Network Analysis as a Research Method

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Abstract. Network analysis has emerged as a powerful research approach, breaking down disciplinary barriers to examine intricate relationships across various fields. By depicting entities as nodes and relationships as edges, this method constructs networks that unveil patterns and dynamics. This study delves into the fundamental principles of network analysis, emphasizing its effectiveness in revealing hidden patterns, pinpointing influential factors, and understanding the flow of information. It facilitates examination at both micro and macro levels, with key components such as centrality measures and clustering algorithms showcasing its adaptability. Applications span from comprehending social networks to scrutinizing technological systems. Despite challenges in data collection and ethical considerations, network analysis remains a valuable tool, offering a holistic view of complex systems. In conclusion, this study advocates the continual exploration and adoption of network analysis, emphasizing its potential to uncover concealed relationships, patterns, and structures crucial for advancing knowledge.

1 Introduction

The skilful planning of various projects is nowadays one of the most important tasks of an organisation's managers. This is due, among other things, to the fact that running a business is becoming more complex and costly every year. Managers must therefore prepare effective plans and make effective decisions. Unfortunately, this planning is often complicated and protracted. In addition, it may also require high financial expenditure. In order to optimise the plan in terms of both time and effort, it is necessary to skilfully develop suitable methods for planning projects. Methods that enable such optimisation are referred to as network planning methods.

The current state of knowledge about networks in management science, as highlighted by researchers of international networks, synthesises the search for new methods of studying them [1]. This has to do with the dissimilarity of the conditions present in a single organisation and an inter-organisational network, as a result of which it is not always valid to apply methodological solutions suitable for organisations in network research. P. Kale, J.H. Dyer and H. Singh [2] point out that network research can be considered a real

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methodological challenge. They argue that the nodes of a network are linked by a set of interrelationships that leads to their mutual interdependence (which implies the effectiveness of the actions of the individual members of the network, making their actions dependent on each other) and that the variability of the network causes difficulties in fully capturing the essence of the network. This paper presents an analysis of network planning using the methods: PERT, CPM and Delphi.

2 Network planning methods

Network planning methods, which are used as a method to reduce costs or shorten the time of various activities, make it possible to prepare a plan of action that identifies those activities in the plan that should be particularly analysed. The identification of such activities makes it possible to make better use of manpower and other resources owned by the company.

Network planning methods make it possible to select the optimum programme of action for a given project, thereby helping to determine the sequence in which individual tasks are to be performed. Network planning methods also help to:

- set start and completion dates for individual tasks,
- optimise the time of overall project implementation,
- select so-called "critical activities", which are activities that have an impact on the deadline for completion of the entire project,
- distribute the means of production owned by the company, e.g. labour, machinery between tasks.

Social network analysis, also called network analysis and structural analysis, is a method of analysing networks of actors linked by social relations [3]. It should be pointed out, however, that social analysis itself is seen as a collection of individuals, actors, institutions, or units - so-called nodes, linked to each other by a system of relationships [4].

Network analysis is a research method aimed at identifying arrangements and patterns of relationships in a network based on the ways in which nodes are connected. It is used to describe and explore patterns of interaction occurring in networks [5] and to identify these patterns for individual network members. The following assumptions should be met when using network analysis:

- nodes are channels for the transfer of tangible and intangible resources,
- nodes are interdependent [6],
- ties, their interconnectedness and the structure of the network are taken together, jointly building the background of the entire network and its individual members [7],
- network structure represents the arrangements of permanent ties between nodes [8].

The number and mutual arrangement of relationships and nodes in a network influences the structure of the network under analysis. Research shows that the network structure influences the diffusion and transfer of innovations or technologies [9], the situation and behaviour of network nodes [10], determines the members' ability to benefit from the resources gathered in the network, affects their competitive position and social capital, and influences the managerial performance of the network [6,11].Figures and tables, as originals of good quality and well contrasted, are to be in their final form, ready for reproduction, pasted in the appropriate place in the text. Try to ensure that the size of the text in your figures is approximately the same size as the main text (10 point). Try to ensure that lines are no thinner than 0.25 point.

The procedure for conducting a network analysis boils down to the following steps:

a) defining actors and relationships. The nodes of a network can be either organisations or/and individual units, objects, events, geographical locations and points in time, while relationships can represent commonalities, hierarchy within an organisation, friendship,

contract, competition, interaction, trust or service subordination and be formal or informal in nature. Important in the context of relationship ownership is the establishment of [6,7,12]:

- direction of the relationships considered in the analysis, which lists directed relationships, where the direction of the flow, which is the content of the relationship, matters and which are divided into unidirectional and multidirectional, and non-directed relationships, where the direction of the flow is not important or is not measured,
- strength of the relationship, i.e. the depth and intensity of the bond or the frequency and value of the flow occurring between the nodes of the network,
- content of the relationships, i.e. identifying what they are about, what they re-present or what they reflect.

These properties determine the type of network analysed and the type of measures used in the study [6,13]. In addition to the basic properties, the relationships in the network can be negative or positive [14]. Moreover, it should be pointed out that, under certain conditions for the analysed collective, it is possible to identify more than one different relationship occurring simultaneously, i.e. multiple networks, which are always value networks and their connections are usually stronger and more durable [6,15].

b) data collection, where the typical data source is primary sources, providing data primarily through interviews and survey techniques [7,16]. Data collection can be done using a geocentric approach, which is used when network boundaries are blurred, the size of the network is too large, or an egocentric network study (a questionnaire is used in which respondents indicate the nodes with which they have specific relationships) or the sociometric approach [8,17], where respondents are presented with a closed list of network nodes and asked to mark the nodes with which they have relationships of interest to the researcher (this method of data collection is referred to as roster recall and is indicated in studies of complete networks with fewer than 100 nodes [6,18]). In addition to primary data, secondary sources can also be a source of data, where project information, depending on the project assumptions, can come from publicly available databases. The use of publicly available data is an important advantage of network analysis, reducing the costs of the data collection process and increasing the research possibilities. It should be emphasised that, regardless of the selection of data sources at the design and implementation stage of the data collection process, the choice of a particular type of data will determine the form of the relational matrix and, consequently, the type of network analysed [6,19].

c) construction of relational matrices, where the raw data is transformed into the form of relational matrices, which will then be examined. The data matrices can be created from the characteristics of the nodes to be analysed or include directly the relations-hips between the nodes themselves. Two types of relational matrices are mentioned, the use of which depends on the type of relational data collected and the way they are organised: (1) unimodal matrices (symmetric matrices with dimensions n x n, where n denotes the number of analysed nodes), (2) bi-modal matrices (asymmetric matrices with dimensions n x m, where n denotes the number of analysed nodes and m denotes the number of examined properties of these nodes; they are also called membership networks or bilateral graphs) [8,20]. Considering the cognitive value of the results obtained and the possibilities of performing transformations, bi-modal matrices are more valuable.

d) data analysis, where it is possible to use a number of different metrics, the use and scope of which depends on the level of analysis [6,21], the objectives of the study, or the specifics of the network studied. It is also possible to use a wide range of software to assist the researcher in processing the network data set and to visualise the analysed networks [22]. Computer support is possible for networks consisting of at least 25 no- des [23]. The network analysis can be carried out on the basis of a visual assessment of the sociogram, which should be the first step of the network study [6,24] and allows quick information on the number of elements and possible isolated nodes, as well as a preliminary assessment of the level of

density and centrality of the network. However, visual assessment should not be the only assessment made, as this limits the analysis and exposes the researcher to errors related to subjectivity. Hence, the use of structural measures appropriate to the study is indicated as the next step of data analysis, followed by the final step of network analysis.

e) interpretation of the results obtained with them.

Network analysis, depending on the assumptions of the research being conducted, can be carried out simultaneously at the three levels or separately at each of the three levels:

- analysis of the whole network: macro-level, the network is considered as a whole and its centrality and density are assessed, i.e. properties that are key primarily for the stability of the network; it is also possible to analyse the presence of periphery and core in the network. The measures used are useful for comparing different networks with each other, assessing the overall health of the network, managing network stability, collecting data used to guide the network and managing the information and knowledge flows that occur within it;
- analysis of sets of nodes: meso level, includes potential sub-networks/sub-groups that can be formed inside the network [6,25]. Subgroups are separated on the basis of: the similarity of arrangements and type of ties maintained by individual nodes (structural equivalence) and the ties existing between nodes (social cohesion). Here, the stability and cohesion of the network is assessed based on the existence and number of cliques, n-cliques, n-clans, k-plexes, n-centres and m-clusters present in the network. These measures make it possible to determine the degree of internal cohesion and integration of the network, or the division of the network into more internally coherent components. This analysis is cognitively valuable for the network as well as its individual members;
- analysis of individual nodes: micro level, the analysis of nodes is carried out using measures of centrality, (i.e. eigenvector, proximity, degree and agency), as well as individual density. These measures allow the assessment of the prestige and power of individual nodes, the identification of relationships that require monitoring (which can be caused by the rupture or occurrence of unintentional energy, material, information and social flows) and the identification of potentially closest and best cooperation partners [23,26]. Furthermore, they can be used to compare the position, importance and functions performed by individual members in inter-organisational networks, but it should be pointed out that such comparisons are methodologically justified only when considering networks of the same size [27].

The wide range of possible measures of network analysis influences the high applicability in the area of specific issues related to the management of inter-organisational networks (knowledge flow, manageability and stability) [6,28]. It can also serve to build the competitive advantage of the network as a whole and the cooperative advantage of its members. In addition, all the measures used within network analysis can be successfully applied to a variety of quantitative studies, and what is more, the possibilities of using network analysis in management science can go beyond the scope of research related to organisations, e.g. to be used in research on the development of management science, including bibliometric analysis [29].

A variety of network planning methods can be identified in the literature. These methods are shown in Figure 1.

3 Network methods

Among the most important are the CPM method and PERT [31]. The CPM is the so-called critical path method. This method is used for scheduling projects that are characterised by a determined duration of component tasks. The PERT method (Programme Evaluation and Review Technique), on the other hand, is used for scheduling projects that take into account the randomness of the completion time of the component tasks.

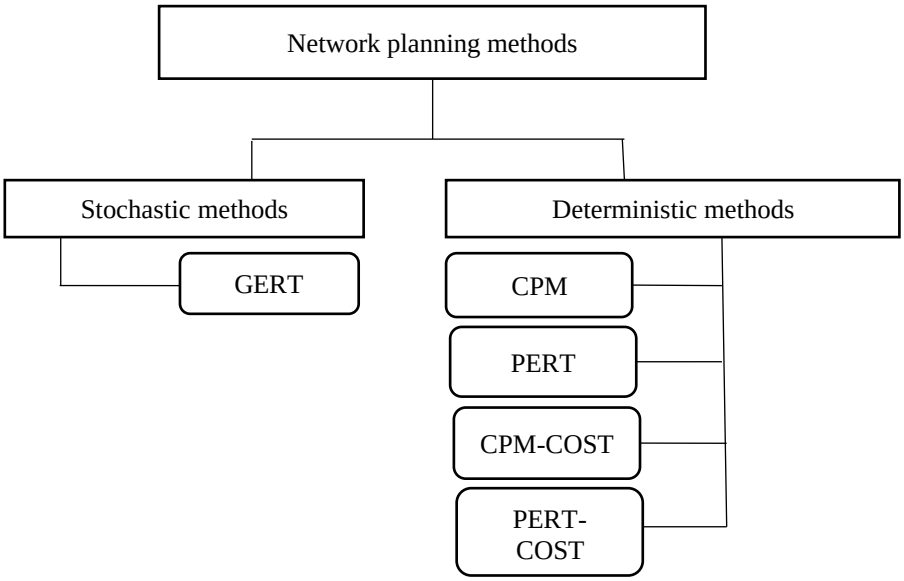

Fig. 1. Network planning methods

Source: own elaboration [30].

3.1 PERT method

The PERT method is a method that makes it possible to plan and control the execution of a project, taking into account that the durations of unique or atypical activities are not deterministically fixed. The PERT method is therefore based on the assumption that activity durations are random variables. This view of the issue of the duration of project tasks enables statistical methods to be used to assess the risk of completing tasks on time and to determine the probability of their completion within a specified time [32].

The PERT method, like the CPM method, presents the project as a network diagram, or so-called directed graph, and aims to determine the critical path of the project. The vertices of the graph in this case represent the tasks that make up the project, while the arcs (the connections between the vertices of the graph) represent the directed links between the tasks, to which the durations of the individual activities are assigned. An example of a graph in the PERT method is shown in Figure 2.

In order to implement a project using the PERT method, among other things it is necessary to:

- define all the activities of the project,
- determine the temporal implications of the activities of the project,
- estimate the duration of each activity of the project,
- determine the critical path,
- develop a timetable for the project,
- estimate and make adjustments in line with the actual situation.

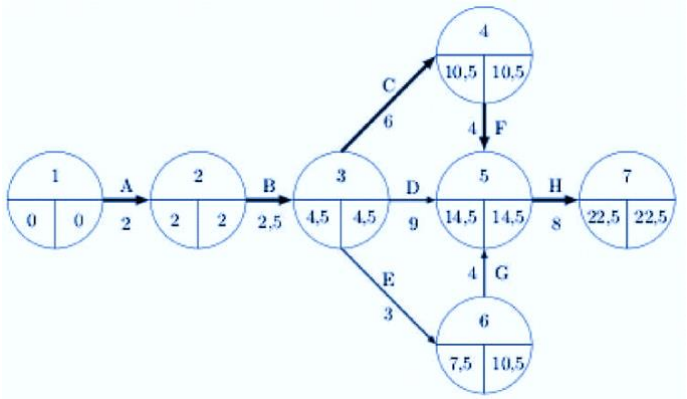

Fig. 2. Example graph in the PERT method

Source: own elaboration.

In the PERT method, the most important element is the estimation of the execution time of individual activities in the project. This estimation is possible based on formula 1.

$$t_a = \frac{a+4m+b}{6} \quad (1)$$

where: m-most likely duration of activity; a-optimistic , i.e. the shortest expected duration of activity; b-pessimistic , i.e. the longest expected duration of activity. On the basis of the time "ta" calculated in this way, the individual activities are calculated and the critical path of the project is determined. In this method, the standard deviation of the activity "s" is also determined, which is a measure of the degree of uncertainty in the estimation of time ta. The magnitude of "s" is determined based on equation 2.

$$s = \frac{b-a}{6} \quad (2)$$

if there are activities in the project that are performed at the same time, the standard deviation will be calculated for the activity with the longest duration. The next step of the PERT method is to determine the probability of not achieving the goals of completing the individual tasks of the project within the set time T and to determine the value of the 'z' factor for the tasks according to formula 3.

$$z = \frac{T-ta}{s} \quad (3)$$

where: T - is the set date for completion of the task; t - is the time ta.

Another element of the PERT method is the mapping of z-values to probabilities. This is done using appropriate curves, which are provided, for example, in mathematical tables.

As a result of applying the PERT method to project planning in a company, the following benefits can be obtained:

- the possibility to present a project in the form of a relationship graph, and thus to be able to present projects graphically, which are much more convenient and easier to read than, for example, bar charts,
- the development of a relationship graph requires careful consideration of the entire project, so we can be sure that the project has been planned meticulously,
- the determination of the critical path makes it possible to identify problems and disruptions to the project at an early stage of planning - corrective action can be taken,

- it allows comparisons to be made in terms of cost and time for different ways of running and achieving the project objectives.

However, the PERT method also has limitations, which include:

- this method does not make it possible to determine the types of risks that may arise, their scale, categories and signs because it focuses only on: the duration of the tasks,
- the use of the method when working on a large project is associated with high costs,
- the accuracy and thoroughness of the calculation is dependent on the skills of the staff carrying out the calculations.

3.2 CPM method

The CPM method is otherwise known as the critical path method. This method enables the planning and control of a project, taking into account the duration of the project and the possibility of predicting the effects that may result from changes in the course of project tasks.

The CPM and PERT methods are similar in terms of the results achieved, as well as the presented approach to variables such as financial resources, materials and machinery, equipment, as well as human potential, which are treated as immutable quantities during the project. The most important common feature of these methods is the determination of a sequence of tasks (activity networks) that limit the time of project realisation and which are called the critical path. The main difference between the two methods, however, is the way the network graph is constructed.

It is also important to note that there are variations of the CPM and PERT network methods that allow for the optimisation of the total cost of a project, for a pre-estimated duration, or the optimisation of the project lead time at a fixed cost. These variations are called:

- CPM-COST,
- PERT-COST.

Network methods use graphical symbols to represent the grid of relationships between tasks that need to be completed in order to complete a project, which illustrate concepts such as activity and event.

An activity can be defined as a sub-activity of an undertaking that consumes time and resources, e.g.: labour, materials, financial means, etc. An activity is represented by a symbol, such as an arrow. The duration of the activity is written above the arrow.

An event, on the other hand, can be defined as the point in time at which an activity can start and is conditional on the completion of a previous activity on the dependency graph. Only the first event does not have a preceding activity. An event is denoted by a circle symbol (it is treated as a node of the network). Events are numbered with natural numbers.

In network methods, there may be situations in which there are activities that do not need any input. These activities are called apparent activities.

The CPM method, follows specific stages. These stages include [29,33]:

- Summary of activities that make up the project.
- Determination of the duration of individual activities.
- Establishment of interrelationships between activities.
- Determination of start and end dates for the various activities.
- Identification of the resources required to carry out each activity.
- Identification of the costs associated with carrying out the various activities.

An example of a network graph used with the CPM method is shown in Figure 3.

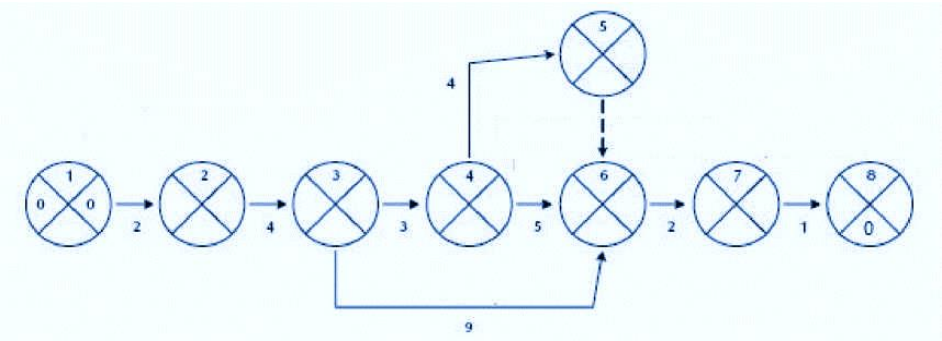

Fig. 3. An example of a network graph used in the CPM method

Source: own elaboration [34].

In the figure above, events are labelled from 1 to 8. This means that the project consists of 8 events and 9 activities, including an apparent one. In the top quarter of each event, the event number is entered. In the left-hand side of the quadrant, the earliest time the activity started is entered. In the right-hand section of the quadrant, the latest time the event ends is entered. The bottom quarter contains the remaining time.

The CPM method is a method that aims to streamline project delivery. It is used most often for planning repetitive projects. The method is a very popular tool for planning and controlling project implementation in Poland and has the following advantages:

- enables the planning and control of the course of the project,
- makes it possible to anticipate the effects of changes in the implementation of activities,
- enables the detection of bottlenecks in project implementation,
- enables the use of IT tools such as: MS Project,
- allows evaluation of the duration of individual activities.

However, this method does have some limitations:

- the method involves a significant amount of time and cost to prepare a project implementation plan,
- the method does not automatically solve problems,
- the method does not take qualitative problems into account.

3.3 The Delphi method

The increasing complexity and dynamics of the development of the management sciences has given rise to postulates related to methodological eclecticism and polymethodicity of management [35], as well as methodological triangulation [36]. The effect of meeting these postulates, which presupposed the need for diverse and mutually corrective and verifying research methods resulted in the development of the Delphi method [37].

The name of the method takes its origins from ancient Greece and the oracle located at Delphi hence the name Delphic oracle [38]. The priestess residing in the oracle (Pythia) predicted the future thanks to her ability to communicate with the god Apollo, who spoke through her.

Nowadays, the Delphi method is based on a far more rational, as well as scientific basis. However, the method is further linked to the prediction of the future [39]. The modern Delphic method was developed in the early 1950s. At that time, three basic foundations were developed on which to base prediction [40]:

- knowledge that is supported by incontrovertible evidence,
- speculation for which there is no evidence,

- opinions whose veracity is only indicated by some evidence.

Given these foundations of prediction, it can be concluded that the Delphi method is used to extract expert opinions, on the basis of which it seeks to build chances for solving problems and determining the likely future.

To be effective, the Delphi method must be carried out in accordance with methodological rigour and an appropriate research procedure [41]:

❖ Defining the methodological basis of the study, within which:
- research questions are developed,
- problem is formulated,
- research objectives and hypotheses are set,
- the choice of research methods, techniques and tools is justified,
- survey questionnaire is developed,
- pilot studies are carried out.

❖ Identification and selection of potential experts to participate in the study, as well as definition of the conditions for their participation in the study:
- defining the scope of the study in terms of subject matter and time,
- defining the rules of communication or remuneration of experts,
- selection of session administrator.

❖ Transmission of the survey questionnaire to the experts with the definition of the rules and the deadline for returning the questionnaire.

❖ Start of Round 1 of the survey, completion of the questionnaire by experts and return of the questionnaire.

❖ Analysis of completed questionnaires by the survey administrator.

❖ Sending to the experts a compilation containing the results of the first round of surveys and an anonymous list of comments and justifications for the answers chosen, as well as the questionnaire (modified if necessary) with comments.

❖ Start of Round II of the survey, re-completion of the questionnaire by the experts. Re-completion takes place after the experts are aware of the results of Round I.

❖ Analysis of the completed questionnaires by the survey administrator, resulting in the elaboration of results and modifications of the questionnaires, after which the survey rounds are repeated. These rounds can be several to a dozen until the required convergence of expert opinion is achieved.

❖ Development of a solution that was accepted by all experts involved in the study.

❖ Presentation to experts and those commissioning the study of its findings.

❖ Performance monitoring.

As can be seen from the study procedure presented, there is no direct communication between experts in the study. The main purpose of eliminating face-to-face communication is the desire to reduce its undesirable aspects [42]:

- the assumption of the existence of independence of opinions expressed by experts,
- the assumption of anonymity of the judgements made,
- the assumption of a multi-stage survey,
- the assumption of seeking to agree and aggregate the views of participants.

The above assumptions are the result of experiments conducted by the RAND organisation, which found that problem solving using a group of experts communicating directly is less effective than when direct contact is eliminated. The lower effectiveness of unifying opinions by experts in face-to-face communication was related to [29,43]:

- the existence of dominant entities that influence the other participants in the study,
- the existence of group disorder,
- in the case of shy people, there was group pressure that limited the shy person's judgements.

It is worth stating that, once the above problems have been eliminated, the method has many advantages. The advantages and disadvantages of the Delphi method are shown in the Table 1 below.

Table 1. Advantages and disadvantages of the Delphi method.

Advantages	Disadvantages
The ability to find a solution to a problem, under conditions of uncertainty or in the absence of empirical evidence	Dependence of results on the quality of the expert selection of the survey questionnaire
Creative synergies from combining the knowledge of many experts	High cost and time-consuming study
Iterative deduction and learning mechanism	
Autonomy of expert opinions	

Source: own elaboration on basis of [44].

As the Delphi method can be applied primarily to large projects, undertakings in large organisations, its main areas of use in management science can therefore include [45]:

- ❖ Business development issue - identifying and analysing factors that influence the development of an organisation or forecasting market trends.
- ❖ Problems in business management at the level of resources, processes or business functionality.
- ❖ In the case of links between the field of management and other areas of knowledge, i.e.:
  - risk management,
  - strategic management,
  - production management,
  - change management,
  - or human resources management,

4 Conclusion

The basic categories of network analysis are nodes and the relationships between them, whose arrangements are depicted in the form of sociograms and analysed using a wide range of structural measures. Measures of network analysis can be used to examine the network of all relationships maintained by members of a given market or sector and the network of relationships formed by a given node.

The popularity of network analysis in management science has been observed for a decade [46]. The method can be applied at different levels of management (from the interior of an organisation, to external relations, to the management of entire inter-organisational network structures) and in different areas [47]. Network analysis makes it possible to study and evaluate processes of inter-organisational learning, knowledge diffusion and transfer [6,48], and provides a wealth of management-relevant information on internal and external relationships, changes within the organisation, the boundaries of the organisation, the flow of communication, the distribution of power, the possibilities of intra- and inter-organisational flows or informal and formal leadership in teams. In addition, this approach can be a useful method of data collection and analysis for improving the organisation and enhancing its performance [49].

Selected PERT, CPM and Delphi methods can form the basis for building research and implementation processes.

The PERT method was developed to estimate approximate durations of tasks and to determine the probability of completing these tasks within the time required by the researcher. The PERT method was developed primarily for costly projects with a high degree of risk. Nowadays, it can be successfully applied to projects of much smaller scope.

The CPM method is geared towards determining the shortest time to complete a project and to ensure that it runs smoothly. CPM assumes that the duration of the individual tasks defined for the execution of the project is determined, i.e. strictly fixed [50].

The Delphi method is understood as a certain iterative way of collecting, compiling, analysing and interpreting empirical data in order to obtain maximally and optimally valid answers to the research questions posed [51]. The Delphi method is also sometimes defined in the literature as a method or technique based on a structured group communication process, which aims to ensure the effectiveness of a communication process involving a group of independent people aimed at solving the problem posed [52].

In conclusion, it should be noted that the above methods are widely used in modern research [53-133], mainly related to the management of sustainability and digitalisation of economic systems.

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