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Uncertainties Influencing Transportation System Performances

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Abstract: The design and operation of transportation systems, as with any large complex technical system, are marked by indetermination—risks and uncertainties (scientific/methodologic and/or socio-economic). This paper analyzes the occurrence and consequences of uncertainties, defined as completely unknown random events ("unknown unknowns"), on transportation system performances. Interest in the topic is justified by the considerable value and long life of transportation system components. In order to reduce the effects of uncertainties, a holistic approach to all technical infrastructures in society, regardless of the flow category (material, energy, information), is necessary. Technological progress and changes in territorial activity systems historically confirm the dynamism of the competition and complementarity relations between civil and industrial infrastructures and transport infrastructures, as well as among different modal transport/traffic infrastructures. Declining discount rates are applied to compensate for the effects of uncertainties on investment project opportunities on long time horizons. There is no unanimous agreement on the discount rate values. Unforeseen exogenous events are considered differentiated/non-systemic or undifferentiated/systemic uncertainties. They can have significant consequences on the performance of a transport system, including a change in the transport market share. Therefore, an adaptive policy is required to reduce the methodological/scientific and socio-economic uncertainties that affect the design and operation of any transportation system.

Keywords: transportation system; traffic infrastructure; investments; uncertainty; risk; discount rate

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1. Introduction

Transport is a distinct type of service, because: (i) it can neither be stored nor preserved; (ii) it must face peak periods; (iii) it is implemented in particular conditions; and (iv) it takes for granted the existence of extremely vast and complex technical infrastructures, adequately designed for the safe movement of a large number of heterogeneous vehicles. Transport is generally a continuous activity (performed day and night, on working days and also on weekends and holidays) but with discontinuous intensities that cause variable efficiency. Despite its difficulty, executing such services seems natural to the beneficiaries, and it is almost impossible to make them understand the magnitude of the necessary involved effort [1].

Most transport policy issues are about long-term decisions. The decisions implemented in the current period have long-term consequences. Additionally, long-term goals may require short-term actions (e.g., road infrastructure construction could be complemented by short-term measures on traffic safety, journey time, limiting the negative effects on the natural and anthropogenic environment, etc.).

In transportation system management, both risk and uncertainty cause decisional indetermination. In case of rare events (natural disasters, political instability, etc.), the analyst must postulate subjective probability laws, such as those introduced by Savage [2,3]. If the analyst has no information on the probabilities of the rare event occurrence, then min-max or max-min criteria are recommended [3,4].

In this framework, this paper analyzes two types of uncertainty that influence decisions on the long-term development of transportation systems: (i) a socio-economic uncertainty, with origins in the size and structure of the demands addressed to the transport system, and (ii) a methodological or scientific uncertainty that introduces ambiguities in decision-making at all levels (and that forces the decision-makers to admit that the result of their actions cannot guarantee the desired optimal use of the initially allocated resources).

The paper is organized as follows. The next section clarifies the concepts of risk and uncertainties and explains their differences. Then, it highlights the difficulties in substantiation of decisions in transportation systems. The main particularities of transportation systems that generate indetermination are presented. Examples of transport particularities argue for the inclusion of the transportation system in the category of complex technical systems. The necessity of a holistic approach to all technical infrastructures in society, regardless of the flow category (material, energy, information), is emphasized in order to reduce the effects of uncertainties. Types of risk and uncertainty are analyzed relative to the difficulties of evaluating traffic infrastructure investment projects.

The results section exemplifies the two types of uncertainty that influence decisions in transportation systems. The first case refers to the Romanian railway system. We analyze how major changes in the socio-economic environment have influenced railway performances. The second case indicates methodological uncertainties in decisions on sizing the traffic capacity of a railway line. The paper concludes with the differences between risks and uncertainties and how their consequences could be compensated.

2. Risk and Uncertainty

2.1. Conceptual Clarifications

Risk and uncertainty are often undifferentiated when referring to unknown events that may affect the operation of any system. However, there are subtle differences between the terms [5]. "Unknown" refers to the occurrence of a particular event that cannot be anticipated. This property is valid for both risk and uncertainty concepts. Risk refers to unknown results with well-defined probabilities and usually implies the probability of an event occurring. Generally, the risk relates to an event with negative, harmful, unwanted effects. Risks can be vaguely referred to as "known unknowns". Unlike risk, uncertainty refers to unknown results with unknown probabilities and not necessarily with negative consequences linked to the event. Therefore, uncertainties can be loosely referred to as "unknown unknowns" [6–8].

Endogenous and exogenous random actions influence complex system dynamics. Therefore, distinctly equivocal predictions cause the incapacity of a priori assessment of the occurrence time and magnitude of uncertain events (even in a probabilistic way).

The future is characterized by uncertainty. The farther the horizon for predicting the states of a particular complex system, the more significant the uncertainty is. In the long term, two types of uncertainty are considerable. One type includes socio-economic uncertainties, with origins in the size and structure of the tasks addressed to the analyzed system. The another contains methodological or scientific uncertainties that introduce ambiguities in decisions at all levels. These force the decision-makers to admit that the result of their actions cannot guarantee, neither initially nor in time, the desired optimal use of the allocated resources.

2.2. Uncertainties in the Dynamics of Transportation System Performance

The outcomes of transport activity are synthetically expressed through performance indicators that reflect the social, economic, and environmental effectiveness and the efficiency of the transportation system operation.

The transportation system comprises tasks and components (infrastructures, vehicles, and technologies) which are structured on subsystems (modes of transport). Consequently, the transportation system belongs to the class of complex technical systems characterized by indetermination in operation. Indetermination is related to two sets of different events:

1. Events with exogenous sources (e.g., some inconsistency of size and structure of tasks/transport demand) and endogenous causes (e.g., deviations from the scheduled operation to ensure the expected performance of the transportation system); these are related to short periods and do not involve decisions on a considerable extension of or reduction in the resources of the transportation system.
2. Events leading to severe changes in the components of the transportation system; these could occur over longer time horizons, due, for example, to significant technological progress and/or the dynamics of the territorial system that determine important changes in transport demand (for a particular mode of transport or the whole system).

The first category of events refers to methodological or scientific uncertainties. They express the incapacity of the analyst to provide an unequivocal solution to a particular known state of the system, e.g., the problem of sizing the capacity of a warehouse. The variation of the quantity of the goods, Q, that require storage is considered for a representative period (Figure 1). Even if it is often recommended, establishing a storage capacity equal to the average between the maximum and minimum storage demand cannot be accepted as a solution (it would lead to a capacity mostly not fully used) [9]. The solution for which A1 + A2 = A3 + A4 (meaning equality between the deficit and surplus capacity) is not without criticism either. Evidently, financial assessments of the consequences of the deficit and surplus capacity must be used to recommend a size for the deposit capacity. Such a solution involves complex calculations that are seldom implemented in practice.

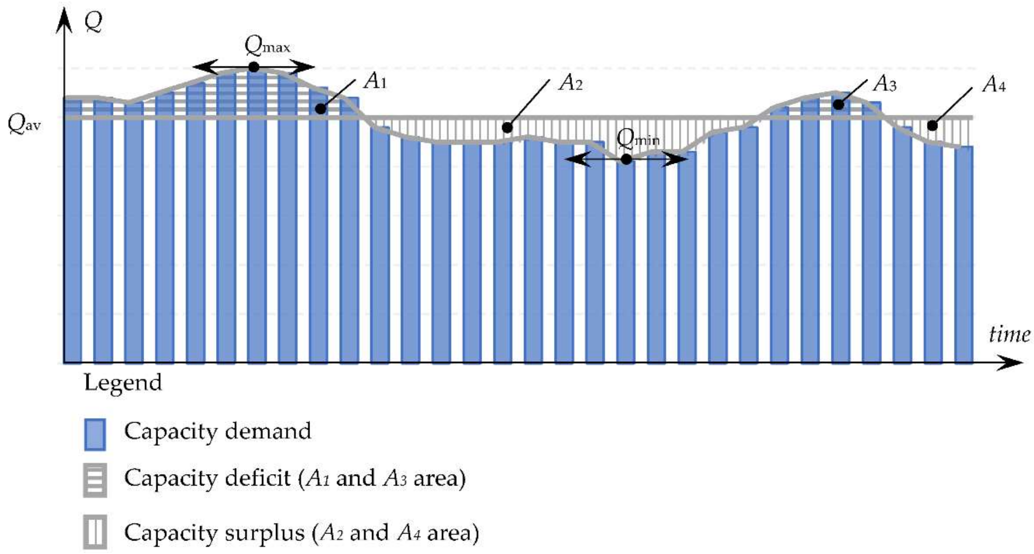

Figure 1. Example of a problem regarding a decision on capacity for variable demand (a warehouse case).

Other examples could also demonstrate the difficulties of substantiating decisions, e.g., solutions at the strategic level in the field of rail freight could rise several questions: how many wagons of each type (adequate for the different attributes of the goods-solid or fluid bulk cargo; boxed, palletized, or containerized goods; special goods, etc.) should the fleet comprise? Or, how many locomotives—and with what technical characteristics—should the fleet include, in accordance with the size and structure of the wagon fleet? On railway infrastructure, is it more advantageous to form long and heavy freight trains with lower frequency or short freight trains with high frequency? In other words, what acquiring strategy should be applied for more wagons or locomotives? Certainly, solving these problems involves the development of laborious mathematical or simulation models that require a large volume of analysis data, programming, and analysis effort.

The events in the second category can affect:

- All components and activities of the territorial system, and, consequently, they can impact the transportation system—these changes define systemic socio-economic uncertainties, or
- Only the transportation system as a whole or only specific modes of transport—these types of change define non-systemic socio-economic uncertainties and are recorded on long time horizons, in solid correlation with the lifetime of the material resources of the transportation system.

Socio-economic uncertainties (whether systemic or non-systemic) introduce ambiguities in the socio-economic substantiation of strategic decisions in the transportation system. These decisions must ensure the use of existing and new resources generated by investment policies for an extended period at a certain judicious demand level. The judicious demand level is that one retained in the substantiation strategy (i.e., the level for which the allocated financial resources will justify the financial, economic, or social efficiency for the considered period). Regardless of the professionalism and precision in substantiation of the investment decisions, the strategic decision-makers cannot eliminate their concerns about the implemented options.

Unlike in other economic sectors, transportation has certain specificities of the relationships between systemic and non-systemic uncertainties. They are a consequence of the fact that the material flows are transferred through different modes of transport in a shared market. Therefore, the modal components record the systemic uncertainties with consequences for the transportation system differently. Another specificity of non-systemic uncertainties is due to technological progress in the transportation system's components and the other systems involved in transferring material, energy, and information flows. Therefore, the following section discusses the necessity for a holistic examination of the technical infrastructures that ensure the mentioned flows.

3. Materials and Methods

3.1. Holistic Examination of Technical Infrastructures

Topology, constructive characteristics, and functionality distinguish each technical infrastructure network according to the particularities of the served territorial system. These particularities are reflected in the nature, size, structure, and technology of the transfer of material, energy, and information flows for each network. Even if the flows have different features and structures, all infrastructure networks need a holistic approach considering that they serve the same territorial system, T.

Let us denote by $\langle S \rangle$ the aggregate set corresponding to the socio-economic subsystems of the territorial system for which the aggregate set of activities $\langle A \rangle$ is defined. The structure of the territorial system is described as:

$$T = [\langle S \rangle, \langle A \rangle]. \tag{1}$$

The aggregate set of activities, $\langle A \rangle$, generates the material, energy, and information flows within each socio-economic subsystem and/or between the aggregate set of the subsystems, $\langle S \rangle$.

The aggregate set of flows, $\langle F \rangle$, is based on the aggregate set of infrastructure networks, $\langle R \rangle$. The structure of technical infrastructure networks is:

$$\Re = [\langle R \rangle, \langle F \rangle], \tag{2}$$

where $\langle R \rangle = \{\{R_m\},\{R_e\},\{R_i\}\}$ and is the aggregate set of material networks $\{R_m\}$, energy networks $\{R_e\}$, and information networks $\{R_i\}$ for which the corresponding aggregate set of material, energy, and information flows, $\langle F \rangle = \{\{F_m\},\{F_e\},\{F_i\}\}$, is defined.

The aggregate set of activities generates the specific demand for transfer between the elements of the aggregate set of the territorial system, i.e., the "ex-ante" demand. The demand correlated with the aggregate set of infrastructure networks determines the aggregate set of transfer flows, i.e., the "ex-post" demand (or the part of the potential transfer demand which could be met under multiple restrictions) [10].

Suppose the changes in T cause only limited quantitative changes in $\langle F \rangle$. In this case, synchronic analysis can predict the evolution of $\langle R \rangle$ that could improve its performance through interventions in operating technologies, through strategic, tactical, or operational management measures. Suppose that the quantitative changes in $\langle F \rangle$ exceed the saturation limits of the existing networks or that structural changes occur. In that case, the prediction on $\Re$ must be based on diachronic analysis, which is characterized by multiple uncertainties. Both extensions and reductions in each of $\{R_m\}$, $\{R_e\}$, and $\{R_i\}$ are possible. Supplementarily, alternative networks can be developed. Without attempting to anticipate the future, a few examples confirmed by contemporary technologies can be mentioned; for example, in $\{R_m\}$, transfers of passenger flow from the air network to the speed rail or liquid bulk cargo from railways to pipelines have been recorded. Transfers between sets of different networks have also been completed, e.g., from $\{R_m\}$ to $\{R_e\}$, in the case of replacing the transport and burning of coal in different sectors with the burning of coal in thermal power plants for electricity production followed by electricity transport. As a result of advances in information and communication technology, reduction in mail transport or even passenger flow are examples of transfers from $\{R_m\}$ to $\{R_i\}$.

Therefore, in a diachronic analysis, the networks $\{R_m\}$, $\{R_e\}$, and $\{R_i\}$ must be examined from a global perspective consistent with the scientific, technical, and technological progress required by sustainable development. Cooperation and coordination of the strategic decisions in a single roundtable are essential in analyzing the decision-making structures in the technical infrastructure domain.

Endogenous and exogenous random events adversely affect the performance of technical networks. The probability of occurrence of these events—interpreted as risks or uncertainties in preserving the structural and functional properties of networks in case of events from the natural environment (earthquakes, floods, frosts, storms)—does not depend on how the network was designed, built, and managed. However, the magnitude of the consequences (i.e., the magnitude of the network malfunctions caused by random events) is interpreted as an individual and collective responsibility of those involved in design, construction, and administration. Certainly, in the case of endogenous negative anthropic events, the probability of occurrence of these events and their consequences are assigned to a wide variety of technical, economic, social, political, and organizational stakeholders. The main categories of endogenous negative anthropic events that demonstrate these situations are [11–15]:

- Economic risks—are generated because technical networks require significant investments and are components of a competitive system subject to intense strategic pressures (financial and economic).
- Social risks—are caused by the fact that: (i) technical networks are used in ways that vary spatiotemporally, depending on the beneficiary requests, and (ii) employee actions can temporarily affect the system's operation and, consequently, network performances.
- Technical risks—start from the dependencies between the different types of networks, technical degradation of the equipment, or technological failures.
- Political risks—are caused by flow detour due to political conflicts.
- Human risks—are caused by possible acts of sabotage or terrorism.
- Organizational risks—are assigned to dysfunctions caused by lack of information, professional deficiencies, delays in decision-making, etc.

The mentioned risk list (without being exhaustive) highlights that including these anthropogenic risks in the endogenous risk category is relative. It depends on how the network is considered: as a distinct part or as an inseparable component of the aggregate technical network system. Furthermore, depending on the technical, socio-technical, or socio-economic approach of each technical network, the anthropogenic risks can be interpreted as either endogenous or exogenous.

3.2. Including Sensitive Aspects in the Evaluation of Traffic Infrastructure Investment Projects

As described above, the transportation sector records, for the aggregate technical infrastructure, several endogenous and exogenous random events affecting system performances. These random events (interpreted as risks or uncertainties) have consequences on performance at the levels of components and of the entire system as well as at the level of the activities in the socio-economic environment served by the transportation system [15–19]. In order to substantiate strategies for transport system development, it is essential to dissociate the uncertainties regarding the whole socio-economic environment and those impacting only the transportation system. Thus, systemic risks include undifferentiated risks in the economic-financial environment affecting the entire market and the economy (on the whole). Additionally, non-systemic or differentiated risks include risks with local consequences.

The stated separation between the two categories of risks and uncertainties is essential for significant investments in technical infrastructure networks. Undifferentiated risks, such as macroeconomic crises, the climate, and the geopolitical environment, increase the difficulty of the cost–benefit analysis (CBA) required in decisions on financing large investment projects. The randomness of the variables used in the economic calculation is involved, on the one hand, in establishing the discount rate (because macroeconomic uncertainty directly impacts the overall effort for optimal usage of limited available resources to ensure the welfare of current and future society). On the other hand, estimating the benefit and cost of investments according to current requirements of sustainability has become increasingly complex. Analysts encounter socio-economic and scientific uncertainties in relation to the multitude of effects whose monetary valuations must be introduced into CBAs. Both physical and financial quantitative estimates (often as hedonic costs) are complex and controversial, at least for some of the effects of new traffic infrastructures. Effects on labor, local and global pollution, health, safety and security, accessibility and land use, biodiversity, and heritage demonstrate the difficulties of the needed estimates [20].

Supposing that, for new traffic infrastructure, the difficulties of estimating the project costs and benefits have been overcome, the following issues regarding traditional CBA impediments still remain relevant [21–23]:

- Legitimacy—i.e., clarifying to policymakers the importance of strict compliance to the results of sophisticated calculations of the effectiveness and efficiency of traffic infrastructure investments. It remains questionable to what extent CBA results are implemented in decision-making. Usually, socio-economic evaluations of projects cannot substitute political decisions.
- Credibility—refers to the ability to eliminate nonconfidence regarding the correctness of the traffic infrastructure investment assessments, considering the not unanimous opinions on the used discount rate.
- Acceptability—refers to one of the fundamental hypotheses for computing the surplus as an algebraic sum of the surpluses of all those affected by the project. At least two issues need to be addressed: the first refers to spatial equity and the second to social equity.
- Considering risk and uncertainty—noting that recent methodologies for public investment substantiation distinguish between risks specific to a project and uncertainties related to exogenous project events, which are incorporated into the discount rate.
- Budget insufficiency—is a systemic and fundamental problem. Public power cannot finance all of the projects recommended by economic assessments. Lack of confidence in calculations indicating overvalued discounted benefits or major risks may cause non-financing. However, budgetary financial resources are not limited to investments in traffic infrastructure but apply to all public investments. Decapitalization generated by large investments in traffic infrastructure can inhibit investment in other economic sectors.

Subsequently, the discount rate and its correlations with uncertainty affect the credibility of the CBA results. Introducing uncertainty into the CBA is more difficult when the analysis period is longer. The probability of a random event occurring is higher and could have significant consequences. Several models have been developed to reveal how ambiguity (one of the many forms of uncertainty) affects the discount rate [24–26]. Research is still necessary.

In different European countries, depending on the time horizon, opinions on the size of the recommended discount rate are not consistent between countries (although they start from variants of the Ramsey formula) [27]. For example, France, the Netherlands, and Norway, with the same reference to risk-adjusted social rate of time preference (SRTP), use the following discount rate values: France—constant 4.5% or project-specific rate; the Netherlands—4% for climate change effects and 5.5% for other effects; Norway—4% up to 40 years, 3% for 40–75 years, 2% over 75 years. Germany, Sweden, the UK, with references to the same SRTP but based on variants of Ramsey's formula, recommend: Germany—constant 1% for long climate change effects, 1.5% for other effects, and 3% for short-term effects (0–20 years); Sweden—constant 3.5%; UK—3.5% for 0–30 years, 3% for 31–75 years [27–31]. Other countries recommend discount rates related to the marginal social cost of capital (SOC), such as Japan—constant 4%—or New Zealand—8%, recommended by the NZ Treasury (and 6% used by the NZ Transport Agency).

Some concluding observations can be formulated:

- The recommended value for investments targeting long time horizons is an issue that continues to arouse interest in research [32,33].
- Different countries apply various discount rates in CBAs [34–37].
- Concern for uncertainty compensation is reflected in the recommended discount rates. For longer time horizons, the discount rates are lower [38–42].
- The lowest discount rates are used in updating the costs of the long-term effects of climate change (the consequence of the fact that socio-economic and scientific/methodologic uncertainties intervene in the evaluation) [43–46].
- Differentiated discount rates depending on the type of investment project are generally not recommended. The above examples show that differentiated values are applied only in France (although the uncertainties in the investment project benefits and costs also essentially depend on the project type) [27].

4. Results

4.1. Examination of Major Changes in the Socio-Economic Environment

Discontinuities characterize local or global socio-economic dynamics. Most of them are difficult to anticipate. Some of them are major, real macroeconomic shocks with significant consequences for the whole socio-economic life. All components of the territorial system are structurally and functionally affected. Therefore, they are included in the category of risks or, more appropriately, of undifferentiated or systemic uncertainties. The transport system, as a whole, is also affected by these changes. However, not all modes of transport are equally affected by the shocks caused by changes in the activities of the territorial system. The differences are mainly caused by the size and structure of the new traffic flows induced by changes in the activity system as well as the transport mode flexibility (i.e., the ability of the operators of each mode of transport to adapt services more quickly to changes).

An examination of the impact of the profound socio-economic changes in Romania, since 1990, on the transport market indicates interesting observations. Certainly, the analyzed framework is a particular one. Nevertheless, synthetic examination of the railway network, operating for over two decades, especially in the conditions of the radical modification of "ex ante" demand, provides a basis for generalized considerations. The analysis is limited only to relevant synthetic data regarding the influence of the rapid change in the economic and social environment on railway performance.

Changes in the system of activities that generate transport demands cannot be identified only based on gross domestic product (GDP) variation. A direct correlation between GDP and transport volume does not always occur. European policy even gave direction on the "decoupling" principle in the transportation sector, i.e., increasing transport performance (in ton-kilometers or in vehicle-kilometers) should not follow general economic growth. A detailed examination of the GDP structure should complement the evaluation. However, in the present paper, GDP growth is used to provide a concise view of the socio-economic situation (Figure 2). Additionally, we emphasize that GDP can be disproved as an appropriate measure for an activity system based on multiple arguments [47].

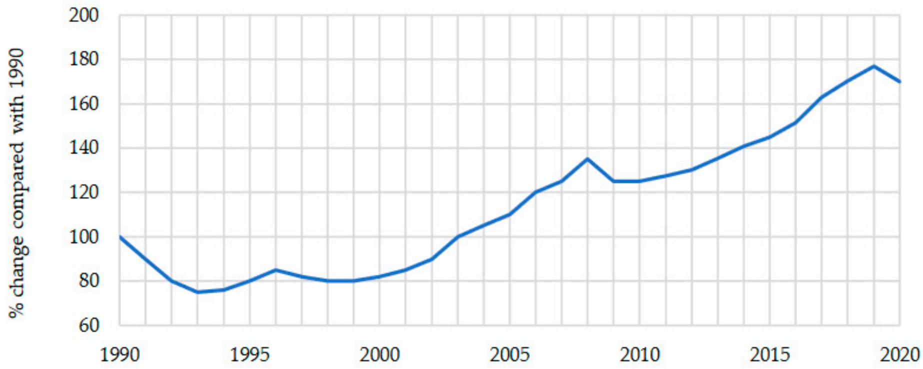

Figure 2. GDP growth in Romania, 1990–2020 [48,49].

Synthetic analysis based on GDP variation could essentially explain the regress of railway performance, expressed in ton-kilometers and passenger-kilometers (Figure 3) [50,51]. Difficult to predict, the quasi-continuous decline in railway activity could be considered a major shock. It was caused by radical changes in socio-economic structure and dimensions for which no timely and correctly oriented solutions have been found. Probably, no other similar situation was encountered by a railway administration at the beginning of the 21st century, especially considering that the vision of the respected former chairman and secretary general of UIC, Louis Armand—"the railway will be the mode of transport of the 21st century if it survives to the 20th" [52]—has been impressively confirmed multiple times in many world regions.

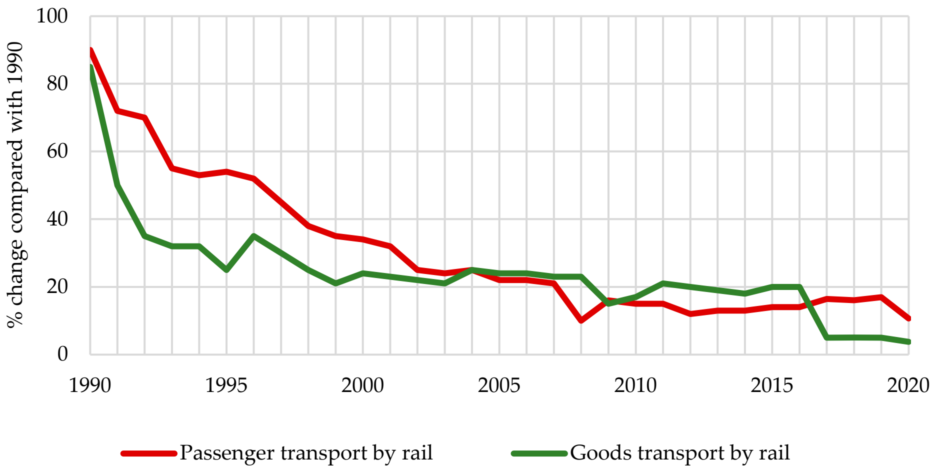

Figure 3. Railway transport performance in Romania, 1990–2020 [48,50,51].

Figure 4 shows the dynamics of land transport market share (the passenger transport split was computed only for public rail and road services; private car usage is not included in passenger road performance). The modal split—for both freight and passenger transport—reveals a flagrant dissonance with the sustainability targets defined by the European Commission [53,54].

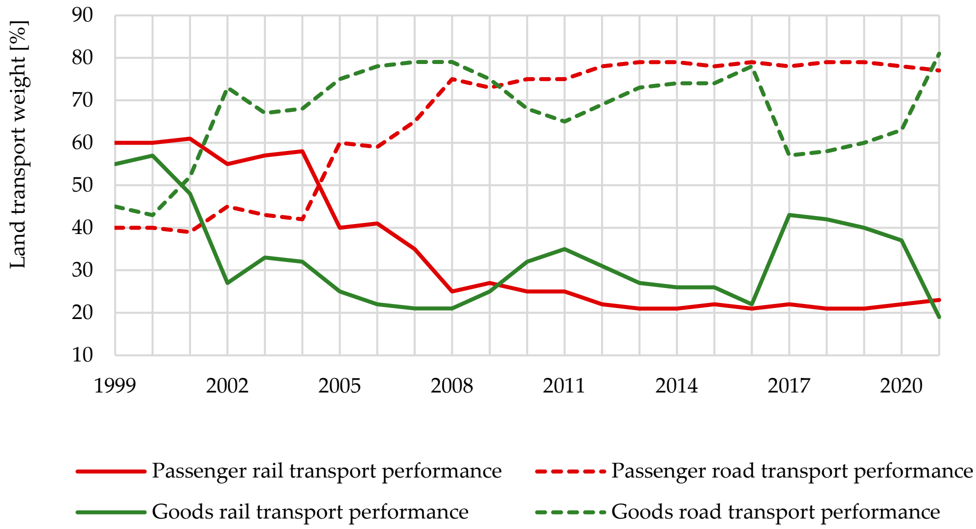

Figure 4. Commercial land transport split in Romania, 1999–2021 [48,50,51].

This analysis concisely emphasizes the consequences of non-diversifiable macroeconomic risks/uncertainties that significantly impacted the transport sector. It does not intend to extensively examine the real shock in the judicious use of available resources in the Romanian railway system in 1990. As an integrated system at the national level, the railway includes large intercorrelated resources (linear and nodal infrastructures, control and management equipment, heterogeneous fleet for specific tasks, personnel and decision-making structures distributed on hierarchical levels). It could not quickly adapt to major changes in demand: volume, structure, and specific requirements. Road transport (as well as air transport) is much more flexible and has proved to be better and faster at adaptation. Consequently, the road transport share has considerably increased in the land transport market. Undoubtedly, the position also results from an insufficiently regulated modal competition, an unpredictable market, and non-performant management at all railway administration levels (regardless of the organizational metamorphosis and the consultancy services).

4.2. Investment Strategies Affected by Uncertainties in Traffic Dynamics, Size, and Structure

The traffic forecast for a railway section is often uncertain. In the case of a conventional mixed-use railway line (for freight and passenger trains), the uncertainty concerns both the number of freight trains and the number of passenger trains over a longer time horizon. It is supposed that the number of freight trains, N_g, and the number of passenger trains, N_p, increase linearly over a period, t_0–T (Figure 5).

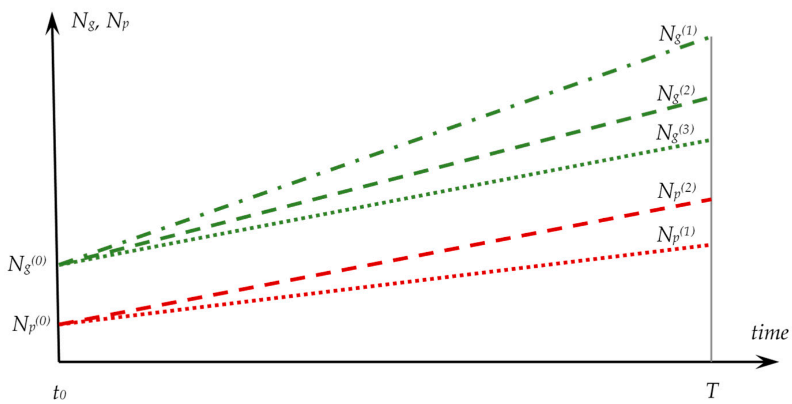

Figure 5. Variation in the number of freight trains (three uncertain variants) and passenger trains (two uncertain variants) on the time horizon t_0–T.

Increasing the required number of trains on a particular horizon involves investment measures to increase the installed capacity of a railway section. For example, to increase the capacity of a conventional single-track railway section, the considered investment measures are:

- increasing the speed of trains by modernizing the single-track infrastructure;
- changing the traction system;
- doubling of portions (partial) of a single line;
- total doubling of the line over the entire envisaged section.

Definitely, there are also other sequences to increase the existing traffic capacity of a section. The representation in Figure 6 corresponds to a certain number of freight trains, N_g, and passenger trains, N_p, and a particular scheme for traffic capacity increase. For t_0–T = 20 years, all six combinations of the estimated values for the number of freight and passenger trains indicate, without exception, that a doubling track is necessary to ensure the required traffic capacity.

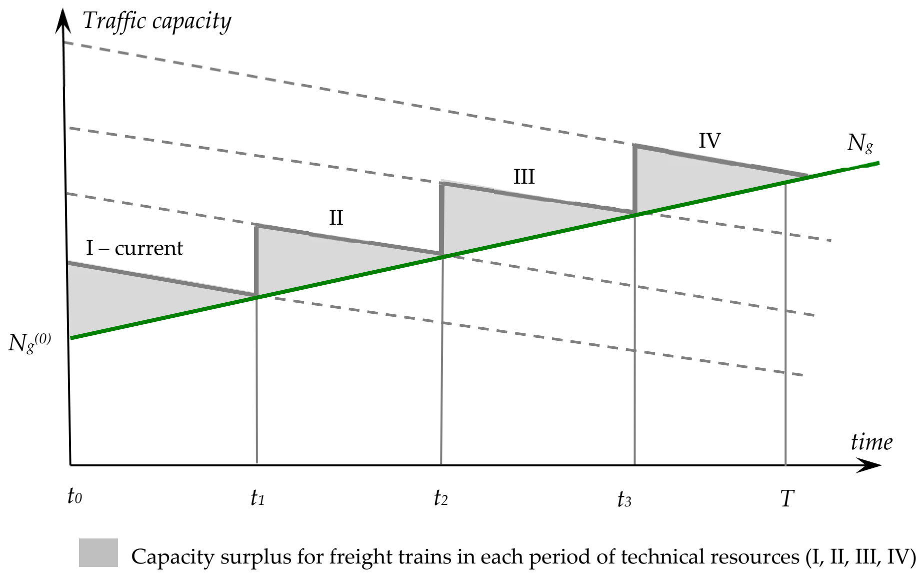

Figure 6. Measures to increase the traffic capacity (II, III, IV implemented at t_1, t_2, t_3) for running the number of freight trains N_g.

Four sequences (S_1 to S_4) must be analyzed to select the recommended investment option. They are chosen due to the fact that they have technical logic. The sequences correspond to different judicious and in-stages decisions (scenarios considering different sets of investment measures), all starting with current status I:

- S_1: I–II–III–IV
- S_2: I–II–IV
- S_3: I–III–IV
- S_4: I–IV.

Each of the four sequences must be analyzed for each of the six combinations of N_g and N_p (Figure 5). For each scheme S_i (i = 1, . . . , 4) and for each $N_p(k)$ and $N_g(j)$ combination (k = 1, 2 and j = 1, 2, 3), the amount of investment and operating expenditures, $C_i(k,j)$, are calculated in millions of the monetary unit (Romanian monetary unit) relative to time t_0 (Table 1).

Table 1. Total expenditures for the analyzed schemes.

Decision Variant, S_i	$N_p^{(k)}$	$N_p^{(1)}$			$N_p^{(2)}$			$\max_{k,j} C_i^{(k,j)}$
	$N_g^{(j)}$	$N_g^{(1)}$	$N_g^{(2)}$	$N_g^{(3)}$	$N_g^{(1)}$	$N_g^{(2)}$	$N_g^{(3)}$	
S_1		319.9	292.9	250.0	324.0	296.5	258.1	324.0
S_2		325.6	293.4	254.2	327.4	295.6	257.9	327.4
S_3		329.2	292.3	259.2	331.9	293.6	262.9	331.9
S_4		342.0	307.6	262.4	340.3	307.5	274.1	-*

* Excluded variant.

The time of deployment measures, $t_1, t_2, t_3 \ldots$, are related to the technical measures envisaged, the total investment, and the additional/surplus of deployed capacity. The more additional capacity deployed at a given time (the larger investment), the more rarely interventions will be needed. However, the additional capacity will remain unused for a longer time.

The variant S_4 ($N_p^{(2)} > N_p^{(1)}$; $N_g^{(1)} > N_g^{(2)} > N_g^{(3)}$), with the highest costs for all k and j, is excluded from the analysis. Besides the highest costs, S_4 leads to a large unuseful capacity increase until the time horizon T.

Given that data about the values of N_p and N_g are not available (not even probabilistic data) on the prospected horizon, the recommendation of one of the four variants is limited to the application of known criteria of decision theory.

The Wald criterion [2–4,55] is applied for the values in Table 1. It results as follows:

$$\min_i \max_{k,j} C_i^{(k,j)} = 324.0. \tag{3}$$

It corresponds to S_1 for $N_p^{(2)}$ and $N_g^{(1)}$, i.e., the largest number of passenger and freight trains with a minimum of expenditure in the case of variant S_1 (for which the existing capacity follows the required capacity as closely as possible).

For the Savage criterion [2–4,55], the values:

$$r_i^{(k,j)} = \max_i C_i^{(k,j)} - C_i^{(k,j)} \tag{4}$$

define the risk matrix (Table 2). Based on the values of max $r_i^{(k,j)}$ (last column in Table 2), the variant that minimizes the maximum regret is selected:

$$\min_i \max_{k,j} r_i^{(k,j)} = 2.90, \tag{5}$$

i.e., S_1 with $N_p^{(2)}$ and $N_g^{(2)}$.

Table 2. Risk matrix.

Decision Variant, S_i	$N_p^{(k)}$	$N_p^{(1)}$			$N_p^{(2)}$			$\max_{k,j} r_i^{(k,j)}$
	$N_g^{(j)}$	$N_g^{(1)}$	$N_g^{(2)}$	$N_g^{(3)}$	$N_g^{(1)}$	$N_g^{(2)}$	$N_g^{(3)}$	
S_1		0.00	0.60	0.00	0.00	2.90	0.20	2.90
S_2		5.70	1.11	4.20	3.40	2.00	0.00	5.70
S_3		9.30	0.00	9.20	7.90	0.00	5.00	9.30

For the Hurwicz criterion [2,56,57], the values:

$$\overline{C_i}^{(k,j)} = \alpha \max_{k,j} C_i^{(k,j)} + (1-\alpha) \min_{k,j} C_i^{(k,j)} \tag{6}$$

are computed for different α values (Table 3) and indicate S_1 as the recommended decision variant.

Table 3. Values for the Hurwicz criterion.

Decision Variant, S_i	$N_p^{(k)}$ $N_g^{(j)}$	$\max\limits_{k,j} C_i^{(k,j)}$	$\min\limits_{k,j} C_i^{(k,j)}$	$\overline{C_i}^{(k,j)}$				
				$\alpha = 0.0$	$\alpha = 0.2$	$\alpha = 0.3$	$\alpha = 0.5$	$\alpha \neq 1.0$
S_1		324.0	250.0	250.0	264.8	272.2	287.0	324.0
S_2		327.4	254.2	254.2	268.8	276.2	290.8	327.4
S_3		331.9	259.2	259.2	273.7	281.0	295.6	331.9

Thus, scheme S_1 is recommended in all decision-making hypotheses. However, the uncertainty (ambiguity) regarding the investment strategy is not eliminated. It persists in the moments of transition from one technical resource to another, i.e., t_1, t_2, and t_3 (Figure 6). They differ for each combination of N_p and N_c. It should be noted that the traffic capacities provided in each of the four variants of technical resources refer to the capacities available for freight train running. Additional scenarios need to be analyzed for the capacity demand for passenger trains. Consequently, to decide on the appropriate moments of capacity increase, an adaptive policy is required according to the diminution of uncertainties regarding the evolution of traffic volume and structure (i.e., for a certain combination of N_p and N_g).

5. Discussion

The analyses conducted in the paper lead to several practical recommendations, as follows.

- Changes in the system of activities that generate transport demands cannot be identified only based on GDP variation.
- The quasi-continuous decline in railway activity (especially in some Eastern European countries) could be considered a major shock, caused by radical changes in socio-economic life structure and dimensions. No timely and correctly oriented solutions have been found.
- Road transport (as well as air transport), being much more flexible, proved to show a better and faster adaptation. Consequently, road transport share has considerably increased in the land transport market. Undoubtedly, the gained position also results from an insufficiently regulated modal competition, an unpredictable market, and non-performant management at all railway administration levels (regardless of the organizational metamorphosis and the consultancy services).
- The traffic forecast for a railway section is often uncertain. In the case of a mixed-use conventional railway line (for freight and passenger trains), the uncertainty is generated by the difficult prediction of both the number of freight trains and the number of passenger trains over a longer time horizon and the number of investment measures. The analysis of the combination of an uncertain needed number of trains over the *T* horizon and several investment measures (with technical logic) also includes the uncertainty related to the methodological CBA parameters as well as the risk of lower or higher traffic flows due to the lack of accurate predictions of general socio-economic variation.
- Moreover, the decision on the most appropriate moments for additional capacity deployment is even more ambiguous because of the necessity for rare interventions into infrastructure (i.e., works on transport infrastructure generate negative social and environmental impacts during implementation). The question of which option is the best—(i) more frequent intervention in infrastructure for smaller additional capacity deployment or, on the contrary, (ii) rare interventions for larger additional capacity, even if this will be unused for a longer time—has no certain response.
- Even if decision-making models under the risk and uncertainty conditions were elaborated, ambiguity, especially regarding the strategies of large investment in the long term, is not completely eliminated, and more research is needed toward this aim.

6. Conclusions

This study draws to the attention of decision-makers, communities, and transport administrators the problem of uncertainty and risk, which must be considered in decision-making processes related to transport development. In this matter, we have highlighted several particularities of the transport system and conceptual clarifications:

- Transportation system performances depend on the functional characteristics of its components, the implemented technology, and the size, structure, and spatiotemporal attributes of the demands generated by the socio-economic activities of the territorial system. In the short term, the variation of demands addressed to the system involves operational and tactical management actions aiming to meet the beneficiary requirements with the most judicious use of system resources. In the medium and long term, the estimated dynamics of the demands addressed to the system involve strategic management actions aiming to adapt the system resources to the estimated tasks.
- All operational, tactical, and strategical decisions for any complex technical system, such as transportation systems, are affected by indetermination (categorized as uncertainties and risks). Therefore, decision-makers cannot affirm that their decisions, in the perceived concrete circumstances, are the optimum ones.
- Uncertainties, unforeseen random events (indicated as "unknown unknowns"), are: (i) methodological—differentiated or non-systemic—and (ii) socio-economic—undifferentiated or systemic. There is always a certain level of uncertainty in the operation and design of any transportation system or modal subsystem. Uncertainty increases as the complexity of the system increases. The more interacting parts a system includes, the more its complexity increases. The unitary approach to technical infrastructure confirms the existence of greater uncertainty encountered in developing the aggregate of the general technical infrastructure and each modal transport infrastructure.
- Appropriate differentiation must be made in assigning the responsibility for the negative consequences of exogenous and endogenous risks. The risks, which also impact transportation system performances, are random events but in a known probabilistic sense ("known unknowns"). They are generated inside or outside the system. In the case of exogenous risks, the magnitude of the consequences is interpreted as the individual and collective responsibility of those involved in design, construction, and administration, while in the case of endogenous events (anthropogenic type), both the probability of adverse events and their consequences are assigned to a wide, diverse range of stakeholders in the technical, economic, social, political, and organizational domains. Such responsibility in case of uncertainties cannot be dissociated.
- Both uncertainties and risks affect transportation system performances over time. Therefore, reports include average values over longer periods but do not include uncertainty and risk effects.
- Avoiding uncertainty should not be confused with avoiding risk. Uncertainty, as opposed to risk, is not linked to probability. It is the situation in which anything can happen. The decision-maker is completely unaware of the future. As soon as uncertainty is expressed as a risk, it stops being a source of concern. The decision-maker can include it in the analysis, considering the negative consequences of the event in a probabilistic way.

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