THESES OF DOCTORAL (Phd) DISSERTATION

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METHODS FOR ANALYSING SUPPLY CHAIN PROCESSES AND OPPORTUNITIES FOR IMPROVING EFFICIENCY THROUGH SIMULATION MODELLING

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Declaration
I, the undersigned, Csaba Attila Péterfi, author of the thesis entitled 'Methods for analysing supply chain processes and opportunities for improving efficiency through simulation modelling', hereby declare that, whilst preparing this thesis, I acted in accordance with the Hungarian Academy of Sciences' (MTA) current Code of Scientific Ethics, and was aware of and complied with the necessary research standards and authorisations applicable to my field of study. Where the thesis does not contain my own ideas or my own findings, I have indicated this clearly and in an identifiable manner within the thesis.

..... PhD candidate

1. INTRODUCTION

Increasing competition, efficiency and a profit-oriented approach largely determine the operations of today's companies. Whilst in the 20th century the emphasis was on mass production, large production runs and economies of scale, consumer demands have now shifted significantly towards unique, personalised products and services. Consumers expect near-perfect quality, favourable prices and immediately available stock. For this very reason, the supply chain must be tailored as closely as possible to consumer demands. However, every minor change in a company's operations can have various effects, to which managers must respond immediately.

In a company where there is any flow of raw materials, fuels, semi-finished or finished products, the proper design of the supply chain is a key focus that largely determines its operation and effectiveness, as logistics costs significantly influence the consumer prices of products and services. My topic is firmly grounded in logistics knowledge and the broader field of supply chain management, which examines the entire supply chain rather than individual participants. Advances in information and IT in the 21st century enable the application of new approaches in this field as well, and the development of a mindset whereby the effects of changes can be anticipated rather than assessed retrospectively.

My research focuses on the optimisation of logistics activities through simulation. Simulation has been an integral part of technical sports and engineering work for several years now, yet it is not yet in use in the field of supply chain management, where it would provide an opportunity to analyse the effects of changes without risk and serve as a tool for companies to model and measure their activities. Measurability, in turn, would provide an opportunity for correction and improvement, which plays an essential role in enhancing efficiency and effectiveness.

This topic is of particular importance to our experts today, as the world changes, so too do the tools of the supply chain and the methods used to improve its efficiency. In order to meet consumer demands to the highest possible standard, it is necessary to introduce state-of-the-art methods, which can ensure the company's long-term success and survival. The aim of my research is to present an innovative, entirely new approach in the field of logistics and the supply chain, through which I will present new opportunities and research findings. A key focus of my research is to conduct an analysis that defines the relationship between logistics and simulations, as well as the direction of their development, which I will present through a systematic review covering more than five thousand publications. In addition to exploring the current relationship between visual simulations and logistics, I will use a new methodology in the field of logistics to ascertain the views of senior logistics managers and decision-makers, which I will organise into opinion groups. I will be aided in this by the Q-methodology and factor analysis. Therefore, in addition to exploring the convergence achieved between the scientific fields of logistics and simulation, my chosen topic will present the attitudes of practitioners towards the application of simulation in logistics, as reflected through their various opinion groups.

My topic may be of interest to all those who view logistics merely as a support function within business processes, as logistics is now recognised as an opportunity for value creation, the generation of added value, and the fulfilment of customer needs at a higher level. On the other hand, the introduction of new technologies can provide an opportunity to gain a competitive advantage, which may ultimately ensure the company's long-term survival; for this reason, my topic will be of interest to all those involved in the supply chain.

1.1. Objectives

As the first stage of my research, I will define the aims and objectives, which will be addressed on the basis of a detailed analysis of the literature review. Subsequently, the hypotheses will be defined, and an analysis conducted using qualitative research methodology will help to either accept or reject them. Thus, in this subchapter, the research objectives are presented; however, given the logical progression of the research, they will not necessarily be carried out in sequence.

C1

To produce a literature review that highlights the common ground between simulations and logistics, and which summarises the current state of these two fields in an entirely new format. This literature review of the common ground between visual simulations and logistics involves mapping the topicality and publication coverage of the subject based on the most recent published sources. My aim is for this systematic review to be of such a high standard and informative nature that it can serve as a basis for further research. The methodology of the systematic review enables me to analyse a comprehensive database from various perspectives, from which I can identify trends and correlations.

The importance of logistics is constantly growing in the lives of companies, and innovation and development can provide a competitive advantage in the markets; therefore, simulation, as a revolutionary new tool, also offers new opportunities. It is precisely for this reason that my aim is to systematically review the latest literature in the fields of logistics and simulation.

C2

The current state of the literature is very important from a research perspective; however, mapping the current direction of the field is also crucial for internationally relevant research. Thus, my second objective is to observe publication trends based on the literature review, from which I can draw conclusions about the future research directions in the fields of logistics and simulation.

In my view, these two subject areas have undergone remarkable development in tandem; therefore, to investigate this, I will subject the records in the database to be analysed to keyword analysis, which I will supplement with a thematic map.

C3

The preparation of a Q-methodological analysis, which has long been used in political science but is not yet widely adopted in the social sciences, particularly in Hungary. The application of this revolutionary methodology to such a complex field as logistics and simulation will shed entirely new light on the connections that have hitherto been presumed or are in fact real.

My third objective is to apply the Q-method in practice, a prerequisite for which is gaining an understanding of the Q-methodology and developing a Q-set as a prerequisite for the actual study. To develop the Q-set, I will conduct written interviews, primarily with professional contacts of mine who hold senior management and decision-making positions in logistics at various companies. Naturally, the fundamentals of the specialist literature and the findings of the systematic review will also be incorporated into the Q-set statements; supplemented by these, I will provide the research participants with a set of statements that comprehensively covers the topic.

C4

Analysing the literature and observing trends is essential; however, exploring the opinions and thoughts of practitioners can shed interesting light on the results of this analysis. My fourth objective is therefore to conduct research in which I will map out the thoughts of senior logistics managers and decision-makers regarding the topics of logistics and simulation.

To ascertain the views of these professionals, I will use a written questionnaire, which, in addition to gathering their opinions, will also assist me in developing the Q-set.

C5

Having gathered the views of logistics decision-makers, I aim to identify patterns and trends in their responses, on the basis of which they can be grouped into opinion clusters. My fifth objective is to identify common variables on the basis of which I can categorise respondents into groups, thereby enabling me to make broader observations based on the opinion groups observed amongst practitioners in the fields of logistics and simulation. Theoretical knowledge is most useful when combined with practical application; therefore, I consider it of paramount importance to understand the various attitudes held by practitioners.

By analysing the results of the Q-methodological study, I will identify different opinion clusters (factors) using factor analysis. I will use Varimax rotation to ensure the factors can be distinguished from one another. Based on the methodology used, similar opinion groups can also be observed when other individuals are surveyed; therefore, it is particularly interesting to observe the differing opinion groups.

C6

Using the Q-methodology, I can identify clearly distinguishable factors with a relatively small number of respondents, which remain similar when other individuals or subjects are surveyed. To test this, as part of the Q-factor survey, the sixth aim of my research is to repeat the survey using the Q-set in order to validate the results, and I will then compare the findings of the two studies. My sixth aim is to verify construct validity and the stability of the factor structure across samples.

1.2. Hypotheses

H1

H0: There is no significant relationship between logistics and simulation in the literature.

H1: A significant relationship between logistics and simulation can be demonstrated in the literature.

H2

H0: The combined publication volume and significance of the topics of logistics and simulation are not increasing.

H1: The combined publication volume and significance of the topics of logistics and simulation are steadily increasing.

H3

H0: The topics of logistics and simulation are not undergoing continuous structural/thematic development.

H1: The topics of logistics and simulation are undergoing continuous structural/thematic development.

H4

H0: The Q-methodology is not suitable for structuring the attitudes and opinions of logistics decision-makers using a new approach.

H1: The Q-methodology is suitable for structuring the attitudes and opinions of logistics decision-makers in a new way.

H5

H0: Practitioners do not use simulations in their day-to-day work.

H1: Practitioners actively use simulations in their day-to-day work.

H6

H0: Practitioners are not open to the use of simulations.

H1: Practitioners are open to the use of simulations.

H7

H0: The distribution of opinion groups amongst logistics decision-makers does not follow a consistent pattern.

H1: The distribution of opinion groups amongst logistics decision-makers follows a consistent pattern.

H8

H0: The factor structure identified in the baseline study cannot be reproduced in a subsequent survey (the factors will differ).

H1: The factor structure identified in the baseline study can be consistently reproduced in a subsequent survey (the factors will be similar).

In testing the hypotheses, the research combined several methodological approaches. I used econometric modelling to analyse economic growth, based my assessment of the financial intermediation system on macroeconomic and institutional analyses, whilst I employed the MACTOR method to examine the network of relationships between strategic actors. The combined use of these different analytical methods enabled a comprehensive approach to the research questions and a multi-faceted evaluation of the hypotheses.

2. MATERIAL AND METHOD

2.1. Stages of the research process

The research is divided into two main phases; in the first half, I explore the relationship between visual simulations and logistics. I review the specialist literature of the past few years concerning logistics and simulations, on the basis of which I examine the extent to which the topic has been addressed and its significance through a systematic review. To further develop the research, it is primarily necessary to explore the current state of the literature on the topic and its main trends.

In the second part of my research, as part of the primary research, I carry out a Q-methodological analysis – a method long used in the social sciences – based on the literature review. The survey is conducted with the assistance of professionals who hold senior decision-making positions in logistics companies across various industries but face similar challenges.

The research methodology comprises the following:

- Compiling and analysing the relevant literature database to substantiate the hypotheses;
- Conducting primary qualitative/methodological research and processing the data using appropriate statistical methods.

2.2. Research methodology

This chapter presents the two main research methodologies on which my thesis is based. The systematic review identifies the current state of research and potential avenues for further development, after which the qualitative method enables the presentation of different perspectives. In this chapter, I outline the steps of these two methodologies, which determine the answers to the research questions, the evaluation of the hypotheses and the research findings.

The two research methodologies complement one another in my thesis and provide a more complex and comprehensive picture of the relationship between logistics and simulation. On the one hand, through a systematic review, I present the common ground between the two topics as identified by the relevant literature, and analyse them in various ways; whilst, on the other hand, using the Q-methodology, I map out the views of senior logistics managers, and once the opinion groups have been identified, it will become clear how these senior managers view the use of simulations in the day-to-day operations of their companies. It is therefore necessary to carry out both analyses so that I can compare theory and practice side by side.

2.3. Systematic review

In order to carry out the comprehensive literature review specified in the research objective, I conducted a multi-level bibliometric analysis on the topics of simulation and the supply chain. For this research, I utilised a dataset from the Web of Science (WoS) database. In order to obtain results that are relevant to the study and of high quality, the search query must be formulated with great care to ensure that a sufficient number of articles corresponding to the specified keywords are available across the various fields of application. The search results were initially very broad and varied; I identified 31,580 academic articles, which had to be narrowed down. After refining and organising the results of the search process, this number fell to 30,804, representing the exclusion of 776 articles. This was followed by the third stage, in which I identified the records based on their relevance to the topic and the objectives of the study. I excluded articles deemed irrelevant by discipline, as well as those published before 1995, leaving a total of just 5,723 articles. This process is illustrated in Table 1.

Table 1: Summary table of the search, refinement and classification of records required for the systematic review

Stages	*Steps*	*Descriptions*	*Number of records*
Search	Collection of articles	Web of Science	31,580
Refine	Data filtering-1	Exclude review articles	30,804
	Data filtering 2–3	Exclude articles by irrelevant subject areas and year of publication	5,723
Classification	Exporting, organising and categorising	Grouping articles into clusters	5,723

Source: Compiled by the author.

In structuring and developing the methodology for this systematic review, I followed the following logical sequence:

- Data collection
- Analysis
- Evaluation of results
- Drawing conclusions

Data collection is followed by analysis. Based on the data collected previously, the analysis covers two main levels (Kabil et al., 2021). These main levels comprise seven sub-categories of analysis, which can be used to answer the questions posed in this study. The levels of analysis are presented in Table 2.

Table 2: Levels of analysis in the systematic review

Levels of analysis	*Sub-levels of analysis*
Basic information	Analyses of scientific output
	Source analyses
	Record-type analyses
	Field-of-study (disciplinary) analyses
Basic content	Keyword analyses
	Theoretical Analyses
	Author analyses

Source: compiled by the authors (Alreahi et al., 2023; Kabil et al., 2021)based on

Following the description of patterns in the literature and hidden correlations revealed by the systematic and bibliometric analyses, the second, primary phase of the research involves a deeper exploration of the individual perspectives of experts in the field. The qualitative research module of the thesis serves this purpose.

2.4. Qualitative research

For my primary research, I have chosen Q-factor analysis, a method that initially gained prominence in Anglo-Saxon research within the fields of psychology and political science. It is considered a relatively new method in Hungarian academic literature, having only emerged in the 21st century.

The main aim of the method is to identify perspectives based on disposition, attitude or (consumer) behaviour, thereby helping to identify individuals' opinions on a given topic (S. Brown et al., 2007; S. R. Brown, 1996; Póka et al., 2025).

In the survey, forced-response answers follow a normal distribution, meaning that a specific number of statements can be assigned to each point on the rating scale, which implies fewer than the two extreme values but more than zero.

In my research, I focus on identifying different opinion groups, a task facilitated by the Q-methodology. The structure of my research is based on a similar procedure and framework as recommended by international and domestic sources (Hofmeister Tóth–Simon, 2006; Parádi-Dolgos et al., 2023; Stevenson, 2019):

(1) defining the research question;

The research question is based on two main pillars:

- on the one hand, the systematic exploration and assessment of the views of decision-makers and experts,
- and, on the other hand, the identification of patterns, clusters of opinions and correlations emerging from the views obtained.

(2) designing the Q-set;

I used interviews to develop the Q-set. I conducted the interviews in a structured format, i.e. using pre-determined questions, and made them available to the interviewees in written form via email. During the process of compiling the Q-set, I kept three key considerations in mind to ensure I could carry out effective research:

- The principles and fundamentals identified during the literature review should be incorporated into the statements in accordance with the specific characteristics of the Q-methodology,
- The keywords identified and current topics uncovered during the systematic review should be incorporated into the statements in some form, and
- Based on the responses received during the pilot study, the statements should reflect various perspectives, thereby enabling the identification of differing opinions.

Taking the above into account, I identified 41 statements for my research, which the participants were required to categorise into pre-defined slots.

(3) Selection of participants;

In the Q-methodology, a non-random sampling technique is used to select participants. Convenience or random sampling is not appropriate, as the aim of the Q-methodology is to ascertain the perspectives of a specific group on a particular topic. The number of experts involved in my research was 23, a figure I determined on the basis of recommendations in the literature.

(4) Collection of Q-sort data;

I used Q Method Software to assist with the survey and, consequently, the collection of data; this software was specifically designed for conducting such research and provided an excellent framework for the survey.

(5) conducting factor analysis using specialised Q software; and

(6) interpreting the qualitative meaning of the factor structure.

To ensure the clarity of the thesis's logical structure, the final two steps of the Q-method research (conducting factor analysis using specialised Q-software and interpreting the qualitative findings of the factor structure) are discussed in the 'Results' section.

Taking into account the specific nature of Q-method analysis—which involves the identification of subjective opinions and the opinion groups based on them, coupled with a relatively small number of respondents—I consider it essential to conduct a validation or confirmatory study. My aim in the confirmatory study is to conduct the research using new respondents instead of the original participants, and then to compare the two factor structures.

3. RESULTS

In this chapter, I shall present the results of my research, which I have divided into two main sections to improve the clarity of the chapter: the first section covers the systematic review, whilst the second summarises the findings from the qualitative research.

3.1. Systematic review

During the systematic review, I compiled an extremely large and comprehensive database; by analysing this, I obtained different results at different levels, which I will present below:

Up until 2002, no more than 12 publications appeared annually on this topic. From then on, the importance of the topic and the annual number of publications began to rise sharply. From 2017 onwards, a further surge can be observed, representing exponential growth.

The rise in the number of publications shows a close correlation with the spread of IT infrastructure. In parallel with this, general daily internet usage has also risen steadily, which may have contributed to the increase in the number of articles. The past decade has also seen revolutionary developments in the field of simulation, which not only entails a large number of applications but also the emergence of entirely new modelling solutions and software frameworks.

The relationship between the supply chain and simulation can touch upon numerous scientific disciplines, as it is becoming increasingly important in the life of companies. The 5,723 records collected show that this is a very popular and well-known topic worldwide; based on the number of journals, it can be stated that supply chains and simulation are addressed from various perspectives. The 5,723 scientific articles appeared in 317 different journals.

The 4,351 publications issued by the 10 most prolific scientific publishers account for 76.03 per cent of the total data collected – that is, more than three-quarters – whilst the remaining 1,372 entries originate from 307 different sources. This indicates that this topic – supply chain and simulation – has seen a massive surge in publications and is very widespread across the academic landscape.

In the collected data, 146 different academic disciplines are linked to the topic. Each of the 20 most common categories was closely related to supply chains and simulation modelling, which I also verified individually.

Keyword analysis is one of the most important checks in a literature review, particularly a systematic review and, of course, a meta-analysis. The results comprised 986 different keywords, which were categorised into 9 clusters, with 33,055 links between them.

The analyses show that the earliest topics relate to logistic regression, regression, inference and the generalised linear model, dating from around 2016. The focus was on the selected model or method, the data and the inference. In the following years, the main focus shifted to optimisation, demand, management, efficiency and performance. The emphasis shifted from the method itself to how the method could be made more efficient. Looking at the most recent keywords, these are: big data, innovation, sustainability, Industry 4.0, machine learning. It is clear that this field has moved in a new direction, linked to new approaches where the main aim is to utilise new opportunities for analysing vast amounts of data and fully understanding causes and root causes.

Finally, this programme is also capable of generating a heatmap from the recorded data, which can reveal new insights into keyword analyses.

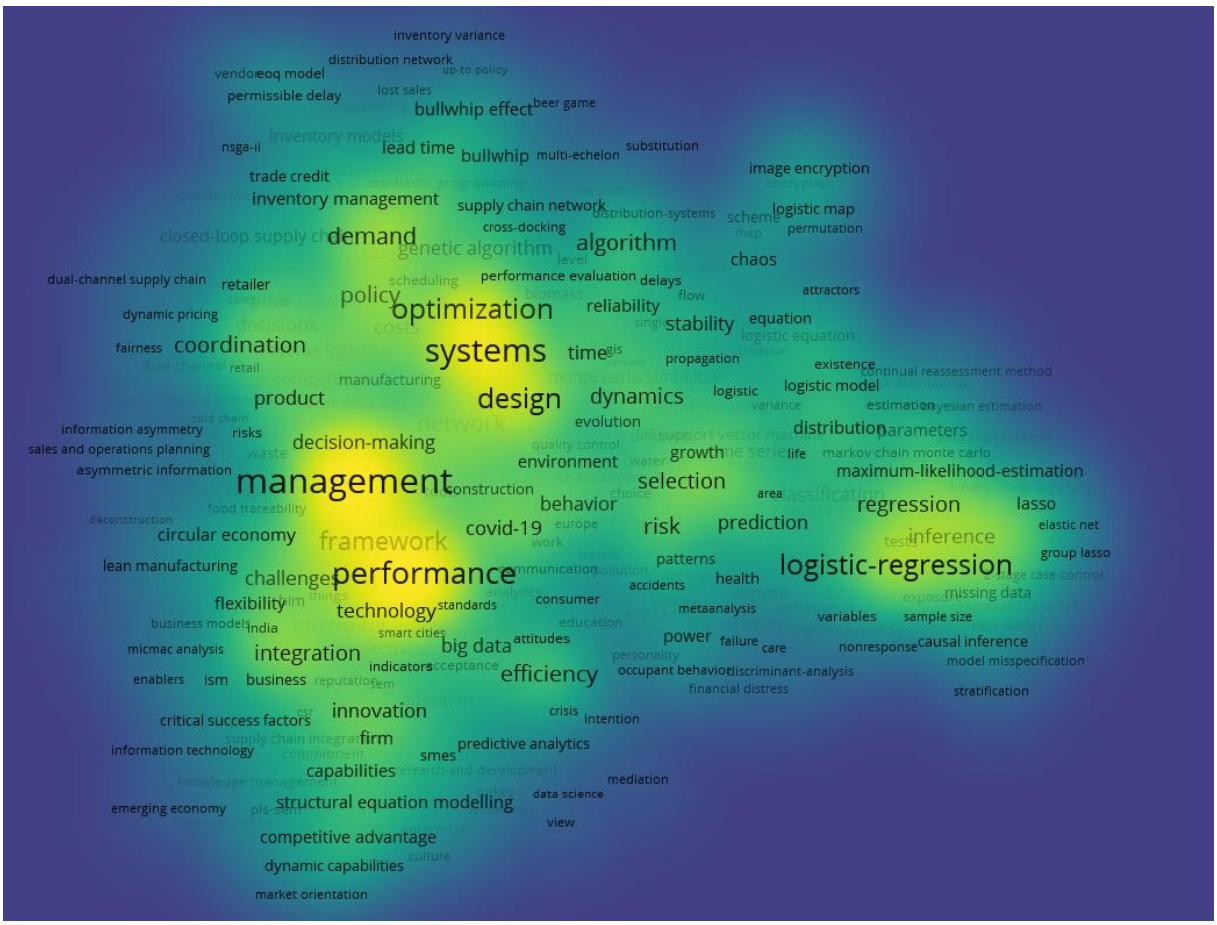


Figure 1. : keyword heatmap

Source: created by the author using VOSviewer

This heatmap shows the areas with the most frequently mentioned keywords, highlighted in bright colours. Based on Figure 1, three distinct hotspots in the records are easily identifiable:

- Logistic regression, regression, inference, missing data
- Optimisation, systems, planning, demand
- Management, framework, performance, technology

It is evident that, alongside the three highlighted hotspots, numerous transitional (green) areas can also be identified, which may indicate a continuous shift in research focus towards emerging sub-fields.

Upon examining the tables of keyword analysis and the theories used, I draw the conclusion that the most important theories appearing on the thematic map, and, upon observing the figures from the keyword analysis, it is evident that the terms ‘logistic regression’, ‘management’, ‘regression’ and ‘performance’ appear in a lighter colour on the heat map and in a larger font size in the keyword cloud; these are immediately noticeable at first glance. On closer inspection, the terms from the nine clusters of the keyword analysis can be found on the thematic map. These are the words and concepts that also arise in corporate management, and performance indicators can be derived from them. It is therefore important for corporate managers to translate theoretical knowledge and the simulation toolkit into strategic and operational processes.

The connections between authors in the WoS database records reveal 155 different authors on this topic. Of the 5,723 records extracted from the WoS database, 992 were published by staff from different institutions, whilst exactly 126 countries are represented on the list of publications.

3.2. The qualitative research

During my qualitative research, I carried out a Q-method analysis, which enabled me to examine the relationship between simulations and logistics from a new perspective. To arrive at the results of the Q-method analysis, I performed a factor analysis, followed by an interpretation of the qualitative significance of the factor structure, and then compared the opinion groups.

I analysed and evaluated the responses – that is, the collected data – using factor analysis and correlation. The aim of the analysis was to identify, distinguish and compare structured opinion groups, based on the similarities and differences in the distribution of the responses received.

I first examined the data using Pearson's correlation coefficient. The vast majority of the coefficients were positive, which indicates that there is a general consensus amongst the respondents. Overall, an examination of the correlation matrix reveals a predominance of moderate to strong values between 0.30 and 0.60, which provides an ideal basis for factor analysis, as there is sufficient shared variance to extract common factors and or patterns of thinking from the data; furthermore, the correlations are not extremely strong (above 0.90), which suggests that the respondents are not entirely alike and that there are distinct, specific subgroups and alternative patterns of thinking.

During the principal component analysis, I identified eight factors. To determine which factors to retain, I applied the Kaiser–Guttman criterion – which states that factors with eigenvalues greater than 1 should be retained (Yeomans–Golder, 1982) – and thus retained eight factors. Retaining the eighth factor ensured that no potentially relevant, specific respondent perspectives were lost during the rotation.

Since, prior to rotation, the majority of respondents load cumulatively onto both the first component and the secondary components, Varimax rotation is required to identify distinct, independent perspectives.

In the 8-factor model, the communality values range from 0.59 to 0.91, with a sample average of 76.3 per cent. The literature considers values above 0.50 to indicate adequate representation of individual perspectives; therefore, the results confirm that the extracted factors cover the individual decision-making patterns of the respondent sample with a high degree of effectiveness.

Following the quantitative research, statements characteristic of the opinion groups—that is, the factors—are available, which distinguish the factors from one another, as well as information on which opinion groups the respondents belong to. Based on this information, I carried out a qualitative evaluation and named the factors. During the analysis, 70 per cent of respondents were successfully classified into one of the eight factors. The opinions of respondents placed in the same factor or opinion group are clearly distinguishable from those of other opinion groups.

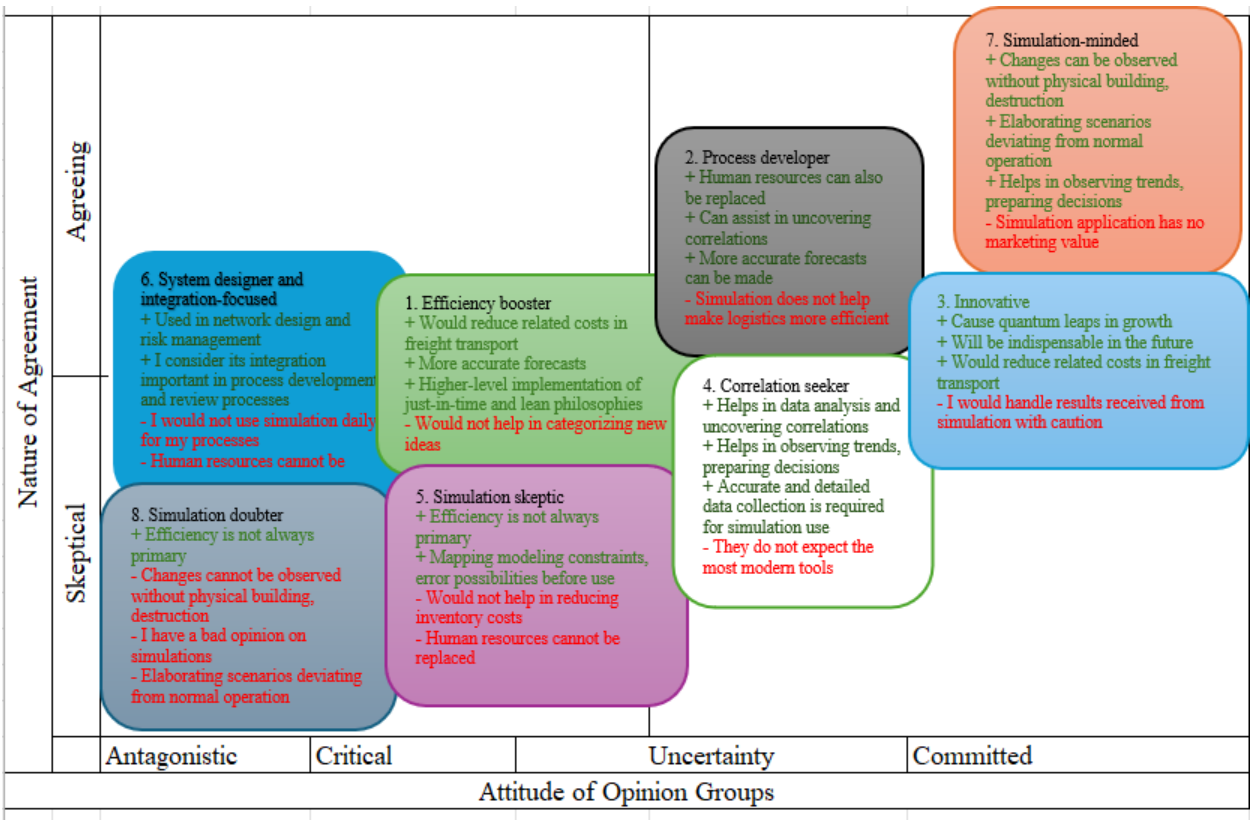


Figure 2: Comparison of opinion groups

Source: Author's own

As can be seen in Figure 2, the opinion groups cover the entire spectrum from a sceptical, antagonistic stance right through to an agreeable, committed one. The groups overlap to a certain extent; however, it is evident that the 'doubtful' group in Simulation 8, the 'automation-critical' group in Simulation 6, and the 'sceptical' group in Simulation 5 are all sceptical about the use of simulations in logistics. They do not agree with the possibilities offered by simulation methodology and approach the topic with a rather antagonistic and critical attitude. Members of the first 'efficiency-enhancing' opinion group are already on the borderline between agreement and scepticism; they recognise some of the potential benefits, which is why they are characterised by an uncertain attitude.

The fourth 'context-seeking' group and the second 'process-development' group already recognise the opportunities offered by simulation, but they believe that logistics does not require the use of the most modern tools, or that simulation does not contribute to more efficient logistics operations; I have therefore classified them as having an uncertain attitude, whilst in terms of the nature of their agreement, I have placed Group 4 on the borderline between sceptical and agreeable, and Group 2 in the agreeable category.

Groups 3 (innovative) and 7 (simulation-oriented) were both classified in the 'agreeing' and 'committed' quadrants, as they recognise the potential benefits of simulation and their statements of disagreement are not related to the use of simulations.

In order to verify the results and reliability of the basic research, I conducted a validation study, a detailed presentation and analysis of which follows in the next chapter.

3.3. Results of the verification study

During the validation study, I carried out the same analyses to ensure comparability. The aim of the analysis in this case was also to identify structured opinion groups. I also carried out data collection and data processing using the Q Method Software, in the same way as I did during the original study.

A comparison of the input Pearson correlation matrices, containing the individual Q sorts from the two independent samples collected during the research, highlights the differing internal dynamics of the respondent groups. Whilst the matrix from the original study confirms the presence of an extremely strong, homogeneous core of respondents, the follow-up study reveals a more nuanced and finely differentiated structure of opinions. In the baseline study's dataset, the correlation coefficients between individuals are exceptionally high, in many cases reaching values in the range of r = 0.80 to 0.92. This significant degree of overlap points to a widespread and dominant consensus within the sample, which results in the emergence of a single main factor with outstanding explanatory power during factor analysis. In contrast, the structure of the data collected in the confirmatory study is considerably more balanced, with more moderate maximum correlation values. The peak value is r = 0.67, whilst the majority of correlations fall between 0.20 and 0.45, a range considered ideal in the Q-methodology. A further difference is that the more pronounced negative correlations appearing in the matrix (for example, r = −0.39) indicate clearer differences of opinion and more polarised opinion groups.

Following the analysis of the Pearson correlation matrices, I turned to a comparison of the principal component matrices from the baseline study and the follow-up study prior to rotation. In both the main study and the confirmatory study, the characteristic pattern of pre-rotation principal component analysis emerges, namely that the first principal component accounts for the vast majority of the variance in the sample. In the data set of the main study, the loadings on the first factor are high almost without exception, which points to the strong internal consensus observed in the respondents' correlations. In the sample of the confirmatory study, the first factor remains dominant; however, there are also respondents here whose loadings on this principal axis are negligible.

I then continued the data analysis by analysing and comparing the eigenvalues of the factors. Whilst in the main study it was possible to retain the 8th factor by relaxing the rule, this was not necessary in the confirmatory study, as the eigenvalue of the 8th factor also falls within the rotation range (EV=1.067). In line with the initial study, the dominance of the first factor is also evident in the confirmatory study, as it accounts for 30.9 per cent of the variance, which similarly confirms the strong underlying trend in the sample. The combined variance of the eight factors is 76.87 per cent, which is an extremely high value; as in the initial study, this is explained by the retention of the eight factors in a sample of 23 respondents. A difference can be observed based on Humphrey's rule: whilst in the initial study only the first factor met this criterion, in the confirmatory study the first two factors do so.

To distinguish between pure perspectives, I applied Varimax rotation, in a similar manner to the baseline study. In the baseline study data, 16 of the 23 respondents received a pure classification; of these, 5 had a pure loading on the first factor, demonstrating its dominance. At the same time, the second, sixth and eighth factors each form an independent dimension with a single respondent's pure loadings. In the validation study, 18 respondents received a pure classification, with the first factor represented by 6 respondents and the third by 3. In this model, too, three single-respondent peripheral factors—F6, F7 and F8—appear.

In both studies, the first factor exhibits the lowest hyperplane value (26.09 per cent, 21.75 per cent). This means that, relative to the first factor, the fewest respondents are in an indifferent position; respondents are associated with the first principal dimension via significant positive or negative loadings. In the baseline study, F2, whilst in the follow-up study, F6 and F8, nearly half of the respondents are located in the hyperplane, which means that for the majority of respondents, these factors are irrelevant. The proportion of hyperplanes rose from 31.52 per cent in the baseline study to 35.87 per cent in the follow-up study.

The 8-factor Varimax model achieved an outstanding average communality in both data collections (baseline study: 0.767; follow-up study: 0.765). This indicates that, on average, the model retains 76.7–76.5 per cent of the information contained in the respondents' individual rankings. Upon examining the individual fit, I found that even the lowest values did not fall below the methodologically critical threshold of 0.50. The consistently high level of communality confirms that the 8-factor model does not lose any significant individual information in either the baseline or the confirmatory study.

In view of the results of the factor analysis, I conclude that, with regard to the main study and the control study, the results of the two studies are almost entirely consistent with one another, both structurally and diagnostically. The remarkable parallelism observed between the two independent data sets demonstrates that the results obtained in the main study are not due to random measurement errors, but rather to systematic methodological regularities, which were precisely replicated in the confirmatory study. The first of the main similarities was the presence of a dominant first factor, which formed the stable centre of the opinion structure. The second similarity was that in both studies, three single-item peripheral factors emerged. The degree of communality was also almost identical between the two studies. Finally, the identical maximum discrimination error measured for the peripheral factors also supports the view that the distinguishability of the lower-order factors from one another is statistically uncertain in both data sets.

Following the quantitative factor analysis – in line with the methodology of the main study – the next step is to interpret the qualitative meaning and contextual relationships of the extracted factor structure.

As in the original study, in the confirmatory study I also turned to interpreting the qualitative meaning of the factor structure following the statistical analysis. Upon completion of the quantitative analysis, the statements characterising the factors are available, which I present in a manner similar to that of the original study. Of the 23 participants, 18 could be clearly assigned to one of the eight factors.

As in the baseline study, I place the eight factors of the confirmatory study into context using a diagram. The factors express the relationship between logistics and simulations in different ways, which I identified and presented with the help of the respondents. The comparison of opinion groups is made even more illustrative by visualising them on an opinion scale, on which I have positioned the eight factors along axes representing the nature of agreement and the orientation of the opinion groups. As in the original research, the eight factors in this case also cover the entire spectrum from the sceptical antagonist to the agreeing advocate. The factors overlap to a certain extent, which can be attributed to a degree of agreement found in the views of the research participants.

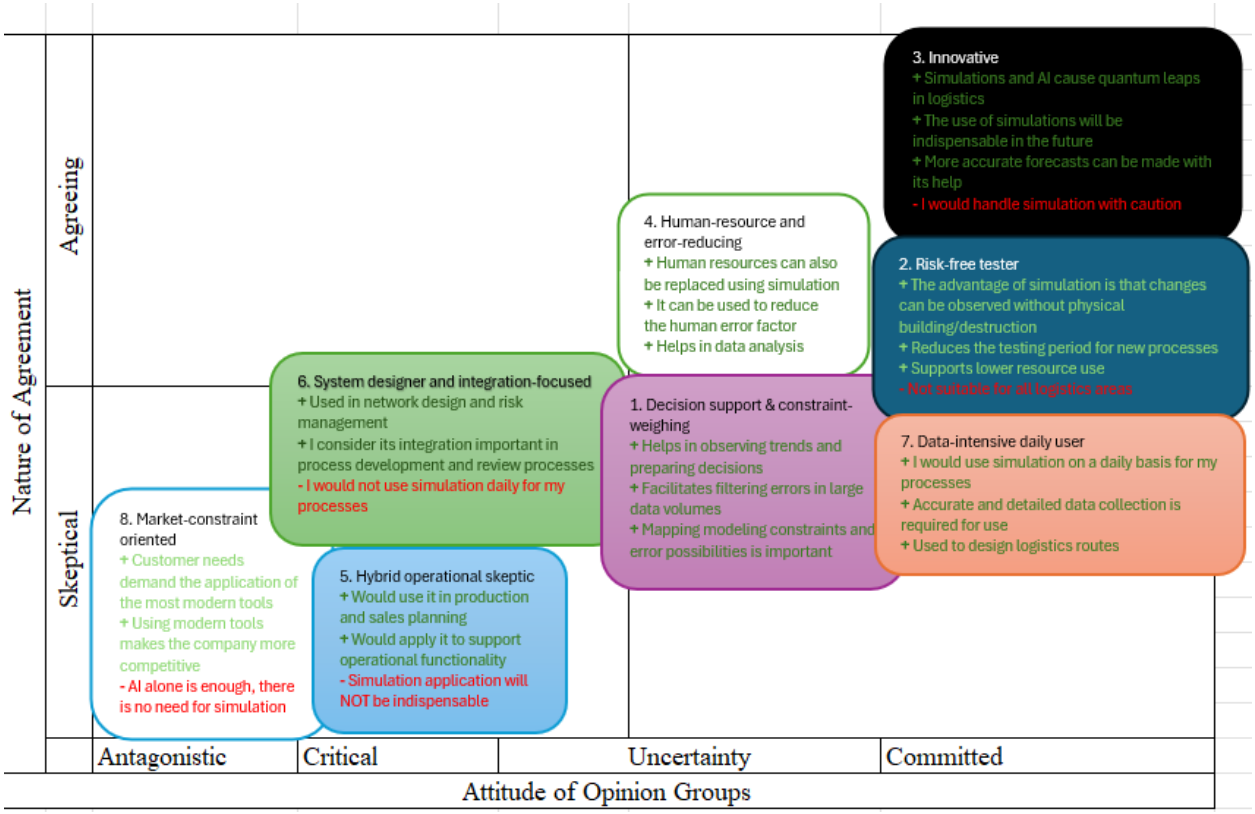


Figure 3.: Comparison of opinion groups

Source: Author's own

Figure 3 shows that, in the 'sceptical antagonist' area, only the 8th factor – 'market constraint-oriented' – is present; the use of simulations is not considered necessary. The 'sceptical-critical' attitude is occupied by factor 5 (Hybrid operational) and factor 6 (System design and integration-focused); respondents in these groups do not consider the use of simulation necessary, but do acknowledge some of its benefits. Looking further at the diagram, the 1st Decision-Support and Constraint-Balancing factor is situated in the area characterised by an uncertain attitude and sceptical agreement. They recognise the benefits of simulation, but in their view, efficiency is not necessarily the most important consideration. Also reflecting an uncertain but already agreeable attitude, 'Error Reduction' has become the focus of Opinion Group 4: 'Human Resources and Error Reduction'. Finally, Factor 7 (Data-intensive daily users), Factor 2 (Risk-averse testers) and Factor 3 (Innovative factors) belong to the committed opinion group. Factor 7 is somewhat sceptical in nature, whilst Factors 2 and 3 represent opinion groups with a conciliatory stance.

4. Confirmation or refutation of research hypotheses

I evaluate the research hypotheses formulated at the beginning of my doctoral thesis in the light of my theoretical (systematic literature review) and empirical (basic research and confirmatory Q-methodological study) research findings as follows:

1. Hypothesis (H1): *A significant relationship between logistics and simulation can be demonstrated in the literature.*

Based on a systematic review carried out in the fields of simulation and logistics, which began with a search yielding 31,580 articles and was subsequently narrowed down to 5,723 publications. Following a number of different analyses, the 5,723 scientific works were characterised from

several perspectives. Analyses carried out at the basic information analysis level clearly revealed that, within the period under review (1995–2023), the number of publications on the subject grew at an exponential rate. The geographical distribution of the publications shows that simulations and logistics are a globally relevant field of research, as they are being studied in numerous countries across every continent. The sources of the publications are also diverse, as the 5,723 publications were published by 307 different sources. Naturally, there were publishers that published nearly a quarter of the articles examined during the systematic review, whilst others published just one. The results were also highly diverse in terms of scientific disciplines. Statistical probability, which accounts for a large proportion of the other scientific fields, is distributed in a highly varied manner across disciplines ranging from operations research to mechanics.

The systematic literature review – which, starting from 31,580 articles, was narrowed down to 5,723 relevant publications – clearly confirmed the close theoretical and practical link between the two fields. Between 1995 and 2023, the number of publications grew exponentially, appearing in 307 different sources and demonstrating global coverage; **I** therefore **consider my hypothesis H1 to be confirmed**.

2. Hypothesis (H2): *The combined publication volume and significance of the topics of logistics and simulation are steadily increasing.*

During the systematic review, the analyses carried out in the subchapter on basic content analysis enabled me to identify correlations and trends. On the one hand, I created a word cloud based on the frequency of keyword occurrences, which visualises the keywords appearing in the topic according to their frequency. Subsequently, using VOSviewer, I was able to visualise the keywords along with their relationships and classify them into eight clusters. In this way, I was able to present the frequency of the keywords grouped according to their relationships; however, I also wanted to place them in a temporal context, so I created a heatmap from which the timing of the keywords' occurrence is clearly visible and hotspots have been identified.

The bibliometric analyses, the keyword cloud, the VOSviewer cluster analysis (8 identified clusters), and the heatmap analyses confirmed that the volume of the topic is expanding year on year; therefore, **I consider my hypothesis H2 to be confirmed**.

3. Hypothesis (H3): *The topics of logistics and simulation are undergoing continuous structural/thematic development.*

During the bibliometric analysis, I used the R-Bibliometrix programme to examine a database comprising 5,723 records via keywords and abstracts; based on this, the thematic map and the hotspots on the heatmap demonstrate that the literature has shifted from classical operations research and mathematical models, through integrated network design, towards the most modern concepts of digital twins and artificial intelligence (AI)**;** therefore**, I consider my hypothesis H3 to be confirmed.**

4. Hypothesis (H4): *The Q-methodology is suitable for structuring the attitudes and opinions of logistics decision-makers using a new approach.*

Using the Q-methodology – which is already widely used in political science but not yet in economics – I wanted to explore the views of logistics professionals on simulations from a completely new perspective. The Q-method study, conducted with the participation of 23 international corporate decision-makers, successfully covered the entire spectrum of opinions. Using this methodology, I was able to identify and position eight clearly distinguishable groups of opinions (factors) that are meaningful both statistically and in terms of content**; I** therefore **consider my hypothesis H4 to be confirmed.**

5. Hypothesis (H5): *Practitioners actively use simulations in their day-to-day work.*

Theories and practices only truly hold water when companies begin to use them productively; therefore, I wished to obtain information from practitioners regarding the relationship between simulation and logistics and its application. As part of a Q-method survey, I asked senior decision-makers at 23 international companies to rank statements relating to simulation and logistics according to the extent to which they agreed with them. The Q-method survey revealed that day-to-day usage is extremely low. For seven factors, the statements 'I use simulation tools in my work' and 'I would use simulation on a daily basis for my processes' were among the least typical, whilst for the sole remaining factor, they received only a neutral rating.

Taking all this into account, **I reject Hypothesis H5**, which posits that practitioners in logistics actively use simulations.

6. Hypothesis (H6): *Practitioners are open to the use of simulations.*

During the Q-method research conducted with practitioners, eight opinion groups, or factors, were identified. These factors reflected different attitudes, which, when compared, were successfully positioned relative to one another and presented in a diagram. The opinion groups covered the entire spectrum, ranging from an antagonistic, sceptical attitude, through sceptical and uncertain, to a supportive and committed one.

The most characteristic statements from the opinion groups show that professionals recognise the benefits offered by simulations (e.g. risk reduction, decision preparation, error analysis) and would support their use in several areas (e.g. 'I would use it to support operational activities'). However, due to the presence of sceptical and critical factors, data-related barriers and reluctance to use them in day-to-day practice, this openness is not universal; taking all this into account, **I consider Hypothesis H6 to be partially confirmed.**

7. Hypothesis (H7): *The distribution of opinion groups among logistics decision-makers shows a consistent pattern.*

In both the baseline study and the confirmatory study, the opinion groups covered the entire spectrum of attitudes, ranging from the antagonistic sceptic through the balanced uncertain to the agreeable committed, displaying a consistent structural pattern; therefore, **I consider Hypothesis H7 to be confirmed.**

8. Hypothesis (H8): *The factor structure identified in the baseline study can be reliably reproduced in a subsequent survey (the factors will be similar).*

A comparison of the 8 factors from the baseline study and the confirmatory study revealed a high degree of content and item agreement (e.g. in the case of the 1st 'Efficiency-enhancing', 3rd 'Innovative', 4th 'Process-improving' or 5th 'Sceptical' dimensions), which demonstrates the stability of the factor structure.

The research hypotheses and their evaluation are set out in Table 3, which summarises that hypotheses H1, H2, H3, H4, H7 and H8 were accepted, H5 was rejected, whilst H6 was partially accepted.

Table 3: Evaluation of research hypotheses

Hypothesis number	Definition of hypothesis	Evaluation
H1	A significant relationship between logistics and simulation can be demonstrated in the literature	Confirmed
H2	The combined volume and significance of publications on the topics of logistics and simulation are steadily increasing	Confirmed
H3	The fields of logistics and simulation are undergoing continuous structural and thematic development	Confirmed
H4	The Q-methodology is suitable for structuring the attitudes and opinions of logistics decision-makers from a new perspective	Confirmed
H5	Practitioners actively use simulations in their day-to-day work	Rejected
H6	Practitioners are open to the use of simulations	Partially confirmed
H7	The distribution of opinion groups among logistics decision-makers shows a consistent pattern	Confirmed
H8	The factor structure identified in the baseline study can be reliably reproduced in a subsequent survey	Confirmed

Source: compiled by the author

5. NEW SCIENTIFIC FINDINGS

1. **Thesis (T1):** I have produced the first comprehensive systematic bibliometric mapping of the literature examining the relationship between logistics and simulation; this analysis identified the main thematic clusters and future directions of development within this field of research.
2. **Thesis (T2):** Through a systematic review of the literature, I demonstrated that simulation methodologies are present in all major sub-fields of logistics research (e.g. supply chain optimisation, warehouse processes, transport systems). I have demonstrated the strong interdisciplinary link between the two fields, as evidenced by the 33,055 connections identified amongst 986 keywords, as well as the exponential growth in the volume of publications.
3. **Thesis (T3):** I have traced the thematic development of the research fields of logistics and simulation over three decades: from early model-selection approaches, through optimisation and efficiency improvement, to the integration of Industry 4.0, machine learning and sustainability. I have demonstrated that the proliferation of machine learning is fundamentally transforming the future application of simulation methodology.
4. **Thesis (T4):** Using the Q-methodology, I have demonstrated that logistics decision-makers and senior managers view the potential benefits of using simulation in a fundamentally positive light and show a high degree of agreement with the majority of the positive effects identified in the literature.
5. **Thesis (T5):** During the empirical study using the Q-method, I identified eight distinct decision-maker opinion groups (factors) with clearly distinguishable attitudes. I demonstrated that the differences between these opinion groups arise primarily along the dimensions of technology acceptance, decision-support requirements and organisational culture.
6. **Thesis (T6):** I demonstrated the existence of a significant ‘adoption gap’ in logistics practice: although decision-makers are theoretically aware of the benefits of simulations, these tools are not yet widely used in day-to-day decision support and operational work.
7. **Thesis (T7):** Through a confirmatory study using the Q-method, I have demonstrated that the factor structure identified in the sample of decision-makers exhibits a high degree of stability and consistency, despite the relatively small sample size.

Objectives	Hypotheses	Research methodologies	New scientific findings (Theses)
Exploring the relationship between logistics and simulations	H1: There is a relationship between logistics and simulation. *(Confirmed)* H2: The significance of these topics is growing. *(Confirmed)*	Keyword analysis (word cloud, visualisation, heat map), systematic literature review	**T1, T2:** Confirmation of a strong interdisciplinary link and a growing global volume of publications.
Observation of publication trends	H3: The topics are undergoing continuous development. *(Confirmed)*	Systematic review, thematic map, R-bibliometrix	**T3:** Identifying shifts in thematic focus from foundational models towards AI and Industry 4.0.
Mastering and applying the Q-methodology	H4: The Q-methodology sheds entirely new light on the problem. *(Confirmed)*	Written interview, development of a Q-set, Q-methodological analysis	**T4:** Verification of decision-makers' positive underlying attitude and high level of agreement.
Mapping the thinking of senior managers	H5: Professionals use simulations. *(Rejected)* H6: Professionals are open to simulations. *(Partially confirmed)*	Q-methodological study, in-depth interviews	**T6:** Identification of the 'adoption gap' (they are aware of the benefits but make little use of them in practice).
Identification of opinion groups	H7: The distribution of opinion groups is stable. *(Confirmed)*	Q-factor analysis	**T5:** Identification of eight decision-maker groups with distinct opinion structures.
Validation of the Q-method (Follow-up study)	H8: The factors will be similar in a new survey. *(Confirmed)*	Re-running the Q-method (follow-up study)	**T7:** To demonstrate the stability and consistency of the factor structure.

Table 4: Table of objectives, hypotheses and research methodologies

Source: compiled by the author

I have used Table 4 to summarise the objectives, hypotheses and the new and novel findings that can be derived from them, thereby providing a clearer overview of my research.

6. CONCLUSIONS AND RECOMMENDATIONS

The use of simulation modelling and analytics in logistics and supply chain management has become one of the most important tools for improving efficiency, managing risk and preparing for strategic decision-making. Modern simulation techniques enable the virtual testing of complex, dynamic and stochastic systems without the high risks and costs associated with modifying or disrupting physical systems in real time (Grigoryev, 2018). Whilst the use of simulation in the medical sciences or engineering disciplines is an established practice dating back decades (Bienstock–Heuer, 2022; Tricco et al., 2015), the increasing complexity of global supply chains and intensifying market competition (Ceniga–Sukalova, 2020; Majercak, 2020; Varnavskii, 2019; Yeniyurt et al., 2005) are driving the rise of data-driven, simulation-based approaches in the logistics sector as well (Straka et al., 2021).

This doctoral thesis examined the relationship between logistics and simulation on the basis of two pillars: on the one hand, through a comprehensive bibliometric analysis of the international literature (based on 5,723 cleaned Web of Science records), and on the other hand, through an in-depth, Q-methodological examination of the attitudes and opinion structures of domestic and international logistics decision-makers (within the framework of basic and confirmatory research).

6.1. The main theoretical and methodological conclusions of the research

1. The exponential development and global integration of the field

The systematic bibliometric review confirmed that the number of scientific publications examining the intersections between logistics and simulation has grown at an exponential rate over the past three decades (rising from 6 publications in 1995 to 958 by 2022). The global relevance of this research topic is demonstrated by the fact that the publications can be linked to 125 countries, with the European Union member states, the United States and China leading the way in terms of scientific output. The multidisciplinary nature of the topic is reflected in the fact that the 5,723 identified articles appeared in 307 scientific journals with a wide range of specialisms.

1. A shift in thematic focus: from statistical models to Industry 4.0 and machine learning

Analysis of bibliometric data and thematic maps has revealed the three-decade evolution of this research field. Early literature focused predominantly on fundamental mathematical modelling and statistical fit tests. This was followed by a period of system-level optimisation and operational simulations aimed at improving the efficiency of warehousing and transport processes. Based on the latest research networks' 'hot spots' and clusters, the defining trends of today are the integration of Industry 4.0, Big Data analytics, Digital Twins and Machine Learning with simulation. Machine learning is not merely another tool alongside simulation, but heralds the adaptive, self-learning transformation of the simulation methodology itself.

2. The methodological validity of the Q-methodology and the stability of the factor structure

The Q-methodology, already widely used in political science and psychology, has been successfully adapted to the structuring of decision-makers' attitudes in logistics. Factor analyses carried out during the basic and confirmatory research identified eight clearly distinguishable opinion groups (factors) in the sample of logistics managers (ranging from a committed, innovative, process-improvement-oriented mindset to sceptical, withdrawn attitudes citing a lack of data). A key scientific finding of the confirmatory Q-survey is that it confirmed the consistency and stability of the factor structure (H8/T7): the dimensions of the identified opinion groups are

reproducible despite the small sample size, thus the methodology is suitable for standardising research into logistics attitudes.

3. The phenomenon of the ‘Adoption Gap’

The main practical conclusion of the Q-methodological analysis is the identification of the so-called adoption gap. Although the logistics decision-makers surveyed, regardless of their opinion group, recognised the theoretical and practical benefits of simulation with a high level of agreement (e.g. risk reduction, error rate improvement, decision preparation), the integration of simulation tools into day-to-day operational work is extremely low. The majority of decision-makers view simulation as a process that is theoretically worthy of support, but which is difficult to implement in day-to-day practice or is excessively data-intensive.

6.2. Practical and strategic recommendations (Management implications)

In order to bridge the ‘application gap’ and promote the practical adoption of simulation technologies, the following three-tiered set of recommendations can be formulated based on the research findings:

1. Recommendations at the corporate organisational level

Improvement of organisational data infrastructure and data quality: As sceptics primarily cite incomplete or inaccurate corporate data as a reason for resisting simulation, it is essential to clean up the data quality of corporate ERP, MES or WMS systems and to automate data integration.

Gradual implementation (pilot projects): Management scepticism can be reduced if companies do not start with a full-system simulation, but instead demonstrate the return on investment (ROI) by testing simulation models on narrow, well-defined logistical bottlenecks (e.g. a key warehouse picking route or gate allocation).

In-house skills development: To reduce dependence on external experts, it is recommended that logistics engineers and analysts receive targeted further training in the use of user-friendly simulation software.

2. Recommendations for training and knowledge transfer

Practice-oriented renewal of higher education curricula: In logistics and supply chain management courses, greater emphasis should be placed on software-based, case-study-driven simulation-based teaching (e.g. AnyLogic, FlexSim, Plant Simulation) alongside theoretical modelling

Simulation-based decision-making games integrated into everyday practice: The openness of future decision-makers to simulation can be increased by incorporating business simulation games into management training programmes.

3. Software development and market recommendations

Cloud-based solutions with a low barrier to entry: It is recommended that software developers create modular, no-code/low-code simulation platforms that do not require in-depth programming skills or complex knowledge of operations research.

In summary, it can be concluded that, in the age of the Fourth Industrial Revolution and artificial intelligence, the integration of simulation tools into logistics decision-making is no longer merely a convenience but a fundamental prerequisite for sustainable corporate competitiveness.

6.3. Limitations of the research and directions for future research

Like any academic work, this doctoral thesis also has certain methodological and scope-related limitations, which simultaneously point to possible directions for future research on this topic.

Limitations of the research

Limitations of the bibliometric database: The systematic literature review was restricted exclusively to the Web of Science (WoS) database to ensure the highest level of scientific quality assurance. Although the 5,723 records obtained after this restriction provide a representative picture of the international mainstream, the inclusion of other databases (e.g. Scopus, Hindawi) could have provided further nuance regarding the proportion of publications with an engineering and IT focus. Due to the study's temporal cut-off (2023), the most recent AI and simulation publications from 2024 to 2026 were only included to a limited extent in the statistics.

Sampling characteristics of the Q-methodology: A fundamental methodological feature of the Q-methodology is that it does not aim for representativeness with regard to the population of respondents, but rather seeks to uncover opinion structures and patterns of attitude (Hofmeister Tóth–Simon, 2006). The use of a P-sample of 10–50 respondents, as prescribed by the literature (S. R. Brown, 1996), and a Q-set comprising 40–80 statements (Stevenson, 2019) ensured that respondents' attention was maintained and that statistical factor analysis could be carried out. Consequently, no representative conclusions in terms of percentages at national or sectoral level can be drawn from the results.

Validation of the factor structure: The methodological limitation arising from the sample's limited sample size was successfully mitigated in the thesis by conducting an expanded confirmatory study. A comparison of the baseline study and the confirmatory study demonstrated the stability of the factor structure of the eight opinion groups (H8/T7), confirming the reproducibility of the identified attitudes.

Directions for future research (Research Roadmap)

This doctoral thesis can be regarded as the first, fundamental stage of a comprehensive, multi-stage research programme. Building on the findings and the identified 'adoption gap', future research can be pursued in the following three interrelated phases:

1. Root Cause Analysis of decision-makers' inaction:

The Q-methodology has confirmed that logistics decision-makers recognise the theoretical benefits of simulation but are reluctant to use it in their day-to-day work. As a first step in future research, it is necessary to identify the underlying organisational, human and technological barriers (e.g. explicit lack of time, high software licence costs, resistance from organisational culture, lack of internal expertise) through semi-structured in-depth interviews and exploratory case studies.

2. Representative quantitative survey:

Based on the eight opinion groups identified using the Q-method and the root causes uncovered, a large-scale, representative questionnaire survey can be conducted amongst logistics and supply chain decision-makers. This makes it possible to determine the numerical proportions of each attitude group and their sectoral distribution (automotive, FMCG, services).

3. Development of a decision-support framework for simulation implementation:

As the theoretical and empirical culmination of this research series, a practical decision-making model and methodological guide can be developed to assist corporate decision-makers. This

'maturity model' would support companies in identifying which of their logistics sub-processes could achieve the highest return on investment (ROI) using which type of simulation tool.

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