Szczecin stakeholders.

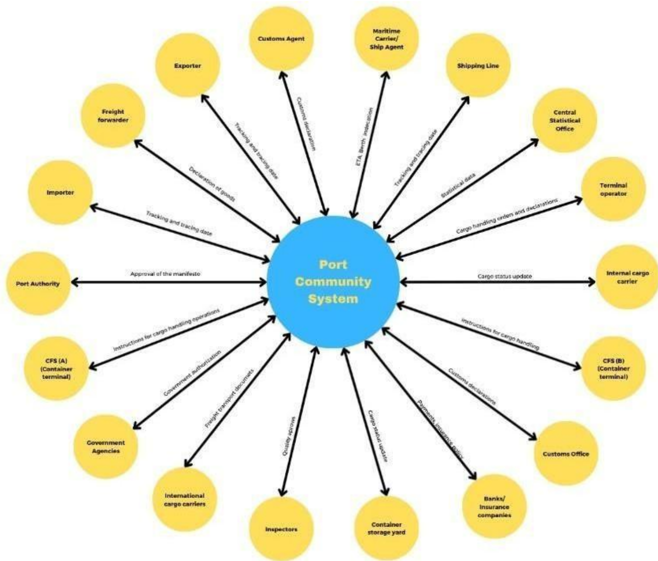

Figure 3. Information flow within the PCS community of the Port of Szczecin.

Taking into account the PCS standards and its structural and functional capabilities, a conceptual PCS model was developed for the Port of Szczecin (Figure 3). The model presents a simple, smooth and harmonised system of information exchange within the port community, which minimises the risk of duplication and delays. The streamlined organisational network is effectively connected to enable the free flow of relevant information and documents, facilitating the smooth handling of cargo. In addition, Table 2 shows the standard flow of information and data between port community participants prior to and after the implementation of PCS.

As a result, thanks to the implementation of PCS, the flow of information and data between port community participants becomes more automated, efficient and consistent, contributing to faster port operations and better coordination of activities throughout the logistics process.

Table 2. Data exchange standards before and after PCS implementation.

	non-PCS standards	PCS standards
Shipper ↔ Forwarder	The Shipper appoints a Forwarder to manage internal logistics and provides them with transport and cargo information via text message or email.	The shipper appoints a Forwarder to manage internal logistics. ETA/ETD (estimated time of arrival/departure) are made available on the PCS platform
Forwarder ↔ Consolidator	The Forwarder appoints a Consolidator and provides information about container space reservations via SMS or email. Ongoing communication is mainly conducted by telephone.	The Forwarder appoints a Consolidator who handles container space reservations. Information is communicated via PCS, enabling availability tracking and planning.
Consolidator ↔ Shipping Agency	The Consolidator and Shipping Agency communicate via traditional means of communication, paper or email. Documents and information regarding ship reservations are transferred manually.	The Consolidator uses the PCS system to make ship reservations through the Shipping Agency on behalf of the exporter. Reservation information is transferred electronically.
Terminal ↔ Shipping Agency	The Terminal communicates with the Shipping Agency regarding container transhipment, and information is transferred manually. Ongoing communication takes place via traditional means of communication.	The Terminal communicates with the Shipping Agency via the PCS system regarding container transhipment. Information on the number of containers, terminal availability and other operations is made available on the platform.

IV. CONCLUSIONS

The study aimed to analyse the process of implementing PCS in the Port of Szczecin. The research was based on targeted interviews conducted with a representative group of PCS stakeholders. The above research helped to understand and present the current flow of information and data between entities operating in the Port of Szczecin. A functional model of the future PCS platform was also proposed, which will improve the logistics processes of the port and its surroundings. It was observed that the port management, ship agents, terminal operators, customs agents and road/rail carriers are the entities that handle most of the information and documentation traffic, and they should be given priority in the first phase of PCS implementation.

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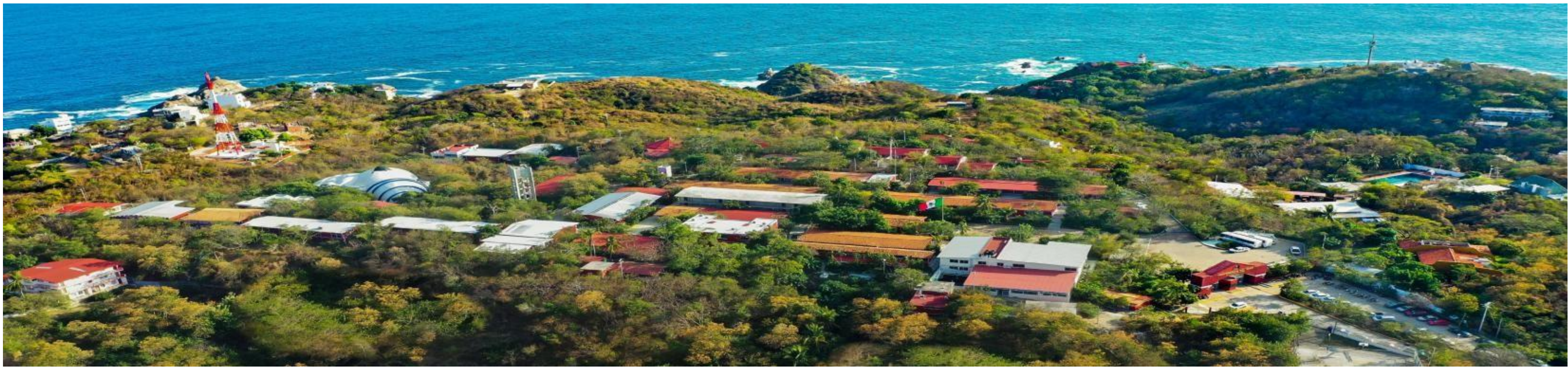

4- Supply Chain Risk Management and Resilience

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Estimating Project Duration for Post-Disaster Road Network Rehabilitation using Monte Carlo Simulation

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***Abstract*— Time management in post-disaster road rehabilitation, within a region affected by earthquakes, landslides, hurricanes, and floods, is crucial, as road infrastructure enables the mobilization of humanitarian aid, restoration of supply chains, evacuation processes, and access to essential services such as health and security. Delays can exacerbate socio-economic impacts, constrain governmental response, and increase community vulnerability. In contexts of high operational uncertainty, like post-disaster environments, efficient temporal management enhances not only physical resilience but also organizational and community resilience by enabling agile and adaptive planning. This study applies Monte Carlo simulation to probabilistically analyze the total duration of rehabilitation projects, revealing how different disaster types affect expected project durations. Results demonstrate the usefulness of this tool for post-disaster logistics management by allowing realistic time estimations, supporting contingency planning, informed decision-making, and efficient resource management to improve regional road infrastructure resilience.**

Keywords- Monte Carlo simulation; disaster management; road network rehabilitation; humanitarian logistics

I. Introduction

The increasing frequency and intensity of disasters globally underscores the critical importance of efficient disaster management. In this scenario, humanitarian logistics (HL) emerges as a fundamental pillar. This discipline is distinguished by its focus on minimizing human suffering and its operation in contexts of extreme uncertainty, damaged infrastructure, and multiple actors.

The stages of HL are associated with the so-called Integrated Disaster Risk Management (IDRM) cycle (Sandoval et al., 2023): mitigation, preparedness, response, and recovery. In each phase, HL has a specific role, from the prepositioning of supplies to the rehabilitation of infrastructure.

Mexico is highly vulnerable to disruptive phenomena. The state of Guerrero, in particular, is one of the most active seismic zones in the country and faces severe hydrometeorological phenomena. Examples of these events include hurricanes and storms such as Ingrid and Manuel (2013), Max (2017), Carlotta (2018), and Otis (2023), which have had serious socioeconomic consequences, such as loss of agricultural productivity, damage in infrastructure (roads, schools, hospitals), displacement of communities, among others (Romero et.al., 2025).

Effective rehabilitation of post-disaster road infrastructure is essential for regional stability. However, planning and execution is hampered by multiple factors: widespread damage, unpredictable access, limited resources, logistical coordination, and bureaucratic hurdles. These conditions make traditional deterministic approaches inadequate.

This study develops a probabilistic model to estimate the duration of post-disaster road rehabilitation projects in Guerrero, using Monte Carlo simulation and transition matrices that reflect the influence of different types of disasters.

While the application of Monte Carlo simulation in project management risk analysis is well established (Raychaudhuri, 2008; Robert & Casella, 2013), the original contribution of the current research lies in its specific focus on estimating the duration of projects to improve logistics management in the post-disaster context of Guerrero. This study provides a methodology for deriving actionable quantitative insights specifically for schedule improvement under pressure. By estimating the likely duration of the project under various scenarios, logistics managers are offered a nuanced understanding of expected execution times. This will allow for a more informed and proactive approach to resource allocation and contingency planning afterwards. The direct linking of probabilistic analysis of project duration with practical logistical decision-making to improve the efficiency of post-disaster road rehabilitation represents an advance over conventional techniques, offering a tool to improve resilience and speed of recovery.

II. Materials & Methods

This study employed an integrated quantitative methodology to probabilistically analyze project schedules for post-disaster road infrastructure rehabilitation in Guerrero, Mexico. The approach combined Monte Carlo Simulation (MCS) with formal Expert Judgment Elicitation (EJE) techniques (O'Hagan et al., 2006; Ioannou et al., 2022), implemented primarily using Microsoft Excel.

A. Overall Framework: Integration of MCS and EJE for Post-Disaster Analysis

Recognizing the inherent data scarcity and high uncertainty characterizing post-disaster environments, the core of our approach involved leveraging structured EJE to inform a probabilistic simulation model. Expert knowledge was systematically elicited to quantify the uncertainty surrounding key variables (e.g., activity durations, potential delays, resource availability influenced by disaster type) which then served as inputs for the MCS. This integration allows for a quantitative analysis grounded in the experience of professionals familiar with the specific operational challenges in the region.

B. MCS

MCS formed the computational basis for analyzing schedule uncertainty. This established technique [Raychaudhuri, 2008; Robert & Casella, 2013] was used to model the project schedule as a network of activities. By assigning probability distributions (derived from EJE) to the duration of uncertain activities, the simulation was run for thousands of iterations. Each iteration calculated a potential project completion time, generating an overall probability distribution for the project duration and allowing for the identification of activities frequently falling on the critical path (i.e., the probabilistic critical path).

C. EJE Protocols

A multi-faceted approach was employed for EJE to capture and synthesize expert knowledge rigorously:

- Delphi Method: An iterative, anonymized process (e.g., Linstone & Turoff, 1975) was used with a panel of selected experts (e.g., civil engineers, logistics managers, disaster response personnel with experience in Guerrero) to achieve a reasoned consensus on the likely ranges and parameters for critical variables, reducing individual bias.
- Cooke's Classical Model: To objectively weigh the judgments of different experts based on their empirical accuracy and informativeness, Cooke's performance-based weighting method was applied [Reference, e.g., Cooke, 1991]. Experts were asked to assess seed variables (quantities known post-event or knowable with certainty), and their performance on these informed the aggregation of their judgments on target variables.
- Sheffield Elicitation Framework (SHELF): The SHELF protocol (O'Hagan et al., 2006) provided a structured framework for eliciting detailed probability distributions for specific uncertain quantities from individual experts, ensuring careful consideration of uncertainty bounds and distribution shapes.

D. Implementation Tools

This study forms part of interdisciplinary disaster research (e.g., Peek and Guikema, 2021) and the humanitarian supply chain management (HSCM). Quantitative tools were used to address the uncertainty in the duration of the rehabilitation of the communication routes, highlighting the MCS implemented in Excel.

The methodology is based on Gelman Muravchik's (1996) systemic approach, which distinguishes between Disruptive System, Affective System and Regulatory System. Road rehabilitation is included in the response and recovery phases, and a Damage Assessment and Needs Analysis (DANA) is an initial critical activity (ADPC, 2000; UNDP/CDEMA, 2016).

Duration parameters and transition probabilities were provided by local experts. Specific matrices were defined for each type of disaster and integrated into a network model of project activities. The simulations were executed for different scenarios: earthquake, hurricane, landslide, flood, and small bridge collapse.

E. Methodology

1. Definition of the problem

The starting point of the model was the identification of the critical problem: the high uncertainty in the duration of post-disaster road rehabilitation projects in the state of Guerrero, Mexico. This uncertainty is related to factors such as the type of disaster, the severity of the damage, and the conditions of access.

2. DANA

DANA has been recognized as a critical initial activity within the rehabilitation process. This technical assessment determines the magnitude of the impact, the type and extent of the damage, and the initial conditions for intervention.

In the proposed model, DANA served as a starting point for structuring disaster scenarios and estimating the linear sequence of rehabilitation activities. Although in this study a network was not used to model critical paths, the DANA was used as a technical reference to define the ordered and unbranched list of representative activities, whose duration and occurrence were subsequently modeled.

The DANA was incorporated as an essential input to construct the probabilities of transition between project states, as well as to establish specific conditions by type of disaster, reinforcing the contextual validity of the model.

3. Consultation with experts

To estimate the duration of the activities considering the probabilistic matrices according to the type of disaster, the Delphi technique was used, widely used in contexts where empirical information is limited and the integration of expert knowledge is required. This technique consists of a structured and repetitive consultation with a panel of specialists, with controlled feedback, which allows a reasoned and well-founded consensus to be reached.

In this study, a group of six experts with operational experience in post-disaster road infrastructure rehabilitation in the state of Guerrero was consulted. Participants included civil engineers, civil protection technicians, and humanitarian logistics professionals with experience in natural disasters. Two rounds of anonymous consultation were carried out: in the first, critical activities, logical sequences and tentative duration distributions were identified; in the second, the probabilities were adjusted and the scenarios were validated under group consensus. The use of Delphi strengthened the robustness of the model in the face of uncertainty, by allowing the integration of specialized perceptions contextualized to the region.

4. Construction of the schedule model

Based on a consultation with experts and the data derived from DANA, a schedule of activities was developed representative of the sequence of tasks necessary for post-disaster road rehabilitation. A linear structure was adopted that reflects the most common operational logic observed in the field.

The sequential list included activities such as damage assessment, debris removal, ground stabilization, road reconstruction and signage. For each one, distributions of probabilistic duration and probability of occurrence associated with the type of disaster were assigned, based on the Delphi technique previously applied. This linear structure was directly translated into the MCS model.

Particular attention was paid to reflecting the realistic sequence of field operations, considering potential overlaps, conditional dependencies, and practical constraints such as accessibility and resource availability. The schedule also included the evaluation points of intermediate progress, useful for monitoring.

Following the expert consultation (described in section 2.5), discrete probability distributions were defined for the duration (in days) of the most representative rehabilitation activities. These distributions, which served as the input data for the Monte Carlo Simulation, are presented in Table 1 and Table 2.

Table I it details the probabilities for the Hurricane scenario. For example, for Activity A (Damage assessment), there is an estimated 50% probability that the duration will be 1 day, a 40% probability of 2 days, and a 10% probability of 3 days. Similarly, Table II presents the corresponding distributions for the Earthquake of Great Intensity scenario. In this case, it is observed that activities such as C (Structural review of bridges) have greater uncertainty, with probability distributed between 2 and 5 days.

TABLE I. ACTIVITY DURATION PROBABILITY DISTRIBUTION (DAYS) – HURRICANE SCENARIO

HURRICANE						
		Duration in Days				
Activity		1	2	3	4	5
A	Damage assessment	0.5	0.4	0.1	0	0
B	Clearing of roads (trees, debris)	0.3	0.4	0.2	0.1	0
C	Drainage and sewer review	0.2	0.4	0.3	0.1	0
D	Repair of sinkholes/erosion	0.1	0.2	0.3	0.3	0.1
E	Repairing damaged bridges	0.2	0.3	0.3	0.2	0
F	Signage and barrier restoration	0.1	0.2	0.3	0.4	0
G	Partial reopening	0.2	0.3	0.3	0.2	0

TABLE II. ACTIVITY DURATION PROBABILITY DISTRIBUTION (DAYS) – EARTHQUAKE OF GREAT INTENSITY SCENARIO

EARTHQUAKE OF GREAT INTENSITY						
		Duration in Days				
Activity		1	2	3	4	5
A	Damage assessment	0.5	0.4	0.1	0	0
B	Debris removal and landslides	0.3	0.4	0.2	0.1	0
C	Structural review of bridges	0	0.2	0.4	0.3	0.1
D	Repair of cracks and fractures	0	0.1	0.2	0.3	0.1
E	Reinforcement of slopes and slopes	0	0.2	0.3	0.3	0.3
F	Signage Restoration	0	0.1	0.2	0.3	0.4
G	Partial reopening	0	0.2	0.3	0.3	0.3

5. Implementation of the model in Excel.

The activity network was digitized in a spreadsheet using Microsoft Excel, which allowed programming a simulation based on the logic of the Monte Carlo method. For each iteration, random duration values were generated for each activity, and the total project time was recalculated considering the critical paths. The transition matrices were also integrated using dynamic tables that conditioned the probability of progress between stages to the type of disaster and the specific day of resolution.

The spreadsheet included basic automation using macros to perform multiple iterations, store results, and calculate output statistics such as mean, percentiles, and standard deviation of the total project time.

6. MCS (1,000 iterations per scenario).

Independent simulations were run for each of the five defined scenarios (Flood, Hurricane, Earthquake, Landslide, Short bridge drop). In each scenario, 1000 iterations of the schedule model were run, which allowed a representative sample of the possible total durations of the project to be obtained.

Each iteration consisted of the random selection of durations for each activity, based on its distribution associated with the type of disaster, and the calculation of the completion time through critical path analysis. The transition matrices dynamically modified the state of the system, affecting the progression of activities in each simulation.

At the end of each set of simulations, the results were statistically analyzed to obtain the mean, standard deviation, interquartile range, and key percentiles (P10, P90), which allowed the variability and reliability of the estimated schedules to be evaluated.

7. Model validation.

With the results of the simulations, a comparative analysis was carried out between the scenarios to identify which type of disaster generates the greatest impact on the duration of the project. It was noted, for example, that hurricanes and major floods tended to produce longer delays because of their cumulative effect on multiple activities.

In addition, a sensitivity analysis was carried out to detect which input parameters (duration of key activities, critical transitions) have the greatest influence on the variability of the total rehabilitation time. This made it possible to identify 'bottleneck' activities and stages where small improvements could translate into significant reductions in overall time.

8. Interpretation of results.

The results obtained allowed practical conclusions to be drawn for post-disaster planning. On the one hand, it was possible to confirm that disasters with a larger territorial extension (such as hurricanes) imply longer schedules and with greater statistical dispersion. On the other hand, the use of simulation made it possible to establish realistic time ranges for each type of threat, which is key to planning resources, equipment and financing.

The implications in terms of governance are also highlighted: having probabilistic timelines allows the expectation of recovery to be communicated more accurately to political, technical and social actors, reducing frustration over non-compliance and improving coordination.

Finally, the structure of the model allows its adaptation to other territories and disasters, strengthening its usefulness as a tool for systemic planning and humanitarian logistics.

9. Results

Table III summarizes average rehabilitation times by type of disaster. The scenario with the longest duration was the flood, suggesting greater complexity. The transition matrices allowed us to capture the differences in progression of the works according to the type of initial damage.

TABLE III. AVERAGE REHABILITATION TIMES BY TYPE OF DISASTER

Disaster	Average rehabilitation times(days)
Flood	21.07
Hurricane	20.45
Earthquake	17.17
Landslide	16.48
Short bridge drop	16.49

III. ANALYSIS & DISCUSION

The Monte Carlo simulations were carried out to estimate the total probable duration of rehabilitation projects under the impact of the two disasters identified with more occurrences for the Guerrero region: Hurricanes and Earthquakes (refer to Tables 1 and 2). Additionally, rehabilitation durations were analyzed below:

- Hurricane: The average total time of completion of the rehabilitation project after a widespread hurricane impact was 20.45 days.
- Earthquake: The average total time of completion of the rehabilitation project after a generalized earthquake impact was 17.17 days.

The results obtained through the Monte Carlo simulation offer a quantitative perspective on the variability in the duration of road network rehabilitation projects in Guerrero under different disaster scenarios. The difference in average completion times, which range from 15.79 days for a light flood to 20.92 days for a hurricane, underscores how the nature and magnitude of the disruptive event directly impacts the complexity and, therefore, the temporal extension of rehabilitation efforts. The hurricane and large flood scenarios, presenting the longest average durations, reflect the likely greater dispersion and severity of infrastructure damage, as well as the possible expanded logistical challenges in terms of access and mobilization of resources.

A crucial element, implicit in methodology and which has a decisive influence on the estimated durations, is DANA. This initial activity, shared by all disaster scenarios, is critical as it lays the groundwork for all subsequent planning. The quality, speed and accuracy of the DANA, carried out by technicians specialized in the specific type of disaster, are vital. Poor or late evaluation can lead to underestimation of resources, delays in mobilization and, consequently, an extension of the overall duration of the rehabilitation project. The model, by incorporating transition matrices reported by local experts, indirectly captures the influence of this initial assessment on the progression of project statuses.

The use of the knowledge of experts from the locality to define the probabilities of transition matrices and the parameters of duration of activities is a strength of this study, especially in a context such as Guerrero, where detailed historical data on post-disaster rehabilitation durations may be limited or difficult to access. This approach allows the model to be contextualized to the operational, geographical, and socioeconomic realities of the region, giving greater relevance to duration estimates.

However, the study has certain limitations. Reliance on expert estimates, while valuable, introduces a degree of subjectivity. Future research could seek to establish these estimates with historical data, if their collection can be systematized. Likewise, the current model could be expanded to include a more detailed analysis of the availability and allocation of specific resources (machinery, personnel, materials), which also significantly impacts durations. The variability in the duration of individual activities, beyond the average, and its impact on the distribution of the total duration of the project, also represents an area for further analysis from the simulation data.

From a practical perspective, the duration estimates obtained for each disaster scenario can be of great use to civil protection agencies and infrastructure managers in Guerrero. They allow for more realistic planning of response and recovery times, the allocation of contingency budgets, and the management of expectations of affected communities. Understanding that a hurricane could, on average, require nearly five more days of rehabilitation work than a light flood, for example, has direct implications for logistical preparedness and resource mobilization differentiated by threat type.

IV. Conclusions

This study showcases the applicability and usefulness of Monte Carlo simulation as a tool to probabilistically estimate the duration of road network rehabilitation projects in the state of Guerrero, Mexico, under the influence of various disaster scenarios. The results indicate that the average duration of these projects varies significantly depending on the type and magnitude of the event, ranging from approximately 16 to 21 days for the modeled scenarios.

The main contribution of this research lies in offering a quantitative method to address the uncertainty inherent in post-disaster planning. By generating probability distributions for the total duration of the project, rather than single deterministic estimates, decision-makers are provided with a more complete view of possible time ranges, which is critical for more efficient and resilient resource and logistics management. The incorporation of the knowledge of local experts for the definition of key parameters, such as transition matrices and durations of activities, has been essential to adapt the model to the specific context of Guerrero.

The DANA activity is identified as a critical component that precedes and significantly conditions the duration of the rehabilitation phases. The accuracy and timeliness of this assessment, carried out by specialized technical personnel, are decisive for effective planning.

In practical terms, the duration estimates generated can serve as an informed basis for contingency planning, resource allocation, communication with stakeholders, and overall improvement of the response and resilience of road infrastructure in a region highly vulnerable to disasters.

Future lines of research could focus on explicitly incorporating resource variability, analyzing sensitivity to different input parameters, validating the model with real-event data as they become available, and expanding the model to include probabilistic cost analyses associated with estimated durations.

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Disruption Mitigation Strategies in the Supply Chain 4.0 Era: A Literature Review

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***Abstract*— Supply chain simulation is an indispensable tool for modeling, analyzing, and optimizing complex processes, offering a crucial, safe environment for experimentation. Fueled by technological progress, the escalating complexity of global networks, and disruptive events like the COVID-19 pandemic, the field has advanced significantly in recent years. Specifically, Supply Chain 4.0 techniques enable a critical shift from reactive disruption management to a proactive and predictive approach. By leveraging real-time data, advanced analytics, virtual modeling, and secure collaboration, organizations can now pinpoint vulnerabilities, anticipate potential crises, and implement more effective mitigation and recovery strategies, thereby enhancing overall resilience. This overview examines the key trends, advancements, and use cases in supply chain simulation and Supply Chain 4.0 from 2019 to 2024, focusing on the essential design components and execution considerations for simulations targeting disaster-induced disruptions.**

Keywords-supply chain; disaster response; demand; challenges

I. Introduction

Supply chain simulation is now an indispensable tool for optimizing operations and making data-driven decisions within complex global networks. It provides a secure platform to test strategic changes—like implementing new suppliers, logistics channels, or facility locations—without risking real-world implementation failures. Simultaneously, simulation allows businesses to proactively model critical "what-if" scenarios, such as sudden demand surges, unexpected supply shortages, or natural disasters. By understanding the potential impact of these events, organizations can develop effective contingency plans and enhance resilience. This proactive capability is essential for managing supply chain disruptions, which are defined as any break in the normal flow of goods and services from initial sourcing to final customer delivery. In this paper we present how linking simulation, digital twins, and cloud computing is a core strategy for achieving proactive mitigation of seaport supply chain disruptions.

Seaport disruptions, which can be caused by events like labor strikes, extreme weather, port congestion, or infrastructure failure, have a profound and cascading impact on multimodal transport (the use of two or more modes of transport, such as ship, rail, and truck). The port is the critical interchange point where the maritime leg connects with the inland transport network. A disruption creates a major bottleneck that ripples through the entire supply chain. Kos et. al. [1].

A. Common Causes of Supply Chain Disruptions:

The common causes of supply chain disruptions in seaports are diverse, often combining operational, environmental, and geopolitical factors. These issues can create bottlenecks that slow down the entire global trade network[2]. The main categories of disruptions:

1. Port Congestion & Capacity: Caused by cargo surges, poor operational efficiency, and older infrastructure unable to handle mega-ships.

2. Environmental Factors: Severe weather (hurricanes, fog, floods) and natural disasters that force port closures and damage infrastructure.

3. Labor Issues: Strikes, disputes, and shortages of skilled dockworkers and truckers that bring cargo handling to a halt.

4. Global Events: Geopolitical conflicts, sanctions, regulatory changes, and pandemics that impact trade routes and workforce availability.

B. Logistical Challenges:

Seaport disruptions do not only cause delays; they trigger a series of complex logistical challenges that affect the planning, cost, and reliability of the entire supply chain. [2]. To cope with these problems, companies and seaports are adopting more resilient approaches, as shown in next Table I.

TABLE I. LOGISTICAL CHALLENGES AND MITIGATION STRATEGIES

Logistical Challenge	Mitigation Strategy
ETA (Estimated Arrival Time) Uncertainty	Digitalization and Visibility: Use of AI and IoT for real-time tracking and demand forecasting.
Congestion and Mis-stacking	Port Automation: Investment in automated cranes and yard management systems to optimize container placement.
Supply Risk	Diversification: Using multiple gateway ports and supply routes to avoid reliance on a single chokepoint.
High Costs	Proactive Collaboration: Closer partnerships with logistics operators (freight forwarders) and shipping lines to negotiate rates and secure capacity.

C. Some impacts of Supply Chain Disruptions:

Operational and Production Impacts

Uncertainty disrupts factory schedules. Manufacturers using Just-in-Time (JIT) models often face production stoppages when critical components are delayed. Scheduling becomes chaotic and traditional forecasting models become unreliable, resulting in costly errors like overstocking or damaging understocking.

Customer and Reputation Impacts

Failure to deliver products results in immediate lost sales and can lead to a long-term loss of market share. Repeated stock-outs and unreliable delivery times damage brand reputation and customer loyalty, requiring significant resources to manage customer service and complaints.

Macroeconomic Impacts

At a broader level, the increased business costs are passed on, contributing significantly to widespread inflation. Globally, disruptions limit the availability of key inputs, leading to reduced economic output. In severe cases, they can also contribute to job insecurity in sectors dependent on steady supply flows. Kleindorfer et al. [3].

In short, supply chain disruptions create a ripple effect, moving from logistics failure to financial stress, and culminating in higher consumer prices and economic instability.

D. Strategies for Mitigating Supply Chain Disruptions

The overall approach is built on three pillars: Technology, Operational Flexibility, and Collaboration/Infrastructure. [2]

TECHNOLOGY AND DIGITAL TRANSFORMATION

Visibility & AI: Use real-time tracking (IoT) and AI/ML to predict congestion, optimize resource allocation, and accurately forecast vessel arrival times (ETA).
Automation: Implement Automated Guided Vehicles (AGVs) and advanced Terminal Operating Systems (TOS) to increase throughput, maximize yard space efficiency, and reduce reliance on manual labor.
JIT Port Calls: Use digital systems to coordinate vessel speed so ships arrive only when a berth is immediately available, reducing waiting time and congestion.

OPERATIONAL AND LOGISTICS RESILIENCE

Diversification: Avoid dependence on single suppliers, ports, or chokepoints by establishing networks of alternative gateway ports and planning for rerouting.
Inventory Buffers: Increase safety stock for critical items to create a cushion against highly variable lead times.
Contingency Planning: Develop strategies to quickly shift cargo to alternative, faster modes like rail or air freight when ocean routes are disrupted.

INFRASTRUCTURE, GOVERNANCE, AND COLLABORATION

Investment: Continuously modernize port facilities, deepen berths, and improve intermodal connections (road/rail) to increase physical capacity.
Collaboration: Foster unified data sharing among all parties (customs, carriers, ports) through platforms like Port Community Systems (PCS).
Labor Management: Engage in proactive discussions with labor unions to mitigate the risk of costly strikes and operational slowdowns.

Building supply chain resilience is increasingly critical in the modern, interconnected global economy. Organizations are implementing several strategies to mitigate disruptions, beginning with diversifying their supplier base to eliminate single points of failure. Another crucial step involves increasing inventory buffers by maintaining safety stocks of critical components to cushion against unexpected shortages. Furthermore, strategic investment in technology—specifically advanced supply chain management systems and data analytics—improves visibility and allows for faster, data-driven responses. Ultimately, resilience is enhanced through consistent monitoring of global events and fostering strong, collaborative relationships with suppliers, enabling businesses to proactively prepare for and anticipate future risks.
According to build resilience we present three techniques to construct it. The combined power of these technologies creates a powerful feedback loop for resilience:

- Real-Time Data (Cloud/IoT) Feeds the Digital Twin.
- Digital Twin Creates an accurate virtual replica of the port.
- Simulation (Cloud HPC) Tests disruption scenarios on the replica to identify weaknesses and optimal solutions.
- Optimized Solutions Are deployed back into the physical port operations to mitigate the disruption immediately and effectively.

This linkage allows port operators to move from relying on historical data and generalized plans to using dynamic, data-driven playbooks that are tested and proven for their specific infrastructure.

II. SUPPLY CHAIN SIMULATION

The practice of supply chain simulation has transitioned significantly since its origins in the 1950s, when it relied on early operations research models. While the Discrete Event Simulation of the 1980s helped optimize specific functions, the current landscape is defined by Supply Chain 4.0, which is expected to play an ever-greater role in shaping the future of supply chain management. Rinaldi et al. [4]. This new paradigm is built on core technological developments that provide unparalleled analytical power:

Digital Twins revolutionize simulation by creating virtual replicas of the entire supply network, which are constantly updated with real-time data for dynamic accuracy.

Agent-Based Modeling (ABM) enables the granular simulation of individual actors, such as customers, suppliers, and carriers, and their unique interactions within the system.

Cloud Computing and Big Data provide the large-scale infrastructure and data access necessary to run complex, distributed simulations.

By integrating these tools with AI, IoT, and advanced analytics, organizations achieve real-time visibility and data-driven decision-making. This modernization strategy optimizes operations, enhances efficiency, and drastically improves responsiveness to market changes. We will now review several key papers related to these advanced simulation approaches.

III. THE DIGITAL TWIN PARADIGM AND SUPPLY CHAIN RESILIENCE

A Digital Twin (DT) is a dynamic, virtual representation of a physical entity—be it an asset, product, or the entire supply chain system. Unlike traditional static simulations, the power of DT lies in its continuous integration of business, sensor, and contextual data, a capability enabled by the Internet of Things (IoT) and Big Data technologies.In supply chain management, applying the DT concept creates a mirrored simulation model encompassing all processes. This offers two significant, interrelated advantages:

1. **Cost Reduction and Efficiency**: DTs provide enhanced connectivity and real-time information, enabling timely decision-making and the proactive identification and resolution of inefficiencies that might otherwise go unnoticed for weeks (Marmolejo et al. [5]).
2. **Continuous Improvement:** The model facilitates a continuous cycle of near-real-time analysis and adjustment across the entire chain, streamlining operations, creating transparency, and exposing pre-existing vulnerabilities (Le and Fan [6]).

Over the past decade, rapid technological advancements, including Industry 4.0 and blockchain, have driven widespread digitization across sectors. While this shift promises benefits like faster information access and improved efficiency, it also introduces challenges such as legal complexities, a shortage of digital skills, and security threats. The need for highly functional DTs has been urgently underscored by major, high-impact disruptions:

- The COVID-19 Pandemic (2020): This event created widespread uncertainty, highlighting the fragility of production, warehousing, and distribution networks [7].
- The Ever-Given Suez Canal Blockage (2021): This week-long transport disruption demonstrated the vulnerability of global logistics chokepoints [8].
- Recurring Natural Disasters: Increasing frequency of wildfires, hurricanes, and floods create significant

performance challenges, forcing governmental responses like the US FLOW initiative and the EU's proposed CSDD (Le and Fan [6]).

Furthermore, the complexity of the Logistics and Supply Chain System (LSCS) as a highly connected "system of systems" means a disruption in one part can cause far-reaching consequences. The 2011 Thailand flood serves as a stark example: Japanese car manufacturers lost over 420,000 cars and closed factories for months because local, unaffected assembly plants lacked parts from flooded suppliers, creating international ripple effects (Le and Fan [6]).

A. Digital Twin Frameworks for Resilience and Sustainability

In response to these uncertainties, research is focusing on leveraging DTs to enhance supply chain resilience (the ability to withstand and recover from disruptions) and robustness (a proactive strategy for managing turbulence) (Dos Santos et al. [14]).

Several publications explore frameworks for applying DTs in this context:

Simulation-Based Decision-Making: Longo et al. [7] propose a cyclical framework utilizing the Digital Supply Chain Twin paradigm to increase sustainability and resilience against COVID-like crises. This involves comprehensive data management, risk analysis, defining KPIs (economic, environmental, social), and outlining response strategies before modeling the DT [10].

Visibility and Control: Marmolejo-Saucedo [13] argues that DTs enhance resilience by providing real-time monitoring and control across all operational links, enabling organizations to anticipate disruptions and optimize performance. Similarly, Roman et al. [9] demonstrate how DTs enhance cybernetic and physical systems through real-time data analysis and simulation.

Mitigation of Financial and Physical Risks: Badakhshan and Ball [11] propose a DT framework that integrates machine learning and simulation to manage inventory and cash flows, identifying optimal replenishment policies to mitigate the effects of both physical and financial disruptions.

Conceptual Modeling: Barykin et al. [12] and Dos Santos et al. [14] both propose theoretical DT models aimed at improving supply chain reliability, stability, and robustness through the integration of simulation, optimization, and data analytics.

These collective efforts underscore the growing necessity for a comprehensive DT framework to practically support supply chain stakeholders in making informed, timely decisions amidst a world of persistent uncertainty. Table II summarizes Digital twins articles applied to supply chain.

TABLE II. . DIGITAL TWINS IN SUPPLY CHAIN

Title	Year	Authors
Digital Twins in Supply Chain Management: A Brief Literature Review	2020	Marmolejo-Saucedo, José Antonio, and Hurtado Margarita.
Network concept of intelligent digital supply chain	2020	Barykin, S., Yadykin, V., Kosukhina, M., and Parfenov, A.
Design and development of digital twins: A case study in supply chains	2020	Marmolejo-Saucedo, J. A.
Supply chains resilience in turbulent times: conceptual model and real-world use case	2022	dos Santos Alvim, L. S. Viel de Farias, I., Morosini Frazzon, E., and de Simas D.
The Digital Supply Chain Twin paradigm for enhancing resilience and sustainability against COVID-like crises	2023	Longo, Francesco, Mirabelli Giovanni, Padovano, Antonio, and Solina Vittorio.
Applying digital twins for inventory and cash management in supply chains under physical and financial disruptions	2023	Badakhshan, E., and Ball, P.
Digital twins for logistics and supply chain systems: Literature review, conceptual framework, research potential, and practical challenges.	2024	Le, Tho. V., and Fan, R.
Digital Twins on the Resilience of Supply Chain Under COVID-19 Pandemic	2024	Lv, H. Qiao, L., Mardani, A., and Lyu, Z.
State of the Art of Digital Twins in Improving Supply Chain Resilience	2025	Roman, E.-A., Stere, A.-S., Ros, ca, E., Radu, A.-V., Codroiu, D., Anamaria, I.

Digital Twins (DTs) and Agent-Based Modeling (ABM) are highly complementary and are increasingly being integrated. The primary connection is that ABM provides decision-making intelligence and dynamic behavior that elevates a static or purely process-based Digital Twin into a truly intelligent and proactive decision-support system. ABM addresses a core limitation of traditional simulation models within a DT by modeling individual, local decision-making, which is crucial for systems involving many independent entities (like people or decentralized companies).

In supply chain management (SCM), the combination is particularly powerful for building a Digital Supply Chain Twin (DSCT).

- Agents: The agents in DSCT can represent manufacturers, logistics providers, retailers, and even consumers.
- Benefits: This integration allows the DSCT to simulate:
- Disruption Propagation: How a local disruption (like a factory fire) cascades through the entire network as agents (companies) react and scramble for alternative suppliers.
- Adaptive Strategy Testing: Evaluating the effectiveness of different resilience strategies (e.g., dual sourcing vs. stockpiling) by observing the emergent outcomes across the agent network.
- Route Optimization: Dynamic routing based on real-time data and the predicted behavior of transportation agents.

IV. Agent-Based Modeling (ABM) and Disaster Resilience

Simulation models are indispensable for understanding and lessening the impact of natural disasters on supply chains, empowering companies to forge strong and adaptable strategies. Agent-Based Modeling (ABM) offers distinct benefits by capturing the intricate interactions and resulting behaviors inherent in these disruptive situations. By leveraging ABM, researchers and practitioners gain a deeper grasp of complex dynamics, facilitating the development of impactful strategies for bolstering resilience.

A. ABM Applications in Disruption Analysis

Quantitative studies using simulation have been vital in analyzing various risk scenarios and testing actions to mitigate the effects of major disruptive events (Rinaldi et al. [14]). The following research highlights the specific strengths of ABM for tackling these challenges:

- Propagation and Cascading Effects: Using simulation based on data from over four million supply chain connections, Inoue and Todo [15] demonstrated that the negative impact of disrupted intermediate imports increases exponentially with the duration and severity of the disruption due to cascading domestic effects. They also found that the adverse economic effects are heavily influenced by the structure of the importer network (e.g., the position of affected firms) and can be lessened by reorganizing immediate domestic supply chain connections.
- Human-Centric Urban Supply: For urban emergencies, Huang et al. [16] introduced a novel, human-centric approach using mobile signaling data to model large-scale supply-demand networks. Their simulations showed that high-precision mobility data improves modeling accuracy, and that during cascading failures, population density is a key factor in supply shortages. This work provides insights for strengthening critical urban supply systems.
- Maritime Logistics and Sustainability: ABM can also validate operational changes. Benedecti et al. [17] used an Agent-Based Simulation Model to improve the maritime supply chain's connectivity between the two locations, which are key for Santa Catarina's significant container handling activities. The project aims to create a competitive alternative to current logistics, demonstrating operational and economic viability with potential cost reductions for customers by simulating an integrated system and analyzing its financial impact. The alternative not only showed a potential 2% cost reduction but also drastically improved sustainability, achieving a 65% reduction in greenhouse gas emissions by cutting truck numbers and travel distances

B. Enhancing Resilience with Supply Chain 4.0 Technologies

ABM is often integrated with other Supply Chain 4.0 technologies to enhance its effectiveness in risk management:

- Blockchain and Collaboration: Lohmer et al. [18] explored how blockchain technology and smart contracts can enhance risk management. Their ABM study indicated that time-efficient collaborative processes enabled by blockchain can significantly reduce disruption propagation, network recovery time, and total costs. However, they cautioned that if process efficiency is lacking, negative effects may still arise depending on the disruption's duration.
- Adaptation to New Crises**:** Rinaldi et al. [4] assert that, given the shared characteristics of external, exceptional, and unpredictable disruption, simulation models developed for natural disasters (like earthquakes or floods) are valuable and potentially adaptable for studying the impact and mitigation of pandemic disruptions.

This body of research underscores how agent-based simulation provides the necessary granular detail and dynamic environment to move beyond theoretical analysis and develop practical, data-driven solutions for increasing supply chain resilience. Articles span from ABM disruption analysis to enhancing resilience and are summarized in Table III.

TABLE III. ABM ARTICLES FOR SUPPLY CHAIN

Title	Year	Authors
Analysis of resilience strategies and ripple effect in blockchain-coordinated	2020	Lohmer, J., Bugert, N., and Lasch, R.
A literature review on quantitative models for supply chain risk management: Can they be applied to pandemic disruptions?	2022	Rinaldi, M., Teresa Murino, T., Gebennini, E., Morea, D., and Bottani, E.
Disruption of international trade and its propagation through firm-level domestic supply chains: A case of Japan	2023	Inohue, H., and Todo, Y.
Network invulnerability modeling of daily necessity supply based on cascading failure considering emergencies and dynamic demands	2024	Huang, H., Zhang, W., Zhen, Z., Shi, H., and Zhao, M.
Integrated simulation of an inland container terminal and waterway service for enhancing the maritime supply chain connectivity between Joinville and Itapoá Port	2024	Benedecti, R. C. Macowski Durski Silva,V., Alves da Costa, G.A.

Next section is about Cloud Computing and Big Data, the relationship between Agent-Based Modeling (ABM), Cloud Computing, and Big Data is a synergy where each component enables and enhances the others, forming a powerful platform for simulating and analyzing complex adaptive systems. The core relationship is: Big Data provides the detailed inputs for ABM, and Cloud Computing provides the computational power necessary to run ABM simulations that utilize Big Data.

V. CLOUD COMPUTING AND BIG DATA

Cloud Computing (CC) and Big Data are critical enablers of modern supply chain simulation, providing the computational and analytical infrastructure necessary for agility, scalability, and disaster resilience. CC, defined as the transmission of data over the internet using remote servers and databases, offers numerous advantages for organizations seeking solutions with flexibility and speed (Gammelgaard & Nowicka [21]; Yu, et al. [19]).

A. The Cloud Infrastructure and Service Models

Cloud infrastructure provides the foundation for managing massive volumes of supply chain data (ranging from terabytes to petabytes), enabling rapid information flow and supporting large-scale, distributed simulations (Chen [22]).

CC is typically classified into three distinct service models, each offering varying degrees of operational control:

- Infrastructure as a Service (IaaS): The provider supplies the basic network and storage infrastructure (like virtual machines), allowing the customer to focus entirely on business applications and activities.
- Software as a Service (SaaS): The provider delivers a ready-to-run package with security and updates, enabling users to access applications (often via web browsers) without local downloads.
- Platform as a Service (PaaS): The provider supplies the underlying hardware and software access, allowing clients to develop their own applications hosted entirely in the cloud.

While all models facilitate data management in minutes, speeding up information centralization and supplier management (Yu, et al. [19]), they also introduce new complexities. Because data is managed by an external, globally distributed entity, security depends entirely on the service provider, altering risk dynamics and increasing the potential impact of an attack (Akinrolabu, et al. [20]).

Strategic Advantages for Supply Chain Management (SCM)

For SCM, the integration of CC is rapidly expanding due to the following key benefits, which facilitate agile optimization and enhance decision-making:

TABLE IV. INTEGRATION OF CC BENEFITSS AND THE IMPACT ON SCM

Benefit	Impact on SCM
Real-Time Visibility & Analytics	Enables administrators to anticipate risky situations and identify trends that may lead to future problems.
Supply Chain Mapping	Provides a holistic view of the network, aiding in the identification of weaknesses and the generation of contingency plans.
Collaboration Platform	Facilitates smooth communication and collaboration among all distributed stakeholders and supply chain members.
Scalability & Cost Reduction	Optimizes the supply chain more agilely and guarantees cost-effective data access and processing.
Compliance Management	Provides greater assurance of adherence to regulations and environmental commitments.

B. The Cloud Infrastructure and Service Models

The benefits of CC are most evident in dynamic contexts with high levels of uncertainty, particularly during and after a disaster where local IT infrastructure may be compromised (Niyazi & Behnamian [27]). Disasters frequently lead to poor logistical precision and coordination due to a lack of reliable, real-time information about affected areas, a problem exacerbated by the disruption of critical communication infrastructure (Ali, et al. [22]). Cloud-based solutions address this through:

- Real-Time Data Aggregation: CC allows for the rapid, remote integration and analysis of massive datasets from heterogeneous sources, such as Synthetic Aperture Radar (SAR) satellite imagery, automated weather stations, geospatial layers, and social media feeds (Niyazi & Behnamian [27]).
- Technological Redundancy: CC platforms serve as a critical backup infrastructure, ensuring access to real-time status visualization and robust logistical planning even when conventional IT systems fail (Nagendra et al. [26]).

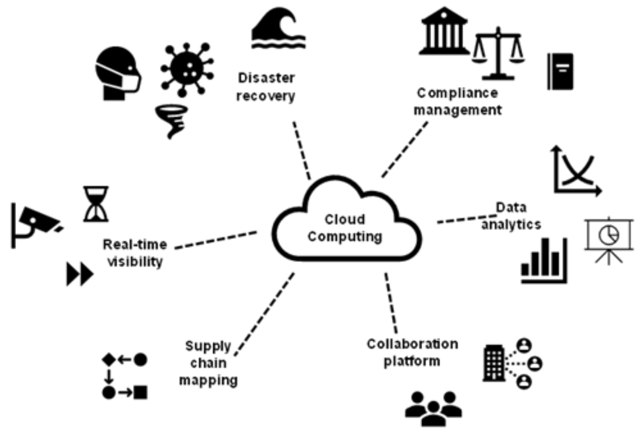

Figure 1. Cloud Computing Benefits

C. Case Studies in Disaster and Pandemic Response

Research demonstrates the transformative role of CC and Big Data in managing major crises:

1. Disaster Early Warning and Response:
   - Xue, et al. [24] developed a distributed, flexible, and collaborative early warning system for the entire supply chain. Its cloud infrastructure supports real-time data analysis via mining and inference engines to categorize potential risks and facilitate preventive action.
   - The "Map Your Risk (MYR)" platform, developed by Jimmy et al. [25], uses web services and cloud-based text mining of data (e.g., from Twitter) to provide risk managers with georeferenced maps and critical alerts regarding the impact of natural hazards (like earthquakes) on essential logistics facilities.
   - During the 2018 Kerala floods, a big satellite data analysis system on a cloud platform provided crucial support by identifying priority areas, compromised medical facilities, viable access routes, and high-density population zones (Nagendra et al. [26]).
2. Pandemic Management and Vaccination Logistics: The COVID-19 pandemic stretched disaster response strategies to the limit, highlighting the need for efficient data systems in post-disaster recovery like mass vaccination planning (Hernandez-González, et al. [28]; Sathish et al. [29]).
   - Resource Allocation**:** Lee et al. [30] utilized cloud computing to run the RealOpt-POD system, which integrates stochastic simulations and differential

equations to determine the optimal allocation of limited vaccines, minimizing infections and deaths.

- Route and Appointment Optimization: Jixiao & Yinghui [31] proposed a CC-based platform for logistics distribution during health emergencies that uses integrated IoT and public data to build optimized rescue routes. Fabbri et al. [32] developed a Mixed Integer Linear Programming (MILP) model housed in the cloud to automate and optimize mass vaccination appointment scheduling in minutes, a significant improvement over slow, error-prone manual processes.

Table V summarizes the articles presented in this section.

TABLE V. CLOUD COMPUTING AND BIG DATA IN SUPPLY CHAINS

Title	Year	Authors
Cyber Supply Chain Risks in Cloud Computing. Bridging the Risk Assessment Gap	2018	Akinrolabu, O., New, S., & Martin, A.
Next generation supply chain management: the impact of cloud computing	2024	Gammelgaard, B., & Nowicka, K.
Intelligent algorithms for cold chain logistics distribution optimization based on big data cloud computing analysis	2020	Chen, Y.
The Role of Industry 4.0 Technologies in Mitigating Supply Chain Disruption: Empirical Evidence from the Australian Food Processing Industry	2024	Ali, I., Arslan, A., Khan, Z., & Tarba, S. Y.
Early warning decision-making system based on cloud computing technology for retail supply chain unconventional emergency	2017	Xue, H., Yuan, Y., Lin, Y., & Cai, J.
Understanding natural disasters as risks in supply chain management through web data analysis	2015	Jimmy, O., Wang, Z., Goh, R., Yin, X., Xin, X., & Fu, X.
Management of humanitarian relief operations using satellite big data analytics: The case of Kerala floods	2022	Nagendra, N. R., Narayanamurthy, G. R., & Moser, R.
Application of cloud computing and big data in three-stage dynamic modeling of disaster relief logistics and wounded transportation: a case study	2023	Niyazi, M., & Behnamian, J.
Simulación y optimización de sistemas de vacunación con capacidad finita	2022	Hernandez-González, S., Jiménez-García, J., Hernández Ripalda, M., & de la Cruz Madrigal, I.
Resource Scheduling for Postdisaster Management in IoT Environment	2019	Sathish Kumar, J., & Zaveri, M. A.
Strategies for Vaccine Prioritization and Mass Dispensing	2021	Lee, E. K., Li,, Z. L., Liu, Y. K., & LeDuc, J.
Distribution of the Emergency Supplies in the COVID-19 Pandemic: A Cloud Computing Based Approach	2021	Jixiao, W., & Yinghui, W.
A decision support system for scheduling a vaccination campaign during a pandemic emergency: The COVID-19 case	2023	Fabbri, C., Ghedini, P., Leonessi, M., Malaguti, E., & Tubertini, P.
Cloud computing and its impact on service level: a multi-agent simulation model	2017	Yu, Y., Cao, R. Q., & Schniederjans, D.

VI. MULTIMODAL TRANSPORT AND DISRUPTIONS

As we point out in Section I, seaport disruptions have a profound and cascading impact on multimodal transport. To surpass this, the integration of Digital Twins, Agent-Based Modeling, Cloud Computing, and Big Data is highly effective for mitigating the impacts of seaport disruptions on multimodal transport. These technologies work together to provide the necessary situational awareness and predictive capabilities for resilient logistics management.

1. Digital Twin creates a virtual replica of the entire multimodal network, extending from the port terminal to the inland rail hubs and road networks.
2. ABM acts as the intelligent simulation engine within the Digital Twin, modeling complex human and asset behavior during a crisis.
3. Cloud Computing and Big Data provide the scalable foundation necessary for these advanced tools to function effectively.

By combining these four technologies, companies can move beyond reactive decision-making to proactive risk mitigation, significantly reducing delays and costs when seaport disruptions inevitably occur.

VI. CONCLUSIONS

The evolution of supply chain simulation, propelled by Supply Chain 4.0 technologies, represents a fundamental shift from reactive risk management to proactive, predictive discipline. The core of this transformation lies in the symbiotic relationship between Digital Twins (DTs), Agent-Based Modeling (ABM), and Cloud Computing (CC).

Digital Twins significantly enhances supply chain resilience by providing real-time visibility and highly accurate predictive insights. These virtual replicas are crucial for robust scenario planning and quick, informed adaptation during crises. When DTs are powered by Agent-Based Modeling (ABM), organizations gain a deeper, granular understanding of complex network dynamics, particularly the cascading effects stemming from high-impact events like natural disasters. This combined capability ensures strategies are not just theoretical, but effective in minimizing negative consequences.

Furthermore, the robustness and expanding coverage of Cloud Computing models have made efficient, agile decision-making possible even in environments of extreme uncertainty. By providing the infrastructure to process petabytes of data, the Cloud enables the rapid analysis and deployment of recovery strategies. The ongoing challenge, however, remains the technical necessity of continuously developing new algorithms for managing, debugging, and interpreting these massive, real-time data streams to ensure optimal decision quality.

In general, the synergy of these three components creates a Digital Twin (DT) of the transportation network, turning ABM into a powerful predictive tool.

a) Big Data:

Provides the fuel (realistic parameters and real-time feeds).

Application to Ports & Multimodal Transport: Collects vessel AIS, terminal traffic, cargo manifests, and weather data to define realistic operating conditions and disruption probabilities.

b) Agent-Based Modeling (ABM)

Acts as the Core Predictive Engine (simulating complex interactions).

Application to Ports & Multimodal Transport: Models vessels, cranes, trucks, and containers as independent agents. Simulates the cascading impact of disruptions (e.g., crane failure) and tests mitigation strategies.

c) Cloud Computing

Serves as the Scalable Platform (hosting and parallel processing).

Provides the necessary power to run massive, complex simulations of entire multimodal networks in real-time, enabling quick analysis and dynamic rerouting decisions.

Based on these, the main results are:

- Port Disruptions: Enables the simulation of disruption scenarios (weather, equipment failure) to predict bottlenecks, optimize resource allocation, and minimize cargo backlog.
- Multimodal Transport: Creates end-to-end supply chain visibility. Predicts the cascading impact of delays across different modes (sea, rail, road) and recommends dynamic, optimal rerouting to maintain overall network flow.

Acknowledgements

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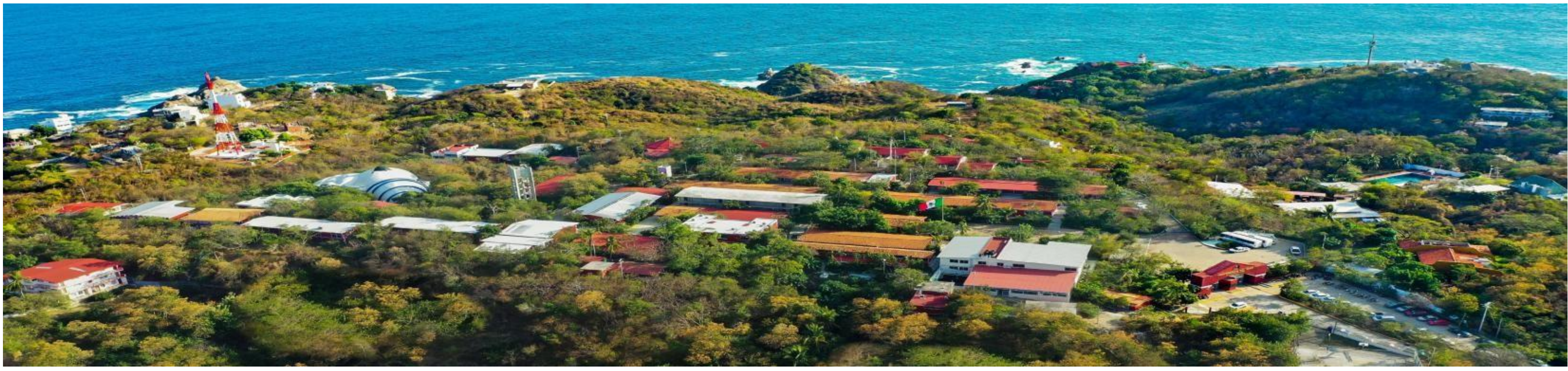

5- Transportation, Infrastructure, and Airport Operations

- **Look-Ahead Airline Seat Allocation: Enhancing Efficiency in Passenger Transfers at Hub airports**
  - Geoffrey Scozzaro
  - Miguel Mujica Mota

- **Freight transportation operational improvement through increasing payment efficiency at toll booths.**
  - Javier Garcia-Gutierrez
  - José Concepción López Rivera
  - Javier Romero Torres
  - Gaston Vertiz Camaron

Look-Ahead Airline Seat Allocation: Enhancing Efficiency in Passenger Transfers at Hub airports

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***Abstract*—This study examines the effect of seat assignment strategies on the transfer time of connecting passengers at a hub airport. Passenger seat allocation significantly influences disembarkation times, which can increase the risk of missed connections, particularly in tight transfer situations. We propose a novel seat assignment strategy that allocates seats to non-paying passengers after check-in, prioritising those with tight connections. This approach diverges from traditional methods focused on airline turnaround efficiency, instead optimizing for passenger transfer times and reducing missed connections. Our simulation, based on real-world data from Paris-Charles de Gaulle airport, demonstrates that this passenger-centric model decreases missed connections by 12%, enhances service levels, reduces airline compensation costs, and improves airport operations. The model accounts for variables such as seat occupancy, luggage, and passenger type (e.g., business, leisure) and is tested under various scenarios, including air traffic delays.**

***Keywords*—Airline seat allocation, Simulation, Connecting passengers, Aircraft disembarkation**

I. Introduction

The COVID-19 pandemic deeply impacted the airline industry, leading to a resurgence of the hub-and-spoke strategy [1]. This change has increased the number of connecting flights offered by airlines to passengers. While this strategy allows airlines to cover a wider range of destinations, it also introduces greater uncertainty into passenger journeys. A delay on the first flight can lead to missed connections, resulting in significant delays at the final destination.

Missing a connecting flight is often the result of a series of interrelated events: a delay on the first flight, a long taxiing time on arrival, a long disembarkation time, long walking distances due to distant disembarkation and boarding gates, or long queues at border control for international flights. These factors can result in passengers arriving late at their departure gate and being stranded.

This scenario is highly undesirable for passengers, who must then wait to be re-accommodated on another flight. However, it is equally problematic for airlines. According to Regulation (EC) No 261/2004 [2], airlines must re-book passengers who miss their connections, and if the delay exceeds three hours, as is often the case when a connection is missed, they must also provide financial compensation.

The literature has explored various methods to improve passenger transfers. For example, Kim *et al.* [3] investigated gate assignment optimization as a way to balance the needs of airports and airlines. However, this approach is challenging to implement due to the complexity of gate allocation, which involves numerous factors such as airport management strategies, taxiway logistics, gate conflicts, aircraft compatibility, and strategic decisions about passenger flows and even shopping behaviour.

Guo *et al.* [4] used a combination of regression trees and simulations to predict passenger flow at immigration and transfer security areas. Their approach allows airports to anticipate late-arriving passengers and assist them in catching their connecting flights by speeding up transfers or early re-booking. However, their study does not clearly outline specific actions, such as reallocating security staff to handle delayed passengers, nor does it address the costs associated with these decisions. While re-booking helps passengers, it does not prevent delays at their final destination.

An important area for improvement is the optimisation of the disembarkation process. Wald *et al.* [5] and Qiang *et al.* [6] have shown that structured disembarkation strategies outperform unstructured ones. In particular, column-based strategies, in which passengers disembark from left to right or from the aisle to the window, tend to reduce total disembarkation time more effectively than traditional front-to-back row-based methods. While these studies evaluate metrics such as total or average passenger disembarkation time, they do not address the specific needs of connecting passengers and focus solely on overall disembarkation efficiency.

This study focuses on a related but distinct issue: seat allocation strategy. The seat assigned to a passenger plays a crucial role in determining his or her disembarkation time, which has a direct impact on transfer times for connecting passengers. We propose a novel seat assignment strategy that prioritises passengers with tight connections, moving away from the current practice of randomly assigning seats to passengers who do not pay for seat selection. By recognising the additional stress and time pressure faced by passengers with shorter transfer windows, we aim to allocate seats in a way that minimises their disembarkation time, thereby reducing the likelihood of missed connections and improving the overall passenger experience.

This approach involves a minor adjustment to the check-in process. Passengers willing to pay an additional fee can still select a specific seat. Those who opt not to pay will check in without an assigned seat. At the close of the check-in period, airlines will allocate the remaining seats based on priority, considering expected connection times. This strategy assumes that airlines possess information about connecting passengers, which is typically available for those travelling within the same airline or alliance.

The proposed seat allocation strategy is evaluated using a cellular automata simulation model inspired by Schultz *et al.* [7]. Although simple, this model can be fine-tuned to realistically simulate passenger behaviour. The case study is on Paris-Charles de Gaulle airport, using historical flight schedules and actual gate delay data. Passenger flows are simulated and a connecting passenger scheme is generated across the airport based on a day of historical operations. Simulations are performed, incorporating stochastic elements such as luggage collecting time or pre-reserved seat selection. The results are compared with those from the traditional random seat allocation to assess the benefits of the proposed seat allocation strategy. To promote open science, all code used to generate this research is publicly available at the following link: https://github.com/geoffreyscozzaro31/planeDeboarding.

The remainder of the paper is structured as follows. The modelling framework is described in Section II. Section III presents the seat allocation strategy and Section IV the disembarkation simulation validation. The case study is introduced in Section V. Finally, Section VI presents the results.

II. Modelling Framework

This section outlines the modelling framework adopted for the aircraft disembarkation process.

A. Simulating disembarkation process

We use a simulation-based approach to model the passenger disembarkation process. This method effectively captures passenger interactions and provides a realistic evaluation of airport operations such as boarding procedures [8] and security screening systems [9].

Our model is inspired by the work of Schultz *et al.* [7] and uses cellular automata to simulate the disembarkation process. In this model, the aircraft is divided into square cells, each of finite size and capable of accommodating a single passenger. These cells represent either a seat or a section of the aircraft aisle. In this work, we adopt the following assumptions:

1) aircraft considered in this study are typical of medium-range configurations, such as the A320 or B737, which feature a single aisle with a 3+3 seating arrangement,
2) disembarkation occurs exclusively through the front door.

Each passenger is assigned a dynamic status, among the following ones: “seated”, “standing up from the seat”, “moving in the aisle”, “waiting in the aisle”, “collecting luggage”, and “disembarked”.

Passenger movement is modelled using a cellular automata approach, where the evolution of passengers’ positions occurs in discrete time steps according to predefined rules. At the start, all passengers are in the “seated” status. As flights may not be fully booked, some seats remain unoccupied. During each time step, passengers who can reduce their distance to the exit by moving to an adjacent available cell will do so. Three types of actions are considered:

1) Moving left/right: Passengers still seated may move to an adjacent cell (either a seat or the aisle) if it is vacant.
2) Moving forward: Passengers in the aisle may move forward, if the next cell is empty, to proceed to the exit.
3) Collect luggage: Passengers with baggage will collect it from the overhead bin directly above their row. They will remain in the corridor cell for a specified time to collect their luggage.

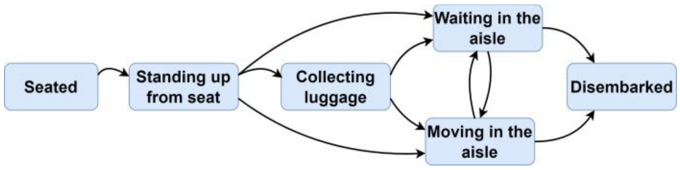


Figure 1. Passenger status transition flow. Each case represents a passenger status, and each arrow represents a possible status transition.

Figure 1 illustrates the passenger status transition flows during the disembarkation process.

B. Conflict resolution strategies

When two passengers from adjacent cells attempt to enter the same empty cell, a conflict arises. Two main rules are introduced to deal with this:

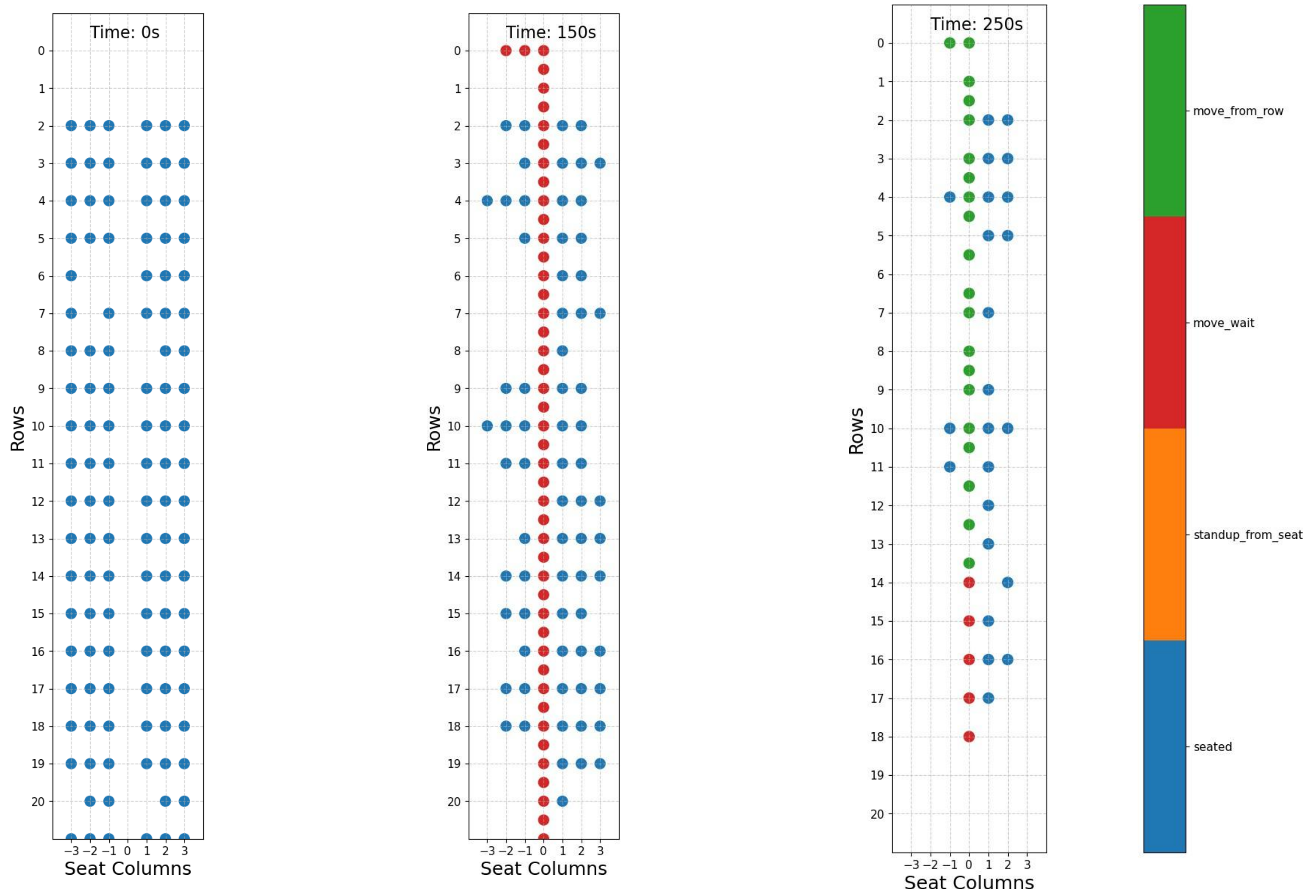
- *Courtesy Rule:* This strategy prioritises passengers closer to the exit, giving precedence to those in the front rows over those in subsequent rows. If passengers from both the left and right attempt to enter the aisle simultaneously, a random selection determines who moves first.
- *Aisle-priority rule:* This strategy always gives priority to the passenger already in the aisle, ensuring that their movement towards the exit takes precedence over those still seated or moving from adjacent cells.

This model accounts for the time required for each passenger action, allowing different speeds to be assigned to various movements. For example, the luggage retrieval process is simulated by a brief pause after the passenger stands in the aisle.

The different movement speeds are represented by the time spent in each cell. The simulation is divided into identical time steps, and the step duration is calibrated to the shortest allowed movement duration.

Additionally, a buffer time is included to account for the deployment of the jet bridge before the gate opens. The different parameter settings used to configure the simulation are thoroughly described and validated in Section IV.

Figure 2 presents a visualisation of the disembarkation process, following the *aisle-priority rule*, at three different time steps. The GIF animation is available through the following link: https://github.com/geoffreyscozzaro31/planeDeboarding/blob/main/medias/deboarding/animations/animation_deboarding_aisle_priority_deboarding_rule_45fps_v2.gif



(a) Frame 0/642 (b) Frame 300/642 (c) Frame 500/642

Figure 2. Screenshots of the disembarkation process simulation at different time steps. In this scenario, disembarkation priority is given to passengers already in the aisle.

III. Seat Allocation Strategy

We propose a novel seat allocation strategy for passengers who have checked in without pre-booking their seats. Airlines can implement this allocation after the check-in deadline, once the total number of unallocated passengers is known. The strategy aims to minimise the risk of connecting passengers missing their next flight by prioritising them based on their estimated transfer time - a value that airlines can usually calculate using available data on passengers connecting to other flights within the same alliance.

Each passenger is assigned a priority index, P_i, where i is the passenger index, based on the urgency of their connection. The passengers are then ordered such that $P_1 > P_2 > \cdots > P_N$, where N represents the total number of passengers still awaiting seat assignments.

The seat assignment process can be formulated as a matching algorithm. Let S_j denote the availability of the j-th seat, where $S_j = 1$ if the seat is available and $S_j = 0$ otherwise. Each seat S_j is associated with a disembarkation time T_j, where $T_1 < T_2 < \cdots < T_M$ represents the disembarkation time for all M seats, ranked in ascending order. The goal of the matching algorithm is to assign the highest-priority passenger to the seat with the earliest disembarkation time.

Here is the pseudo-code of the seat allocation strategy:

Passenger-Seat matching algorithm

1) **Variable Definitions:**
   - **S_j = 1 if the j-th seat is already booked, 0 else**
   - **P_i = Priority index of passenger i**
   - **T_j = Disembarkation time for seat j**
2) **Sort passengers by descending priority index:**
   - $P_1 > P_2 > \cdots > P_N$
3) **Sort seats by ascending disembarkation time:**
   - $T_1 < T_2 < \cdots < T_M$
4) **Initialize indices:**
   - **$i \leftarrow 1$ (Passenger index)**
   - **$j \leftarrow 1$ (Seat index)**
5) **While $i \leq N$ and $j \leq M$ do:**
   - **if $S_j = 0$:**
     - **Assign passenger i to seat j**
     - $i \leftarrow i + 1$
   - $j \leftarrow j + 1$

Parameter	Value
Cell size	0.4mx0.4m
Cell capacity	1 passenger
Number of rows	n
Seat per row	3 +3
Number of cells	$n \times (3+3+1) \times 2$
Simulation's time step	0.5s
Moving left/right/forward	0.5s
Luggage collecting duration	$X \sim Weibull(\alpha = 1.7, \beta = 8)$
Jet bridge deployment time	180s

TABLE I. SIMULATION PARAMETERS

The disembarkation time T_j for each seat is determined by the disembarkation strategy used, such as the *courtesy rule* or the *aisle-priority rule* presented in Section II. For example, if passengers are disembarking under the *courtesy rule*, rows will empty sequentially from the front to the back of the aircraft. In this case, seats in the first row will have shorter disembarkation times than those in subsequent rows. On the other hand, if the *aisle-priority rule* is applied, seats closer to the aisle will have shorter disembarkation times. This means, for example, that a passenger in the third row, seated close to the aisle, should disembark before a passenger seated by the window in the first row.

Exceptions may occur when passengers retrieve luggage from the overhead bins, potentially blocking those behind them and allowing passengers in the rows ahead to disembark earlier under the *aisle-priority rule*. A similar situation may arise under the *courtesy rule* if there are empty seats in a row, allowing a passenger sitting in an aisle seat in a rear row to disembark before a passenger sitting further forward.

For simplicity, we disregard these exceptions and assume that passengers seated closer to the aisle will disembark earlier under the *aisle-priority rule*. Conversely, passengers in the front rows will disembark earlier under the *courtesy rule*.

The performance of the proposed seat allocation strategy is compared to the traditional random assignment method through multiple simulations. Different key performance indicators are assessed, such as passenger disembarkation times, or the number of passengers missing their connections. The details and parameter values used for calibration and simulation are provided in the following section.

IV. SIMULATION

We calibrate our simulation using various parameters inspired by [7], which are summarised in Table I. The disembarkation model developed in this paper is verified by comparing its results with findings from the existing literature. Namilae *et al.* [10] provided reference values for similar aircraft configurations, specifically single-aisle aircraft with 3+3 seats per row. Their study reported disembarkation times of 8 to 10 minutes for a 144-seat configuration and 10 to 12 minutes for an 182-seat configuration, using the *courtesy rule* disembarkation strategy (*i.e.* from the front to the rear of the aircraft).

To maintain consistency with the reference study, this analysis assumes that the aircraft was operating at 100% load factor, with all passengers carrying overhead luggage. Gate bridge connection time was excluded. For each configuration (144 seats and 182 seats), 100 replications of the simulation experiment were performed to account for the stochasticity of baggage collection times. Among the 100 replications, the minimum, average and maximum total disembarkation time are extracted. Table II summarises the simulation results for both the *courtesy rule* and the *aisle-priority rule* followed during passenger disembarkation.

TABLE II. TOTAL DISEMBARKATION TIMES (IN MINUTES) OVER 100 SIMULATIONS DEPENDING ON DISEMBARKATION STRATEGY

Cabin config	Courtesy rule			Aisle-priority rule		
	Min	Mean	Max	Min	Mean	Max
144-seat	7.60	9.42	11.29	5.16	6.47	7.76
182-seat	10.02	11.92	14.12	6.57	8.12	9.60

This table shows that the model produces results under the *courtesy rule* for passenger disembarkation comparable to those in the literature. The average disembarkation times are centred on the expected range, *i.e.* 8-10 minutes for the 144-seat configuration and 10-12 minutes for the 182-seat configuration, with slightly larger minimum and maximum values. This consistency underscores the model's robustness, as it aligns well with established findings and effectively simulates the disembarkation process.

The *aisle-priority rule* was also evaluated to determine whether it reduces the total disembarkation time, as expected, according to [5] and [6]. The results in Table II show a clear reduction in time compared to the *courtesy rule*, further increasing confidence in the simulation model. These findings support the subsequent analyses in Section VI, which assess the impact of seat allocation on connecting passenger transfers.

V. CASE STUDY

This section details the methodology we developed for modelling passenger transfers at Paris Charles de Gaulle (CDG) airport, using historical flight and passenger data. First, the parameters for flight disembarkation are introduced. Next, the methodology for simulating connecting passengers is outlined. Finally, the operational characteristics of the historical operating day considered, including arrival and departure flight sets, are described.

A. Flight disembarkation

The simulation of the disembarkation process is based on a single-aisle medium-haul aircraft with a typical 3+3 seating configuration. The number of rows varies according to the flight selected. Only medium-range arriving flights are analysed, excluding long-range twin-aisle aircraft. Passengers are divided into three groups: (1) those with pre-booked seats, (2) transfer passengers without pre-booked seats and (3) all other passengers. Business class passengers are assumed to have pre-booked seats.

We assume the following distribution of passenger types 20% with pre-booked seats, 40% as transfer passengers with-

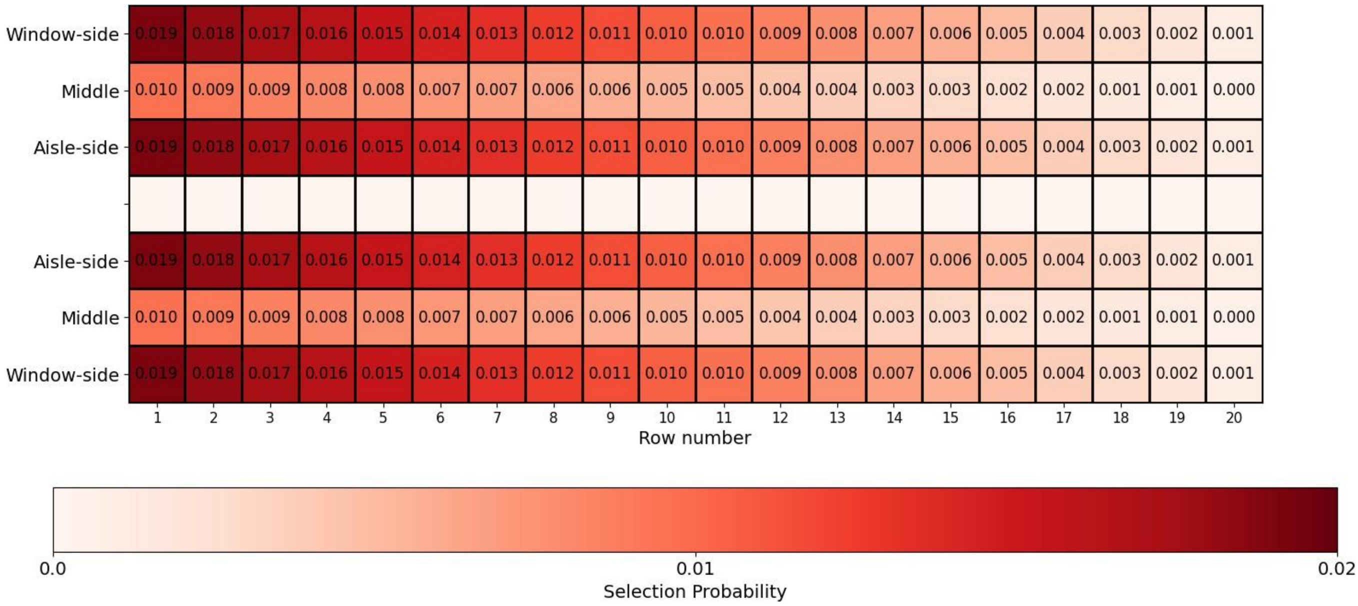


Figure 3. Probability distribution of pre-booked seat selection for a 30-row aircraft. Row 1 is positioned at the front of the cabin.

TABLE III. Parameters for flight disembarking simulation

Parameter	Value
% of passengers with pre-booked seats	$X \sim U(15\%, 25\%)$
% of connecting passengers	$X \sim U(30\%, 50\%)$
% Other passengers	Adjusted to sum to 100%
% Passengers with carry-on luggage	$X \sim U(85\%, 95\%)$
% Aircraft seat occupancy	$X \sim U(81.5\%, 91.5\%)$

out pre-booked seats, and 40% categorised as other. To introduce variability, we apply a uniform random value of ±5% to the proportions of pre-reserved seats, and a uniform random value of ±10% for the share of transfer passengers.

In terms of the location of pre-reserved seats, Shao *et al.* [11] found that passengers have a strong preference for seats at the front of the aircraft and tend to avoid middle seats. Consequently, we design a probability distribution that favours the allocation of pre-booked seats to the front of the aircraft, and specifically to window or aisle seats. Figure 3 illustrates the probability distribution we retain on an example for a 30-row aircraft.

Regarding cabin baggage, the proportion of passengers carrying cabin baggage varies across airlines. Low-cost carriers typically charge extra for cabin baggage, reducing its prevalence among passengers. However, since this study focuses on major airlines operating at CDG that offer free cabin baggage, we assume that 90% of passengers have cabin baggage, with a random variation of ±5%.

Seat occupancy is defined based on Air France's June 2019 activity report [12], which reports an average passenger load factor of 86.5% for short- and medium-haul flights. We adopt this value and apply a uniform random variation of ±5%. Table III summarises the parameters retained for simulating flight disembarkation.

B. *Passenger transfer modelling*

Since the dataset does not include information on the number of transfer passengers per flight, a modelling framework was developed to generate connecting passengers. A specific proportion of transfer passengers and a realistic transfer time window are considered to identify potential connecting flights. A focus is made on flights operated by the airport's main airline, as connecting flights are typically managed by the same airline or by airlines within the same alliance. Due to the absence of gate assignment data for each flight, the average transfer time cannot be directly calculated. Instead, a transfer time is randomly selected from a predefined interval to represent the minimum required transfer time. Additionally, a boarding threshold before departure is also considered.

According to the Paris Ae´roport website [13], the minimum transfer time ranges from 10 to 95 minutes. This range is used to generate realistic walking transfer times for connecting passengers. In addition, we allow a minimum buffer of 10 minutes between the walking time and the scheduled transfer time to avoid generating infeasible transfers, in line with common industry practice where airlines avoid creating impractical transfer schedules.

We assume that, on average, 40% of passengers on each flight are connecting passengers, and consider a random variation uniformly distributed between [-10%, 10%].

Air France, one of the main airlines operating at CDG, states that the boarding time is between 15 and 20 minutes, depending on whether the flight is domestic or international [14]. For this study, 20 minutes is used as no distinction is made between domestic and international flights.

A potential connection is defined as two flights, one arriving and one departing, with a reasonable transfer time for passengers, falling within the following time window:

TABLE IV. CHARACTERISTICS OF THE OPERATIONAL DAY CONSIDERED

Date	2019-06-24
Number of arriving flights	726
Number of departing flights	721
Total number of arriving passengers	121854
Total number of departing passengers	124579
Average delay per arriving flight	8.14 minutes
Average delay per departing flight	20.76 minutes
Number of arrivals operated by the considered airline with fewer than 200 passengers	275
Number of connecting passengers simulated	13698

- Minimum transfer time: 45 minutes.
- Maximum transfer time: 3 hours.

These thresholds ensure that only practical connections are considered. For each arriving flight, the model identifies potential departing flights within the specified transfer time window. Connecting passengers are then randomly assigned to these flights, ensuring a realistic distribution across the available connections.

In this study, we focus exclusively on departures from single-aisle aircraft and connecting passengers within the same airline. Therefore, we only consider arrival flights carrying less than 200 passengers and operated by the main airline operating at CDG airport. In the absence of exact aircraft configurations, we estimate the number of rows based on the passenger load factor for each instance. For example, if 180 passengers were carried and the passenger load factor is set to 90%, the total number of seats is calculated as follows:

$$\frac{180}{0.9 \times 6} = 34 \text{ rows}$$

C. Characteristics of the historical operating day considered

We consider one day among the data set that covered one month of historical traffic at CDG airport. This day was the busiest day in June 2019, with a total of 1447 flights operated during the day. The different characteristics of this day are presented in Table IV.

Both theoretical and actual transfer times are calculated for each generated connection:

- **Theoretical transfer time:** The difference between the scheduled arrival and departure times of the flights used to identify candidate connections. This time is considered when allocating seats to connecting passengers.
- **Actual transfer time:** The difference between the actual block times of the flights, taking into account any operational delays. This time is considered to assess, after simulating the disembarkation time, whether passengers will be able to make their connections.

Figure 4 illustrates the distribution of transfer times for the selected day. The data show that delays contributed to a broader dispersion of transfer times, with arrival delays increasing the pressure on passenger transfers, while departure delays extended the overall transfer duration. Several connections became infeasible due to delays, resulting in some instances of negative transfer times.

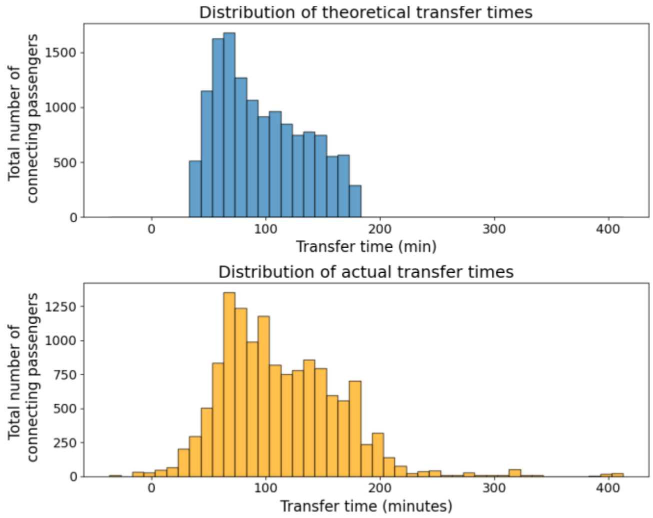


Figure 4. Passenger transfer time distribution for the historical operating day. Scheduled and actual transfer times are represented by blue and orange curves, respectively.

VI. RESULTS AND DISCUSSION

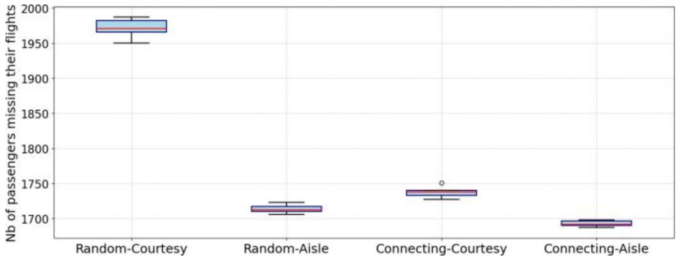
This section presents the results of the case study outlined earlier. We simulated the disembarkation process for all flights with fewer than 200 passengers over a whole day of operations, evaluating passenger disembarkation times. To account for stochastic factors such as the proportion of passengers with hand luggage, luggage retrieval time, the number and distribution of pre-assigned seats, and other variables, we conducted 10 simulations for the whole day.

A. Seat allocation strategies: Random vs. Connecting passenger priority

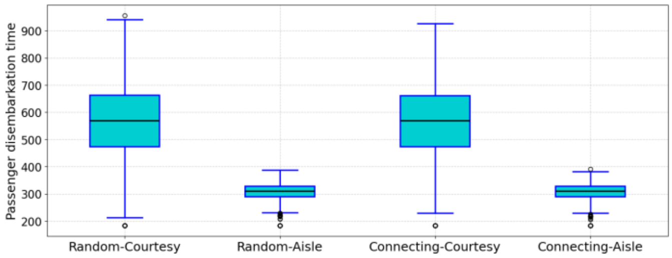
The study aimed to compare two seat allocation strategies for non-reserved seats: a random allocation method and a proposed strategy that assigns seats to passengers with tight transfer times to minimise disembarkation duration. This comparison was conducted under two disembarkation protocols: the *courtesy rule*, where passengers in front rows disembark first, and the *aisle-priority rule*, which prioritises passengers seated closest to the aisle.

A total of 4x10 simulations were conducted to evaluate the outcomes for an entire day of operations. Figure 5a and 5b present box plots illustrating the total number of passengers missing their flights and the average disembarkation times, respectively. Each box plot corresponds to a specific combination of seat allocation strategy for unreserved seats and the disembarkation rule applied. For the x-axis, "random" refers to a random seat allocation, while "connecting" refers to an allocation focused on connecting passengers. Similarly, "courtesy" and "aisle" refer to the *courtesy rule* and the *aisle-priority rule* used for disembarkation, respectively.

The "Random-Courtesy" box plot of Figure 5a, which represents the random seat allocation strategy combined with



(a) Number of passengers who missed their connecting flight during the day



(b) Passenger disembarkation times throughout the day

Figure 5. Box plots illustrating the total number of passengers missing their connecting flights (top figure) and passenger disembarkation times (bottom figure) across the operating day. Each box plot represents the results from 10 simulation runs, with each box corresponding to a unique combination of seat allocation strategy and disembarkation rule.

the courtesy disembarkation rule, translates the worst performance, with 1,950 to 1,990 passengers missing their connections over the day. In contrast, the same seat assignment combined with the *aisle-priority rule* for disembarkation enables approximately 250 additional passengers to make their connections (cf "Random-Aisle" box plot). This improvement is attributed to the significant reduction in overall disembarkation time under the *aisle-priority rule*, as demonstrated through Figure 5b. Specifically, the average disembarkation time is reduced by 45%, from 9 minutes to 5 minutes. This reduction is crucial for passengers with tight connections, allowing about 13% more of them to successfully catch their onward flights.

Equally remarkable is the impact of the new seat allocation strategy proposed in this study compared to the traditional random allocation. This can be done by comparing the "Random-Courtesy" box plot with the "Connecting-Courtesy" one of Figure 5a. The new allocation leads to a 12% reduction in the number of passengers missing their flights. This effect is almost equivalent to that obtained by changing the disembarkation rule, although it does not affect the disembarkation times, as observed in Figure 5b by comparing the "Random-Courtesy" and "Connecting-Courtesy" box plots.

By combining the benefits of a connecting passenger-oriented seat allocation strategy with the *aisle-priority rule* for disembarkation, the total number of passengers missing their flights is reduced to less than 1,700 (cf "Connecting-Aisle" box plot Figure 5a). This represents an overall reduction of 14% compared to the traditional strategy used by airlines, *i.e.* random seat allocation and the *courtesy rule* for disembarkation. However, the savings from the two strategies are not cumulative, *i.e.* the improvement is lower than 13% + 12%, since if disembarkation times are already minimised, the seat reassignment of connecting passengers is less effective in helping them to make their connections.

From a practical perspective, seat reassignment is easier to implement than disembarkation strategies, which require passenger coordination. In particular, *aisle-priority rule* requires the active involvement of staff, making it less practical. In contrast, seat reallocation can be integrated into the pre-boarding process without requiring real-time intervention.

The observed reduction in the number of passengers missing their flights represents a significant improvement in both passenger experience and airline cost management. Indeed, a missed connection can lead to significant delays for passengers at their final destination. Bratu *et al.* [15] estimate that if stranded passengers represent only 3% of the total delayed passenger volume, their delays represent 39% of the total passenger delay, *i.e.* a total delay at their final destination of 303 minutes. This result is also beneficial for airlines, as re-accommodating passengers who miss their connections involves both logistical and financial costs. European Union Regulation (EC) No 261/2004 requires airlines to compensate passengers for missed connections and long delays. In addition, missed connections can degrade passengers' perception of the airline, leading to reduced customer loyalty and erosion of market share. This effect, as highlighted by Cook *et al.* [16], can be a dominant factor in the economics of airline delays. The proposed seat allocation strategy creates therefore a win-win situation for both airlines and passengers.

B. *Influence of the percentage of pre-reserved seats*

The influence of the proportion of pre-reserved seats on the performance of the seat allocation strategy proposed in this paper is evaluated below. The results presented earlier were based on the assumption that approximately 20% of seats were pre-reserved. Here, we ran simulations with pre-reservation rates ranging from 0% to 100% over the day. The 0% scenario, although hypothetical, represents a case where no seats are pre-reserved, allowing the seat allocation algorithm full flexibility to assign optimal seats to passengers with tight connections. In contrast, the 100% pre-reserved scenario reflects a random seat allocation where all seats are already pre-reserved and the seat allocation algorithm is inactive. The only difference is that it assumes a slightly higher probability that passengers will choose front, aisle or window seats, resulting in a higher probability that middle and rear seats will remain unoccupied. For this analysis, we will focus only on the courtesy disembarkation rule, as it is the traditional rule adopted in operational conditions. Figure 6 illustrates the impact of the proportion of pre-reserved seats on the number of passengers missing their connecting flights.

The key observation is that the lower the percentage of pre-reserved seats, the more effective the connecting passenger seat reallocation strategy becomes. This is because pre-reserved seats tend to be those with shorter disembarkation times, such as those at the front of the aircraft or near the aisle. A high proportion of pre-reserved seats limits the ability

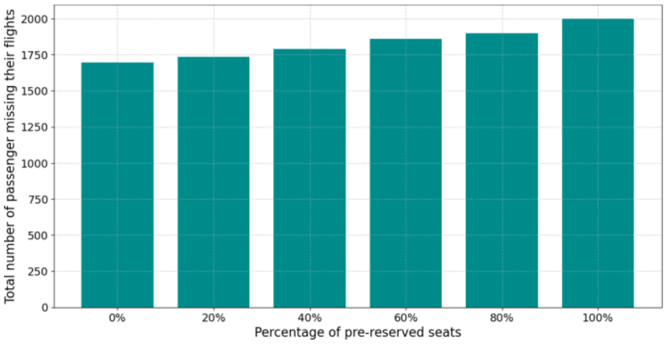


Figure 6. Evolution of the number of passengers missing their flights as a function of the proportion of pre-reserved seats. The 100% pre-reserved strategy mirrors random seat allocation, where connecting passengers are randomly distributed throughout the cabin. The courtesy disembarkation rule, *i.e.* passengers disembarking from front to rear, is considered here.

of the algorithm to optimally allocate seats with shorter disembarkation times to connecting passengers with tight transfer windows. The increase in efficiency follows a linear trend, with 2,000 passengers missing their flights with 100% pre-reserved seats to 1,700 with 0% pre-reserved seats. This represents an improvement of 15%.

VII. Conclusion

This study investigates the potential benefits of an innovative look-ahead seat allocation strategy that prioritises connecting passengers, yielding advantages for passengers, airlines, and airports. Unlike the traditional random allocation of unreserved seats, which primarily benefits airlines, our approach assigns seats with shorter disembarkation times to passengers with tight connections. We tested this strategy using real data from Paris Charles de Gaulle Airport, focusing on small- and medium-sized aircraft operated by a major airline. The analysis incorporated actual flight delays, further constraining passenger transfer times compared to scheduled connections. The results indicate that, under a front-to-rear disembarkation strategy with a single front exit, the proposed seat allocation for non-reserved seats enables approximately 12% of passengers to successfully recover their initially missed connections.

The proportion of pre-reserved seats plays a critical role in the effectiveness of the proposed seat allocation strategy. A higher percentage of pre-reserved seats reduces the algorithm's efficiency, as most seats with short disembarkation times are already reserved. This underscores the potential advantage for airlines that offer paid seat reservations, as limiting the number of pre-reserved seats may increase the benefits of this reallocation strategy up to 15%.

Overall, the proposed seat reallocation strategy offers a win-win solution for airlines, passengers, and airports. Additionally, it helps reduce the costs airlines incur in re-accommodating and compensating passengers as mandated by Regulation (EC) No 261/2004.

Future work could incorporate detailed data on connecting passengers, origin-destination pairs, gate assignments, and terminal configurations for a more accurate assessment of transfer times. The framework's flexibility allows for the integration of more complex data. Additionally, it currently overlooks the behaviour of passenger groups, which strongly influences passenger speed [17] and should therefore be considered in future studies. Including such behaviour in future iterations would improve the accuracy of the seat allocation strategy.

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Freight transportation operational improvement through increasing payment efficiency at toll booths.

Case study of the Circuito Exterior Mexiquense (CEM)

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***Abstract*—** This study examines the impact of toll collection systems on operational and economic efficiency and their effect on freight transport through a case study in Mexico: the Circuito Exterior Mexiquense (CEM), a central corridor in the peripheral industrial area of the Mexico City Metropolitan Area. Manual toll booth operation systematically creates bottlenecks, resulting in low service for users due to increased travel times, fuel consumption, pollutant emissions, and, in the case of freight transport, logistics costs, thereby reducing the competitiveness of freight transport. This research employed a quantitative methodology that included operational diagnostics, cost and emissions modeling, and simulation of different toll collection schemes: manual collection, generalized electronic collection (TAG), and barrier-free collection (free flow). The results presented here indicate that the annual costs associated with congestion at the CEM toll booths exceed 400 million pesos. The eventual implementation of electronic or barrier-free toll collection systems could reduce waiting times by up to 90% and generate savings of between 200 and 300 million pesos annually, while significantly reducing CO_2 emissions and vehicle wear and tear. Improving the operational efficiency of toll booths could enhance sustainability and optimize the financial performance of concessionary companies.

Keywords- tolling efficiency; freight transport; dynamic pricing; congestion management

I. INTRODUCTION

Concessioned highways in Mexico play a crucial role in national connectivity, particularly in freight transportation and the distribution of goods to and from the Mexico City Metropolitan Area. However, manual toll booth operations lead to recurring bottlenecks that affect the operational and economic efficiency of transportation systems that use this infrastructure.

The Circuito Exterior Mexiquense (CEM) is a 110-kilometer peripheral highway in the Metropolitan Zone of the Mexico Valley (ZMVM) that registers an average daily traffic volume exceeding 40,000 vehicles. The congestion at toll booths, especially during peak hours, impacts the operating costs of freight transport fleets, delivery punctuality, and the region's sustainability. The strategic role of this infrastructure as an alternative route for freight traffic, connecting the industrial parks of cities in the Megalopolis, and in turn, avoiding entry routes to Mexico City, is a critical element for the region's competitiveness.

Manual toll collection systems on Mexico's toll roads represent the most remarkable inefficiency in land transportation operations, as they disrupt the continuous flow of traffic, forcing vehicles to slow down, stop to enter the toll booth, and accelerate again to exit. This cycle of stops and starts results in increased travel times, higher vehicle operating costs, and significant energy consumption and greenhouse gas emissions. In freight transportation, operational efficiency and on-time deliveries are critical performance indicators that can have economic repercussions for consignees. Delays due to inefficiencies at toll booths result in higher transportation costs per ton-kilometer, reduced utilization of logistics company assets, and unexpected changes in companies' respective supply chains. Empirical observations at the CEM show that during peak hours, waiting times at its toll booths reach 8 to 12 minutes per vehicle, with queues extending more than a half a kilometer. These systematic bottlenecks reduce the corridor's adequate capacity, resulting in a significant loss of economic productivity. See Figure 1.

Figure 1. CEM operability at toll booths

From an energy and environmental perspective, congestion at toll booths results in excessive fuel consumption from the constant cycles of idling and acceleration. Based on empirical data, and depending on the level of congestion, each cargo truck can consume between 2 and 4 additional liters of diesel to pass through a toll booth, depending on the engine's characteristics; this results in an increase of 8 to 10 kilograms of CO_2 per vehicle in greenhouse gas emissions. In this sense, the total environmental cost along the entire corridor is considerable. Additionally, intermittent traffic at toll booths also affects mechanical wear and tear and maintenance costs for vehicle fleets, including those of braking systems, clutches, and transmissions. Similarly, the level of risk also increases due to frequent lane changes and sudden stops while searching for shorter lanes, increasing the likelihood of minor collisions and rear-end collisions. Furthermore, inefficiencies in manual toll collection can have macroeconomic repercussions, as the competitiveness of logistics corridors is compromised, consequently increasing the cost of transported goods and diminishing the attractiveness of the highway concession model for this type of infrastructure. As international trade volumes expand, streamlining operations at highway toll booths becomes a strategic necessity.

This study analyzes the effects of toll-collection efficiency, explicitly measured in travel times, fuel consumption, emissions, and logistics costs. It proposes scenarios to improve toll operations by generalizing electronic toll collection (TAG) and barrier-free (free-flow) systems.

II. Literature Review

A. *Theoretical Foundations*

The theoretical basis for congestion pricing is founded on the principle of marginal social cost, which seeks to internalize the external costs generated by road users during periods of congestion [1, 2]. Early analytical models, such as the bottleneck model, determined how tolls can regulate departure times and thus efficiently allocate existing road capacity [3].

Subsequent extensions incorporated heterogeneity in users' value of time (VOT). For example, in [4], the authors demonstrated that optimal congestion tolls must consider user heterogeneity to achieve both welfare efficiency and distributive equity. Similarly, dynamic peak-hour pricing schemes show that dynamic tolls can reduce additional delays and social welfare losses [5].

From a behavioral perspective, dynamic pricing influences route choice, mode of transport, and especially scheduling decisions, particularly in freight transport operations, where time windows and logistical constraints are key elements in decision-making [6]. Dynamic tolling can optimize both passenger flow and equity when complementary strategies are implemented, such as real-time traveler information or improved lane management, including preferential treatment for high-occupancy vehicles (HOVs).

B. *Modeling Approaches and Operational Control*

The literature reveals many methodological strategies for the design of toll booths. There are macroscopic traffic flow models based on fundamental diagrams and macroscopic fundamental diagrams (MFDs), which are widely used to analyze network-level congestion under different pricing regimes [7]. At a finer scale, microscopic and mesoscopic simulation tools (e.g., VISSIM) are used to model queue formation and dissipation at toll booths, capturing the impacts of manual, mixed, and electronic tolling systems on delay, idling, and emissions [8]. Queueing-theoretical models such as M/G/1 formulations [9] optimize the configuration of toll booths and lanes to minimize waiting costs and improve throughput efficiency.

Dynamic or predictive control algorithms further extend these approaches. In [10], the authors integrated real-time toll adjustment with ramp metering via stochastic optimal control and extended Kalman filtering, demonstrating reductions in travel time and queuing length exceeding 15% in simulation. In [11], the author provides an overview of recent applications of machine learning and model predictive control for adaptive toll setting based on real-time data streams.

C. Empirical Evidence

Empirical evidence from implementations reported in the literature demonstrates both the feasibility and the limitations of congestion management through toll pricing. Urban congestion pricing systems in Singapore, London, and Stockholm are the most established examples. Singapore's Electronic Road Pricing (ERP) system has maintained a stable traffic flow since its implementation, with fully dynamic pricing based solely on traffic sensor data [5]. In Stockholm, a congestion pricing pilot program conducted in 2006 reduced peak-hour traffic volume by approximately 20% and significantly improved air quality (Eliasson, 2008). Finally, London's congestion pricing system reduced kilometers traveled per vehicle, though it also sparked debate over long-term displacement effects.

In the United States, managed lane projects such as SR-91 in California and the MnPASS network in Minnesota apply the principles of high-occupancy toll (HOT) lanes, using dynamic algorithms to adjust toll costs to maintain target speeds [13]. Evaluations report that dynamic pricing stabilizes traffic flow in corridors and improves travel time reliability [14]. Other studies quantify the elasticity of infrastructure utilization in response to toll price changes. Empirical reviews indicate a short-term elasticity of between -0.05 and -0.3 for passenger vehicles [2]. However, freight transport elasticity is typically lower, yet it still responds to time-of-day variations and queue delays [6]. Analyses confirm that elasticity increases over the long term as users adapt to new operating conditions by changing routes, modes of transport, and schedules [7].

On the other hand, the implementation of electronic tolling (ETC) and free flow generates significant local benefits. Post-adoption analyses in Chile, Portugal, and the United States reported reductions of 40% to 70% in average waiting times and significant decreases in CO_2 emissions near toll booths [8, 9]. These results underscore the direct environmental and economic benefits of eliminating physical toll barriers. In the context of freight transport, hybrid and discrete choice simulation approaches allow for estimating toll sensitivity, including analysis of changes in departure times and route substitutions [6]. Together, these modeling tools allow for calibrating toll-setting rules to minimize queues and emissions while maintaining the target revenue or performance of the toll road.

D. Technology, Enforcement, and Institutional Considerations

Dynamic toll pricing depends on robust technological and institutional frameworks. In this regard, technologies such as RFID tags, Automatic Number Plate Recognition (ANPR), and Vehicle-to-Infrastructure (V2I) communication systems enable continuous toll collection and real-time price updates [11]. It is important to note that its implementation is contingent upon significant investment in this technology, including its administration, payment interoperability, and, above all, data security and protection.

From an institutional design perspective, transparency in revenue allocation and interoperability among concessionaires strongly influence its acceptance [12, 14]. Case studies in London and Stockholm reinforce this idea by allocating toll revenues to expanding and modernizing public transportation and infrastructure. The literature also mentions fair pricing and equity. Mechanisms such as discounts for frequent users or for off-peak trips exist for freight transport [2, 6, 15]. In conclusion, the flexibility of toll collection systems allows for the achievement of institutional credibility and the perception of social justice.

E. Gaps and Emerging Research

At this point, it is worth noting that considerable research exists on mitigating urban congestion through infrastructure pricing; however, only a few studies address congestion at toll booths and their operational inefficiencies. In [8, 9], the authors emphasize the potential of using queuing theory and simulation-based optimization to minimize this type of congestion. In developing economies, these cases are among the least studied, and empirical calibration is scarce.

In this regard, research is needed on integrating operational data from toll booths with dynamic pricing models and agent-based simulation approaches [16]. Elasticity models specific to freight transport on toll highways, such as the CEM model, could link user-level savings (reduced idling time, shorter queue times) with macro-level logistical benefits.

Approaches such as reinforcement learning for dynamic pricing [11], integrating environmental externalities into pricing functions [6], and designing hybrid policies that combine pricing with access regulation and environmental incentives exist. Within this context, toll highways are a natural application area for tariff management and technological implementations to improve freight transport efficiency.

III. Methodology

This study uses a quantitative methodology that combines traffic analysis with microsimulation, economic evaluation, and environmental impact quantification to estimate operational and economic impacts resulting from inefficiencies at the CEM toll booths.

The design of this research is analogous to that used for dynamic pricing and optimal toll booth operation documented in [8, 9, 10], with the exception that it has been adapted to the Mexican context. This analysis evaluates the following scenarios:

1. Operation of toll booths with manual and electronic (TAG) lanes, with partial automation, and with recurring congestion identified during peak hours.
2. Gradual increase in the use of the electronic toll collection system from 40% to 80% of users through greater interoperability and the acceptance and adoption of incentives.
3. Transition to 100% toll collection through a free-flow or barrier-free system, replacing manual collection with RFID and Automatic Number Plate Recognition (ANPR) technologies.

According to the methodologies proposed in [2, 7], toll booth operations constitute one element of a broader, integrated system, in which user delays, queue waits, and pollutant emissions are external costs that could be mitigated through technological interventions or monetary penalties.

A. Data Collection and Sources

- The information for this project was obtained from direct field observations, official data, and parameters obtained from the literature.
- Specific traffic and vehicle classification data, as well as Annual Average Daily Traffic (AADT). This information was obtained from the official repositories: Road Data 2024 of the Ministry of Infrastructure, Communications and Transportation (SICT) [17] and the CEM operator (Conmex) [18], corresponding to the 2023 period.
- Observations of travel time and delays. Field data were collected using the floating-vehicle technique with GPS readings, supplemented by manual measurements of queue lengths and delay times at selected toll booths (Tultepec, Las Américas, Ecatepec, and Chalco).
- Fuel consumption and emissions parameters. For emissions and fuel consumption functions, those of the MOVES model from the United States Environmental Protection Agency (EPA) [19] were adapted, which is widely used for road emissions modeling [6, 8].
- Value of Time (VOT): Estimates were obtained from information from the 2024 Annual Transportation Survey (EAT) [20], assigning a VOT of MXN 350/hour for freight and MXN 120/hour for passengers.
- Costs due to accidents: The expected value of accidents and property damage was based on data from the Statistical Yearbook of Collisions on Federal Highways 2023 [21], and from the Mexican Association of Insurance Institutions (AMIS), using risk factors associated with intermittent traffic conditions [22].

By integrating this information, a multidimensional evaluation is conducted that links traffic conditions to economic and environmental outcomes.

B. Operational and Economic Modeling

The modeling approach was divided into two modules: traffic operation simulation and an economic cost estimation model. A microscopic queuing model was developed to replicate traffic behavior at toll booths based on previous research on their design [8, 9]. Each toll booth was modeled as an M/M/s queue with stochastic arrivals and service rates dependent on the lane type. Service capacities were established as follows:

- Manual lanes: $\mu = 250$ veh/h
- Mixed ETC lanes: $\mu = 500$ veh/h
- Dedicated ETC lanes: $\mu = 900$ veh/h

where arrival rates (λ) were adjusted according to the time of day and day of the week; and queue lengths and average delays were estimated using Erlang-C queuing equations and validated with field measurements taken during morning and afternoon peak hours.

The resulting model estimates: the average delay per vehicle, queue dissipation times, and total lost time (in vehicle-hours/day). Similar methods have been applied to the analysis of toll collection operations on highways in Taiwan and China [7, 8, 10]. The total estimated cost produced by congestion at toll booths is defined as the sum of the components of (1):

$$C_{total} = C_{time} + C_{fuel} + C_{emissions} + C_{accidents} + C_{wear} \quad (1)$$

This structure is consistent with the approach used in the literature by [2, 6], generating a coherent valuation of time, energy, and environmental effects. Each cost component (time costs, fuel costs, emissions, accidents, vehicle wear and tear) was estimated according to expressions (2)–(6).

$$C_{time} = VOT \times \Delta T_{delay} \times N_{veh} \quad (2)$$

$$C_{fuel} = 1P_{fuel} \times \Delta F_{cons} \times N_{veh} \quad (3)$$

$$C_{emissions} = SC_{CO2} \times \Delta E_{CO2} \times SC_{NOx} \times \Delta E_{NOx} \quad (4)$$

$$C_{accidents} = P_{acc}Cost_{avg} \times Cost_{avg} \times \Delta risk \quad (5)$$

$$C_{wear} = Cost_{maint} \times f_{stop-start} \quad (6)$$

where P_{fuel} reflects the national diesel price average, SC_{cO2} and SC_{NOx} are the social costs of pollutants following EPA guidelines [23].

Costs were separated by vehicle type according to the following criteria: light commercial (2 axles), medium freight transport (3-5 axles), and heavy freight transport (6 or more axles). This classification is consistent with variations in fuel consumption elasticity and time valuation, as described in the literature [6].

C. *Environmental Impact Assessment*

Environmental impacts were assessed based on incremental vehicle emissions while idling and emissions during acceleration at toll booths. Total emissions were computed as:

$$\Delta E_{CO2} = (EF_{idle} + EF_{acc}) \times N_{veh} \times t_{queue} \quad (7)$$

where EF_{idle} and EF_{acc} denote emission factors for idling and acceleration phases, respectively, adjusted for Mexico's average heavy vehicle fleet [24]. The analysis estimates that eliminating toll booth stops could reduce annual CO2 emissions by approximately 6,500 tons, NOx emissions by 11 tons, and PM2.5 by 2 tons, highlighting the significant environmental co-benefits of electronic tolling systems.

D. *Sensitivity and Scenario Analysis*

A sensitivity analysis was performed to evaluate the robustness of the results to probable variations through simulation, which was conducted by varying the following parameters:

- Traffic growth: ±10% of the base AADT
- Fuel price: ±20%
- TAG adoption rate: It was assumed to be an increase from 30% to 90%.

For each simulation iteration, an estimate of the total system cost was generated, from which the elasticity of savings with respect to TAG adoption was derived. The results indicate a decrease in marginal benefits when adoption exceeds 80%, consistent with [10] regarding elasticity curves used in dynamic pricing.

E. *Investment and Policy Evaluation*

The transition from manual to free-flow tolling involves substantial capital expenditure (RFID gantries, back-office integration, and enforcement cameras). To assess feasibility, this study calculated the Net Present Value (NPV) and payback period of system modernization:

$$NPV = \sum_{t=0}^{n} \frac{Savings_t - Costs_t}{(1+r)^t} \quad (8)$$

The project horizon was set at 10 years with a 6% social discount rate. These results suggest that the free-flow scenario could yield annual net savings exceeding 450 million MXN and achieve the payback within 3 to 4 years. This approach is consistent with international evaluations of barrier-free tolling in Europe and the United States [7, 8], supporting the cost-effectiveness of investing in toll-collection efficiency.

IV. CEM Operational Evaluation

A. *Overview of the CEM corridor*

The CEM is one of the main toll corridors in the central region of the country and serves as a high-capacity bypass on the eastern and northern periphery of the Mexico City Metropolitan Area (ZMVM). It connects key logistics hubs, including Cuautitlán, Ecatepec, Tultepec, and Chalco. It serves as a key alternative route for freight traffic between the Puebla-Querétaro, Mexico City-Toluca, and Mexico City-Pachuca corridors. The CEM's connectivity with the freight corridors between the cities of the Megalopolis and the international airports of the Valley of Mexico is shown in Figure 2.

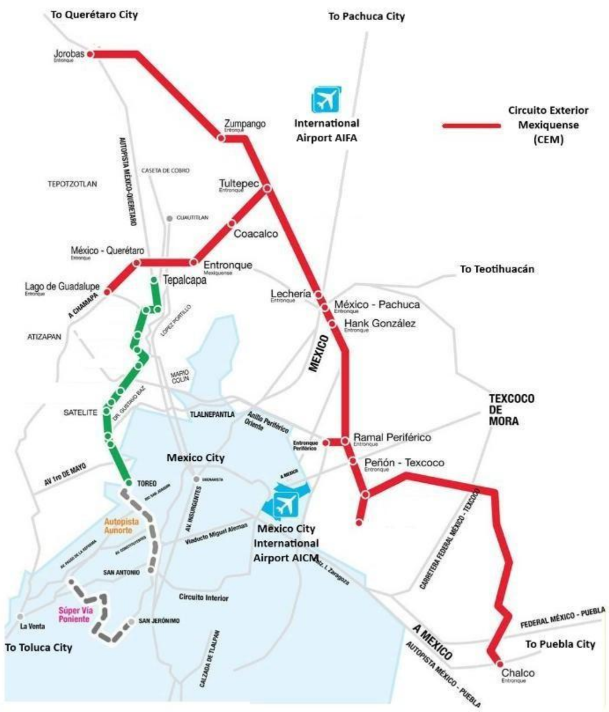

Figure 2. CEM connectivity within the Mexico Valley

The average daily traffic volume is approximately 290,000 vehicles, of which about 34% are freight trucks [18]. The CEM has eleven toll booths and over 120 km of controlled-access highway. These locations still operate with a mixed toll system.

Despite the promotion of the TAG system, manual payment lanes still predominate in some high-traffic toll booths, resulting in queues of 400–600 meters during peak morning and afternoon hours.

B. Baseline Performance

Field observations and model calibration indicate that, under current mixed-mode operations, the average toll transaction time is 18–22 seconds for electronic lanes and 45–60 seconds for manual lanes. During the morning peak (07:00–09:00), queue delays are averaged as shown in Table I.

Total daily delay across all booths is estimated at 6,850 vehicle-hours, corresponding to approximately 2.5 million vehicle-hours per year. Of this, freight vehicles account for 52%, with a weighted-average value of time (VOT) of 350 MXN/hour, yielding an annual time loss cost of approximately 875 million MXN.

These values are aligned with international estimates of toll booths inefficiencies in similar contexts [8, 9, 10].

TABLE I. CONGESTION AND DELAY METRICS

Toll booths	Average delay (sec/veh)	Peak queue length (m)	Share of TAG users (%)
Tultepec	145	520	42
Ecatepec	130	450	39
Las Américas	160	600	47
Chalco	175	580	35

Source: Authors' own work

C. Fuel and Emission Impacts

According to the calibrated MOVES-based model [6, 19], the stop–start patterns and idling during toll queuing result in significant fuel wastage and pollutant emissions.

- Fuel overconsumption: 2.1 million liters of diesel and 1.8 million liters of gasoline per year.
- CO_2 emissions: 6,540.0 tons/year.
- NO_x emissions: 10.7 tons/year.
- $PM_{2.5}$ emissions: 1.9 tons/year.

Applying social cost factors of 1,100 MXN/ton for CO_2, 18,000 MXN/ton for NO_x, and 240,000 MXN/ton for $PM_{2.5}$ [17, 23], total environmental losses amount to approximately 35 million MXN annually.

D. Safety and Mechanical Costs

Stop-and-go traffic also increases the likelihood of accidents, particularly rear-end collisions and side-impact collisions during vehicle merging. SICT accident records from 2023 [21] show that toll booths account for approximately 8% of reported accidents on the Mexico City Highway (CEM), even though they represent less than 2% of the total corridor length. Applying a risk adjustment factor of 1.3 to 1.5 [10] for congested access points, the estimated annual cost of accidents attributable to toll booth congestion is 50 to 60 million MXN.

Furthermore, frequent deceleration and acceleration cycles increase wear on brakes and transmissions. According to interviews with freight fleet operators, mechanical wear costs average 0.15 MXN/km on congested stretches, equivalent to an additional 20 million MXN per year in maintenance expenses.

E. Scenarios Evaluation

The model was run for three tolling scenarios following the methodology described in Section IV. Table II summarizes the results.

TABLE II. COMPARATIVE PERFORMANCE OF TOLLING SCENARIOS

Indicator	Current	High TAG (80%)	Free-Flow (100%)
Average delay (sec/veh)	150	75	10
Annual vehicle-hours lost (million of veh-hours)	2.5	1.1	0.2
Fuel wasted (million of liters/year)	3.9	1.7	0.3
CO2 Emissions (tons/year)	6,540	2,850	520
Annual user cost (million of MXN)	875	410	85
Environmental cost (million of MXN)	35	15	3
Accident cost (million of MXN)	55	40	25
Total annual cost (million of MXN)	965	465	113

Source: Authors' own work

Under the free-flow scenario, total user and environmental costs decrease by approximately 85%, equivalent to 850 million MXN/year in system-wide savings. These estimates are consistent with the magnitude of benefits reported in [8] for Chinese expressway free-flow conversions and [7] for dynamic congestion pricing corridors.

F. *Cost–Benefit Analysis and Financial Viability*

To evaluate investment feasibility, a cost–benefit model was developed following [2, 7]. Assuming a capital investment of 1.9 billion MXN for complete barrier-free system implementation (including gantries, ANPR cameras, and central clearing infrastructure) and annual O&M costs of 90 million MXN, the resulting Net Present Value (NPV) and the Internal Rate of Return (IRR) were computed over 10 years with a 6% discount rate.

$$NPV = \sum_{t=0}^{10} \frac{Savings_t - Costs_t}{(1+0.06)^t} \quad (8)$$

where:

- Annual Savings (Free-Flow vs. Current): 852 million MXN
- NPV (10 years): +3.48 billion MXN
- IRR: 23.6%
- Payback Period: 3.2 years

These findings indicate a strong economic case for modernizing toll collection. The benefits are constituted primarily by time savings (91% of total benefits), followed by fuel/emission savings (6%) and reduced accident costs (3%).

G. *Sensitivity Analysis*

A set of simulations was conducted, varying the following three key factors: traffic growth rate (±10%), fuel price (±20%), and capital investment cost (±15%). Results show that even under conservative assumptions, the NPV remains positive (+2.1 billion MXN). Under optimistic conditions (that is, high traffic growth and moderate investment), the NPV would exceed 4.0 billion MXN, confirming the robustness of financial viability. The elasticity analysis indicates that the marginal benefit of TAG use declines after reaching 80% which emphasizes diminishing returns beyond critical adoption thresholds.

H. *Environmental Co-Benefits*

The shift to free-flow tolling would eliminate approximately 6,000 tons of CO2 annually, equivalent to the annual emissions of around 1,300 passenger vehicles. Reductions in NOx and PM2.5 emissions would directly improve air quality in towns adjacent to toll booths, such as Ecatepec and Tultepec, where the Mexican government and environmental agencies have identified and documented concentration hotspots [23]. These findings could be directly used to design transport policies and concession regulations in Mexico, including accelerating TAG adoption, subsidizing TAG issuance, improving interoperability across concessionaires, and integrating with national payment platforms, among others. Table III summarizes the results.

TABLE III. SUMMARY OF RESULTS

Category	Baseline	Free-Flow	Change (%)
Total annual cost (millions of MXN)	965	113	-88%
Average delay (sec/veh)	150	10	-93%
CO2 emissions (tons/year)	6,540	520	-92%
NPV (10 years)	--	+3.48 billion MXN	--
Payback period	--	3.2 years	--

Source: Authors' own work

The results demonstrate that congestion-related losses at toll booths are economically significant and that technological interventions, particularly free-flow tolling, offer rapid, measurable, and sustainable returns.

V. CONCLUSIONS AND RECOMMENDATIONS

This study estimates the inefficiencies in toll collection in substantial economic, environmental, and operational terms for both road users and concessionaires. The CEM (Central Mexico City) was used as a case study, and a quantitative model was applied, integrating traffic flow simulation, cost-benefit analysis, and emissions accounting to evaluate the impacts of current toll systems and the potential benefits of their modernization. Even modest reductions in queue lengths at toll booths generate large-scale systemic benefits. Extrapolated to the entire CEM corridor, congestion-related costs could exceed 950 million Mexican pesos annually, comparable to the corridor's annual maintenance budget. The transition to a barrier-free or fully electronic toll system would allow these losses to be recovered within three years.

From an economic perspective, toll booths represent micro-bottlenecks that erode the productivity of the freight corridor. Each hour spent waiting in line represents an opportunity cost of approximately 350 Mexican pesos per heavy vehicle. Eliminating these losses could improve supply chain reliability and reduce variability in transit times, a key factor in logistics. Uninterrupted toll collection also supports national climate goals. The projected annual reduction of 6,000 tons of CO_2 aligns with Mexico's Nationally Determined Contribution (NDC) targets. Finally, reducing stop-and-go cycles decreases both the likelihood of rear-end collisions and mechanical wear, improving operational safety and extending asset lifespan. Accident-related costs could range from 40 to 50 million Mexican pesos annually. The empirical results of this study confirm that integrating technology, policy, and demand management can transform toll highways from congestion points into instruments of sustainable logistics and economic growth.

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