POLITECHNIKA LUBELSKA

Decision-making in construction project management

Problems and methods

Lublin 2017

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Introduction

Construction of engineering facilities is a complex undertaking and many factors influence its outcome. Construction is not conducted out in a factory under controlled conditions but in a dynamic environment where many risk factors are being and decisions made by the engineering team are crucial to the success of the project. Managing a construction project involves a number of tasks that require making many difficult decisions and solving problems by following the legal requirements. So, the success of a construction project depends on decision-making skills of the team that is involved in the planning, organization and execution of many different processes at the same time.

Project management is a branch of effective achievement of project goals while neutralizing the impact of existing constraints and risks. Therefore, one of the project management elements is the practical knowledge of eliminating the failure risk at the project life cycle level. The risk in the project is mainly due to the inability to eliminate uncertainty related to future events at every stage of the project resulting from the dynamics of communication between participants, the variable productivity of the project teams, misplaced planning and external factors.

The concept of project management is based on the 1940 "Manhattan" war project. The plan details were a mystery because it involved the construction of an atomic bomb. The methods that were used were further improved, disclosed during the "Apollo" and "Polaris" programs. Project management were developing through the launch of the American Marshall Plan – an aid program for Europe..

Construction project management can be defined as complex planning, coordinating and controlling of the project from the conceptual stage to completion, which aims at fulfilling customer requirements for a functional and financially viable project completed in a timely manner and in accordance with the required quality standards.

This book is an introduction to construction management practices, and aims to develop knowledge and understanding of construction managers responsibilities of making rational decisions. Construction industry is subject to specific constraints. Among others:

- The delivery of construction projects as well as roles and responsibilities of project participants are regulated by a set of specific laws and regulations.
- The construction projects are delivered by temporary organizations of a complex and hierarchical structure, therefore specific management methods need to be applied to reasonably delegate responsibilities and efficiently monitor the progress.
- The construction projects are affected by many risks that negatively influence duration and cost of works to the detriment of project efficiency.

- Managerial decisions need to be taken quickly, often without adequate information as project conditions dynamically change; they call for interdisciplinary knowledge and experience. Due to the complexity of the problems, the managers need to resort to heuristic and metaheuristic methods as well as simulation techniques.
- The decisions are of multi-criteria character. The clients and the contractors strive to maximize their profits, however, in long-term perspective, this means that many aspects of their service quality (among others, reducing environmental impact of their activities) need to be the focus to protect their position in the market.

The specific and risky character of construction projects is reflected in the selection of topics and the structure of this handbook.

This book is organized as follows. The first chapter is an introduction to the construction project and the construction organization. The basic concepts related to the management and life cycle of the construction project, have been explained.

Chapter 2 covers a description of the construction project management methodology using the PRINCE2 method. All the assumptions, roles and stages of the construction project have been presented.

The essence of management, which is decision making, have been discussed in Chapter 3. A scientific approach to decision-making is operations research that is aimed to support managerial problems solving. This part include methodology of operations research and introduction to multi criteria decision-making.

First part of Chapter 4 presents few multi criteria decision-making methods with examples of practical application in construction. Subsequently, construction project scheduling using the PERT method have been described, and finally, tools for project performance monitoring and prediction have been also presented. Discussed methods support decision-making in consecutive project stages.

Chapter 5 is devoted to risk management, which is as much about looking ahead to identify further opportunities as it is about avoiding or mitigating losses. The risk impact on project and the risk analysis methods have been described.

Currently one of the basic assumptions of modern construction is the reduction of negative impact on the environment and human health. Therefore, the last Chapter 6 deals with the topic of sustainable construction as the construction projects management aspiration.

The authors hope that this work will contribute to the deepening of the recipients knowledge, especially the construction engineers and civil engineering students of technical universities interested in modern methods of project management in the construction industry.

1. Construction project management in theory

1.1. Management

Management is defined as a set of functions (Fig. 1.1) directed at the efficient and effective utilization of resources in the pursuit of organizational goals. These functions are, classically (Griffin 2004):

- Planning (defining aims, objectives, and best methods of reaching the objectives, so determining what should be done and how best to do it).
- Organizing (or delegating; developing an organizational structure and allocating resources to ensure that objectives are achieved).
- Leading (motivating people to act and cooperate for the sake of the organization).
- Controlling (monitoring performance to provide input for corrective measures and to draw conclusions on results and learn from experience).

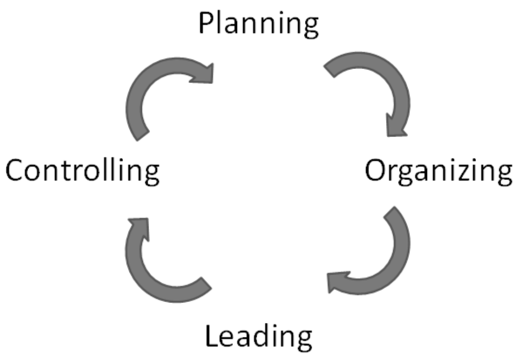


Fig. 1.1. Management functions

Management is conducted on two levels: strategic and operational. Strategic management determines long term objectives to be pursued by the organization and identifies the ways and means of achieving these objectives. It consists in creating complex highest level plans and setting objectives for the organization as a whole – facing opportunities and threats expected to arise over time, and concerning the organization's strengths and weaknesses. It focuses on the organization's resources, on its environment, and on its mission.

Operational management is aimed at individual organizational functions such as procurement, marketing, production, or sub function within them, for improving performance in accordance with the organization's strategy. It focuses on particular resources and particular actions to be taken within particular time horizon. It is concerned with ensuring that the day to day operations of the organization are carried out effectively and efficiently.

Major development in management science proceeds in three complementary directions (Hendrickson, 2008):

- The management process approach.
- The decision support approach.
- The behavioral science approach for human resource development.

The management process approach identifies and examines management functions (as described above) within an organization. By analyzing management along functional lines, a framework can be constructed into which all new management activities can be placed. With this approach, the manager's job is seen as coordinating a process of interrelated functions in a dynamically changing environment. The principles of management are claimed to be derivable from an analysis of management functions. By dividing the manager's job into functional components, principles based upon each function can be extracted and organized into a hierarchical structure designed to improve operational efficiency. The basic management functions are performed by all managers, regardless of enterprise, activity or hierarchical levels. The development of a management philosophy results in helping the manager to establish relationships between human and material resources. The outcome of following an established philosophy of operation helps the manager win the support of the subordinates in achieving organizational objectives (Hendrickson, 2008).

The decision support approach contributes to the development of quantitative methods to support complex decision-making process related to operations and production. It focuses on defining objectives and constraints, and on constructing mathematical models that facilitate solving complex problems such as inventory management or production scheduling to e.g. maximize profit, solve time-cost trade-off problems, or deal with finding best option in multi-criteria assessment. The optimization or sub-optimization often bases on operations research techniques, such as linear programming, graph theory, queuing theory, simulation, or artificial intelligence techniques. Management science and decision support systems have played an important role by looking more carefully at problem inputs and relationships and by promoting goal formulation and measurement of performance (Hendrickson 2008, Hillier and Lieberman 2001).

The behavioral science approach reflects the need of understanding the human factor: needs, drives, motivation, leadership, personality, attitudes, habits, pressures and conflicts of the cultural environment of people that affect operations of any organization (Griffin 1994, Hendrickson 2008).

Directions of changes in economic environment and intensified competition between organizations led to diversification of business models. This implied creation of numerous management concepts that focus on business aspects found critical for particular organization types, and on particular constraints affecting their operations. Some examples of the management concepts are:

- Total Quality Management.
- Lean Management.
- Reengineering.
- Management by Objectives.
- Competency-Based Management.
- Management by Projects.

Total Quality Management (TQM) focuses on providing the customer with quality (as satisfying the customer is a rationale for the organization's existence). Its origins are in late 1970s, in the times of the Western businesses losing competition to Japanese companies able to produce high-quality goods at competitive cost. In search for explanation of some organizations' failures, one concluded that to achieve customer satisfaction.

Lean management's aims are similar to TQM, but the focus is in waste elimination. Any non-value-adding processes in the organization should be tracked down and eliminated, and activities that cannot be further optimized within the organization should be considered for outsourcing.

Reengineering consists in introducing fundamental changes to the design of processes in the organization to achieve dramatic improvement of the organization performance. In contrast to evolutionary approach of TQM, the idea is to revolutionize procedures and organizational structures – to question all that has been established so far. This approach is meant for organizations that are seriously inefficient compared with their competitors, or threatened by changes in the market (such as shifts of customer requirements). The aim of reengineering is, like by previously mentioned concepts, eliminate non-value-adding activities, but its focus is on creative thinking and introducing a clear change.

Management by objectives focuses on human motivation to cooperate. It is claimed that nothing motivates better than having a deep understanding and agreement with the organization's objectives, so the objectives should be determined jointly by managers and their subordinates. Progress towards the agreed-upon objectives is periodically reviewed, end results are evaluated, and rewards are allocated on the basis of the progress. Management by objectives aims to serve as a basis for greater efficiency through systematic procedures, greater employee involvement and commitment through participation in the planning process, and planning for results instead of planning just for work. For practical reasons, the objectives should be arranged in order of their importance, expressed quantitatively, realistic, consistent with the organization's policies, and compatible with one another.

Competency-based management focuses on the most important resource of any organization – people. It consists in assessing the organization's human resources against competencies (and not on the tasks, jobs, trades or professions) needed to achieve organization goals and supporting the integration of human resources planning with business planning. Apart from recruiting, appraising, training and planning development of the employees, it focuses on adjusting and utilizing personnel competencies to meet the company's needs.

Management by Projects is a strategy for project-oriented organizations. A dictionary definition of a project is *a piece of planned work or an activity that is finished over a period of time and intended to achieve a particular purpose* (Cambridge Online Dictionaries, 2015). Project-oriented companies carry out small and large projects, internal and external, to realize their strategy, cope with new challenges and potential in a dynamic business environment. The projects approach takes trained managers, allocates a restricted number of clearly defined responsibilities together with the resources and authority to achieve those responsibilities, and gives complete control over the method by which the results are delivered to the project management team. The project-based approach will be explained further in the chapters to follow.ion the organization should develop a corporate culture empowering and motivating organization members to introduce continuous and systematic improvements to work processes, to cooperate and learn. The idea was that, with small evolutionary steps, the organization should be able to respond to changing requirements of its customers, to eliminate waste, and improve productivity. However, to introduce order in these changes, to be able to check if they work, a thorough system of quality checks needed to be introduced. The concept has grown its set of tools and techniques to control quality, find non-value-adding activities to be eliminated, to communicate within the organization, and to motivate employees.

1.2. Projects

As mentioned above, a project can be defined as *a piece of planned work or an activity that is finished over a period of time and intended to achieve a particular purpose* (Cambridge Online Dictionaries, 2015). Another definition may better reflect the fact that projects are typically aimed at providing economic benefits, and not just completing tasks: *a project is a temporary organization that is created for the purpose of delivering one or more business products according to an agreed business case* (OGC 2009). This clearly presents the point of view of the project owner.

The literature on the subject defines a set of qualities that distinguish projects from other types of organized human activity (OGC 2009, PMI 2009, Burke 2003):

- They introduce a change.
- They are temporary (so have a start and finish).
- They are cross-functional (engage purpose-created teams of specialists of different backgrounds and originating from various organizations that temporarily work together).
- They are unique (conducted under case-specific constraints, in specific environment and location, by a team that may have never met before and may never come together again).
- They are related with uncertainty (the qualities mentioned above make the results of a project unsure; projects are considered more risky than other types of business activities).
- They have a life-cycle composed of distinct phases, filled with unique and non-repetitive tasks.
- They have a budget with associated cash flows.
- They have a single point of responsibility (so the project manager).
- They require that team roles and relationships are defined and updated as the project develops.

1.3. Project management

Project management is the art of directing and coordinating human and material resources throughout the life of a project by using modern management techniques to achieve predetermined objectives of scope, cost, time, quality, and client satisfaction. It consists in applying skills, knowledge, tools and techniques in the course of the project to make it bring expected results (PMI 2009).

According to Prince2 methodology of managing projects (OGC 2009), there are six interrelated project variables that need to be managed, called also six performance targets. If the project is to bring expected results, the manager needs to find a right balance between them in a naturally changing project environment. These variables are listed in Fig. 1.2.

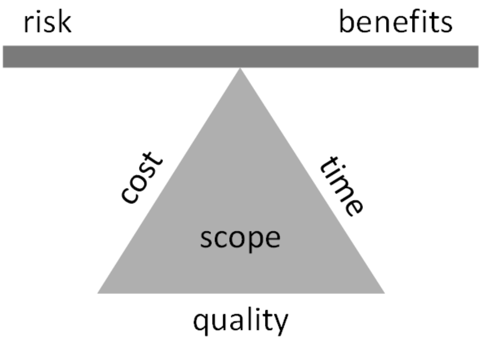


Fig. 1.2. Project performance targets

The **scope** is all the project is to deliver – and this needs to be clearly defined. Managing the scope consists in determining a set of all necessary products to be delivered or tasks to be completed, to make the project reach its aims. Its basis is the specification of requirements created in the initiation phase. The scope, once defined, is broken down into smaller components (e.g. products or processes) easier to be managed. As the project environment is dynamic in its nature, changes to the scope may be necessary. It is possible that some components need to be added or eliminated, and some have to be replaced to keep the project justified and worth continuing. To cope with such changes, the manager needs to monitor the project development and accordingly update plans. Changes to the scope usually affect the project's time and budget, and have a profound impact on the benefits (so the project's aims).

The **cost** is closely related with the economic justification for the project. Any decision taken in the course of the project should be considered in terms of cost, so that the required value for money is achieved, a good balance between cost of project components is maintained, and the project stays affordable and within agreed cost limits (Seely 1996).

The **time** of delivering particular products of the project and finishing the project as a whole has a profound impact on the benefits the project is expected to bring. As the project is usually to fit within other activities of organizations involved in it, it needs to progress as planned. Delays may be as inconvenient as delivering with advance.

Quality is the degree to which a set of inherent characteristics of a product, a person, a process, a service, or a system, meets expectations or fulfils a set of requirements (OGC 2009). Considering the scope of a project as a sum of its product, the manager is required to assure that their quality is as desired (stays within predefined limits). Delivering the products defined in the scope, and doing so within budget and on time is not enough, if they are not fit for purpose.

Risk in uncertain event that, if occurs, will have an effect on the achievement of project objectives. A risk is measured by a combination of the probability of a perceived threat or opportunity occurring, and the magnitude of its impact on the objectives. The risk management's aim is to assure that uncertainty does not deflect the project from its business goals. Unexpected occurrences are likely to impact quality, time, cost, and scope of the project, and even call the point in completing project into question.

Benefits are what justifies the whole undertaking. As most benefits tend to realize after the project is over, it is important to keep them in focus throughout the project and check if, and how, they may be affected by the other variables.

The purpose of project management in the construction industry is to add significant and specific value to the process of delivering construction projects. This is achieved by applying a set of generic management principles throughout the project lifecycle. Some of them are specific to the construction industry, but most of them are applicable to any type of projects, regardless of their being related to certain branches of industry, commercial or non-commercial activity (CIB 2010).

1.4. Construction project life cycle

The project life cycle is a set of phases, typically sequential, where the prior phase is essentially complete before the beginning of the next phase. The first phase is typically devoted to deciding that the project is worth starting, then come phases that consist in project preparation and planning, followed by execution and project close-out.

According to the Chartered Institute of Building (CIB 2010), the construction project's lifecycle comprises the following stages:

- Inception.
- Feasibility.
- Strategy.
- Pre-construction.
- Construction.
- Engineering service commissioning.
- Completion, handover and occupation.
- Post-completion review and project close-out report.

The project starts with the **inception stage** that leads to the client's business decisions that a potential construction project is the best way of meeting a defined need. A business case is prepared, so the justification for the project, which typically contains costs, benefits, risks and timescales, and against which continuing viability can be tested. In the stages to come, whenever there is a change in the project environment, its effects should be juxtaposed with the business case to check if the benefits still exist within the expected constraints. At this stage, a project manager is commissioned.

The **feasibility stage** specifies crucial objectives and constraints of the project in enough detail to make the options of for achieving the objectives possible to be assessed. These objectives and constraints are described by the project's **outline brief**. There are usually a number of ideas how these objectives can be met, so the best option is to be selected, and its **technical and financial feasibility** are to be proved.

Feasibility analyses are presented in reports that usually include summary of the outline brief (as a starting point), studies on requirements and risks, environmental impact assessment, public consultation, study on legal requirements and constraints, estimates of capital and operating expenditures and receipts, and funding issues.

Selection of the best option, in the case of construction projects, means defining such project characteristics as function (in detail), location, timescale and budget. On this basis, site can be selected and acquired, and **detailed project brief** prepared to serve as a basis for detail design brief – a key set of design requirements (CIB 2010).

The next stage is the **strategy stage** aimed at setting up the project organization, establishing procurement strategy and commissioning/occupation issues through identifying project targets, assessing and managing risks and establishing the project plan. At this stage, control systems are designed to enable the manager to control value from the client's point of view, monitor financial matters that influence the project's success, manage risk, make decisions, and manage project information (CIB 2010).

The **preconstruction stage** covers design and further planning. At this stage, statutory approvals and consents are obtained, contractors and suppliers are selected and included into the project team. At this stage the client expects to finalize the project brief with the project team, identify and agree the solution that gives optimum value, and to ensure a detailed design which can be efficiently delivered with predictability of cost, time and quality. Completion of this stage provides all the information needed for construction to begin (CIB 2010).

The **construction stage** is when the built facility is produced. The complex nature of modern built facilities and their close relationship with local conditions of the site means that problems are to be expected – and they must be promptly solved. Information systems are tested to the full, design changes have to be managed, and construction and fitting out teams have to be brought into the team and empowered to work efficiently. Costs have to be controlled and disputes resolved without compromising the value and quality delivered to the client (CIB 2010).

The **engineering services commissioning stage** has been distinguished because of complexity and sophistication of modern engineering services. Each system being a component of the built facility needs to be tested and tuned before the client takes over the completed built facility (CIB 2010).

The **completion, handover and occupation stage** consist in preparing the complex facility to be handed over to the client. The process of testing and checking needs to be prepared, the client needs to be given full information and documents on their new assets, and the users need to be taught how to use the facility. This stage is to assure that the client accepted the project's products and outcomes, and that the project organization is prepared for remedying defects and responding to any unsolved issues (CIB 2010).

The final stage is the **post-completion review and project close-out report stage**, when feedback is collected and effects of the project are assessed. Experience is transferred back to the project organization, which will help future project teams. To facilitate this process, formal reports are often prepared (CIB 2010).

1.5. Impact of construction process regulations

Construction projects consist in delivering capital assets – expensive, custom-made, immobile, durable, consuming large quantities of material resources ad affecting the environment for many years.

For this reason, the number of project stakeholders is considerable. The stakeholders are people and organizations interested in the project, affected by it directly or indirectly, and able to influence it; in general, these are project users, sponsors, members of the project team, and the public. The stakeholders need to be carefully defined with respect to their expectations and ability to impact the project.

Moreover, the built facilities are constructed on site – under impact of natural conditions that are difficult to control, with many processes still done by hand. This makes them specific and prone to specific risk.

Apart from technical and organizational challenges the construction projects pose, they are subject to many regulations that are country- and location-specific. These must be accounted for while planning, as they imply mandatory tasks related with e.g. obtaining permits and approvals. Such tasks need to be completed in a predefined sequence, and they require preparing specific reports and designs. Moreover, the duration of administrative procedures is considerable, and they may impose restrictions on the project development.

To illustrate the impact of regulations on the construction project development, a rough overview of Polish administrative procedures is presented in Table 1.1. It is worth considering, that some procedures take long time. The procedures are to protect the environment and the public, and thus some project stakeholders are entitled to express their objections to the projects – thus blocking project progress for many months. This is possible in the process of issuing the environmental decision, the decision on planning conditions, and the decision on construction permit.

Tab. 1.1. Selected Polish administrative procedures in construction

Is the location suitable for the project? What can be built? What constraints on design?		
Environment	For some projects, environmental decision is not required. This depends on function, scale, and location.	If environmental decision is required, one can optionally apply for definition of the scope of environmental impact report – decision within 2 months. To apply for environmental decision, one presents a report on environmental impact of the project. Decision is issued within 2 months, 1 month for the administrative decision to become valid.
Land use	If a local Spatial Development Plan (SDP, act of local law) is present, it is enough for a copy of the plan and comply to it while preparing designs. A copy is provided by a local authority within 1 month, usually much faster.	If there is no SDP, one has to apply for planning conditions. Required input includes description of the project (with technical details and requirements towards technical infrastructure) and valid environmental decision (if required). Decision is issued within 2 months, with possible suspension up to 9 months or longer (if SDP in preparation), plus1 month for the administrative decision to become valid.
Administrative checks before commencement with works		

Construction permit	Some small project (like individual houses) require no construction permit, but notify the authority providing design with approvals (a broad list of approvals depending on function is defined in many legal acts),declaration of the rights to the land, and **valid planning decision** (if applicable). If no objection of the authority is expressed within 1 month, the project is allowed to proceed.	Most projects require a construction permit. Application must include the design with approvals, declaration of the rights to the land, **valid planning decision** (if applicable), and **valid environmental decision** (if applicable). Decision issued within 2 months, plus 1 month for the administrative decision to become valid.
Notification on commencement with works	Local Building Control Office and Labour Inspectorate must be notified on commencement with works. Information includes personal details of engineers supervising the works and declaration that construction health and safety plan was prepared.	
Administrative checks on completion and occupancy permit		
Notification on completion (1)	If the project requires occupancy permit or if the design was required to be consulted with sanitary or fire protection specialists, one needs to notify Sanitary Authority and State Fire Service on completion. If no objection is expressed within 2 weeks, the next step can be taken.	
Notification on completion (2)	Notification on completion – for projects that require no occupancy permit – must be delivered to local Building Control Office with a set of documents. If no objection is expressed within 2 weeks from receiving the notification, the built facility can be used.	Application for occupancy permit must be delivered to local Building Control Office with a set of documents. A compulsory inspection will be conducted within 3 weeks. Occupancy permit is issued after the inspection, within 2 months.

2. Project Management Methodology

Project Management Methodology is defined as combination of logically related practices, methods and processes that determine how best to plan, develop, control and deliver a project throughout the continuous implementation of processes until successful completion and termination. It is a scientifically-proven, systematic and disciplined approach to project design, execution and completion.

A traditional approach involves a series of consecutive stages in the project management process. It is a sequence step-by-step of design, develop and deliver a product or service. It entails achieving the success of the implemented process and provides the benefits of milestone-based planning and team building. In IT and software development, this methodology type is called "Waterfall" – one portion of work follows after another in linear sequence.

The following stages are included the traditional project management methodology:

- Initiation (requirements specification).
- Planning and design.
- Execution (construction and coding).
- Control and integration.
- Validation (testing and debugging).
- Closure (installation and maintenance).

Modern methodologies do not focus on linear processes but they provide an alternative look at project management. The Project Organization is a very important part of Project Management Methodology.

There are four levels of a Project Management Structure (also called "Project Organization"), (Fig. 2.1). The Project Management Team has three levels. The top level is the Project Board level and the lower level is the Team Manager level. The project team is a temporary structure. It is created for the project and disbanded when the project is completed.

At the top of the Project Management Structure, is the Corporate or Programme Management Level. This level is outside the project, so they do not participate in the project and therefore not a part of the project team. More and more companies have PMO's, which stands for Programme Management Office, and can also have other names like Programme Office and Project Office.

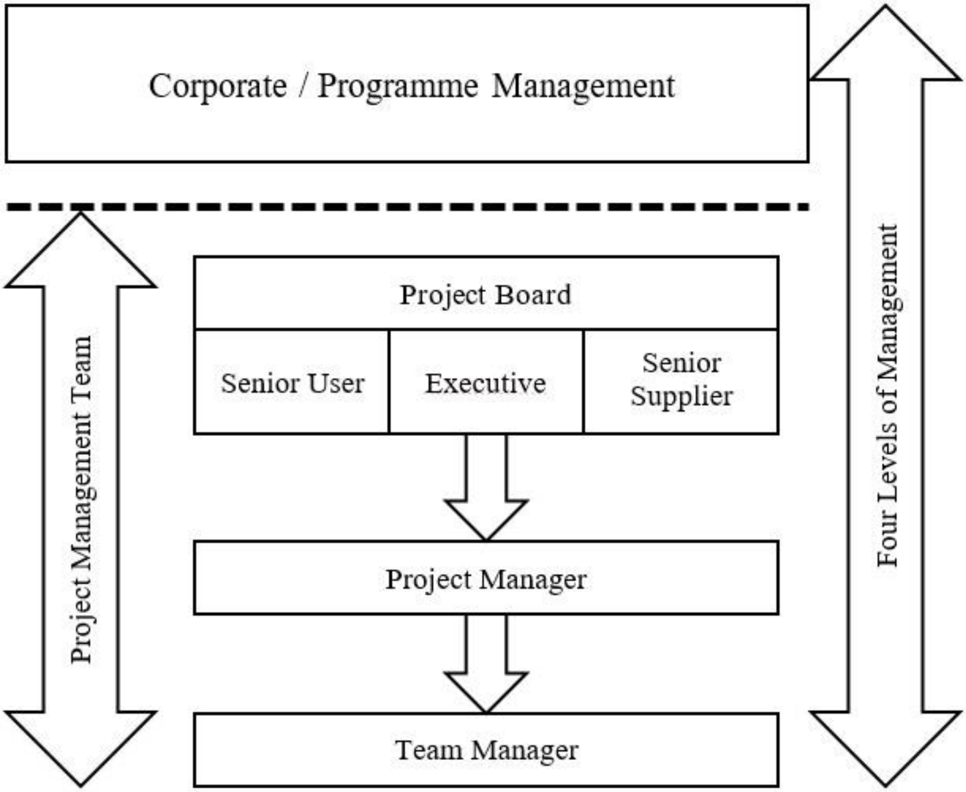


Fig. 2.1. Project Management Structure / Project Organization

The Project Board is responsible for the project success and have the necessary authority to take decisions and approve all major plans for the project. They approve the completion of each stage and authorize the start of the next.

The Project Board has three Roles, which are: The Executive, The Senior User and The Senior Supplier.

- The Executive is the main person responsible for the project, and is supported by the Senior User and Senior Supplier. The Executive represents the business interests of the project and owns the business case. The role of the Executive gives a single point of accountability for the project. Usually the Executive is responsible for designing and appointing the project management team, including the rest of the Project Board and Project Manager.

- The Senior User represents the user interests and is responsible for the specification. They specify the needs of the users and check that the final products meet the required specification. Their main concern throughout the project is “Will it work?” The Senior User also specifies the expected benefits at the project start and reports to the project board the benefits that are being realized during the project.
- The Senior Supplier represents the interests of entities designing, developing, facilitating and implementing the project’s products. Their main concern throughout the project is “Can it be done?” and whether it can be done within the agreed time, cost and quality requirements.
- The Project Manager is appointed by the Executive with approval from Corporate or Project Management. The Project Manager runs the project on behalf of the Project Board on a day-to-day basis and has the responsibility for create the products to the required quality within the specified time and cost.
- There are many different facets of project management role, such as Communication – in fact, it is estimated that more than 70% of a project manager’s time is spent on Communication, but also on Cost Management, Quality, Product Status, Changes, User Needs, Monitoring and Planning.
- The Team Manager has the responsibility for produce the products which were assigned in work packages by the Project Manager, and to provide regular status reports on their progress. This allows the Project Manager to monitor their work. The Team Managers create their own team plans to manage the development of the assigned products. For small projects, the Team Manager may not be required, so the team members will report directly to the Project Manager.

2.1. The PRINCE2 Process Model

One of the methods for project management is PRINCE2. PRINCE2 is a process-based approach for project management providing an easily tailored and scalable method for the management of all types of projects. Each process is defined with its key inputs and outputs together with the specific objectives to be achieved and activities to be carried out.

PRINCE2 (an acronym for PRojects IN Controlled Environments) is a de facto process-based method for effective project management. Used extensively by the UK Government, PRINCE2 is also widely recognized and used in the private sector, both in the UK and internationally. The PRINCE2 (Fig. 2.2, 2.3) method is in the public domain, and offers non-proprietorial best practice guidance on project management.

Key features of PRINCE2:

- Focus on business justification.
- Defined organization structure for the project management team,
- Product-based planning approach.
- Emphasis on dividing the project into manageable and controllable stages.

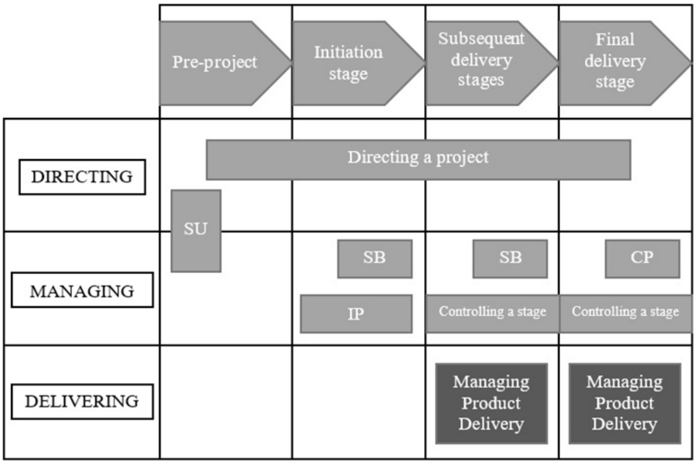


Fig. 2.2. The PRINCE2 Process Model, where SU – Starting up a Project, SB – Managing a Stage Boundary, IP – Initiating a Project, CP – Closing a Project

The PRINCE2 Process Model shows three Management Levels.

Level 1: Directing.

The Direction or "Directing" Level is where the Project Board work. They interface often with the Management Level and provide the above level with a number of notifications. There are three notifications shown in the process model diagram.

Level 2: Managing.

The next level is "Management" and it is where the Project Manager works. It contains most of the activities and processes, such as Initiating a Project and Controlling a Stage. So this diagram shows that most of the management activities for a project are done by the Project Manager.

Level 3: Delivering.

The lowest level, "Delivery," is where the project's products are created. All the products created above the Delivery level are created just to manage the project, e.g.: Project Plan, Project Brief. These are also known as management products.

All the products created in the Delivery level by the teams are the products users want from the project. These products are the reason why the project was started. These are known as specialist products.

Full version of the PRINCE2 Process Model is shown on Fig. 2.3.

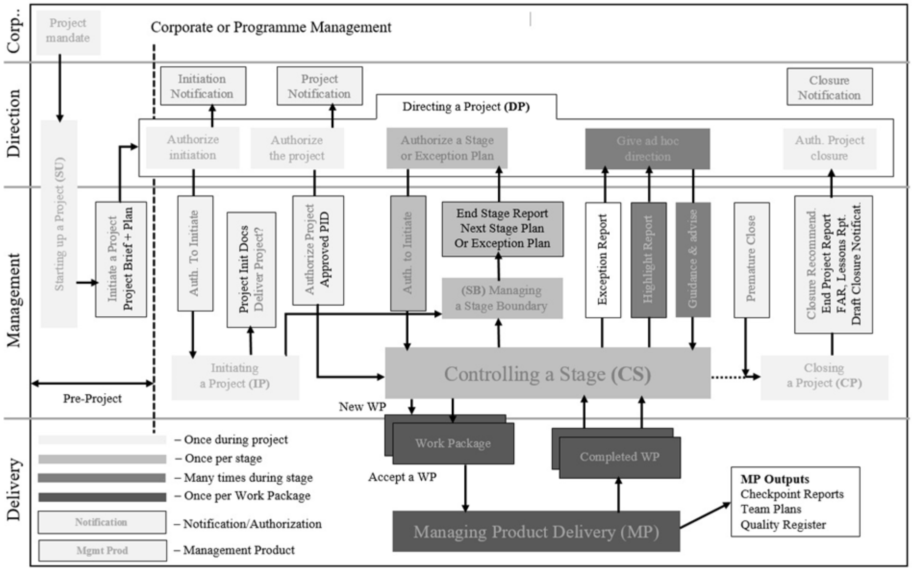


Fig. 2.3. The PRINCE2 Process Model

2.1.1. Pre-Project / Project Mandate

A project mandate comes from a senior person in the organization. It may be referred to as a Project Request or a Project Proposal, but the PRINCE2 name is Project Mandate. Sometimes a project mandate can be just a command, an email or a memo, but it should eventually become a structured document and contain the necessary information to help start the Project.

<u>The project mandate</u>

The project mandate can have a number of formats; it can be just a command, a one-page memo or a ten-page document. The PRINCE2 manual states that the project mandate should identify the Executive and Project Manager. The project mandate may not necessarily be a document. Other information that may be included in a project mandate is:

- The Main Objective of the Project.
- The Business Case, which describes the reasons for the project.
- Project Scope in high-level terms.
- Customers’ quality expectations.
- Information about the customer, e.g.: best practice for documenting requirements.
- Information on related projects that may provide important feedback.

Starting Up a Project (SU)

The Starting up a Project process has three main deliverables:

- The Project Brief, which includes an outline of the Business Case.
- The Design and Appointing of the Project Management Team.
- The Initiation Stage Plan.

The Starting up a Project process can be short. Its goal is to provide a structure to get the project off to a good start; it is made up of six activities:

- Appoint the Executive and Project Manager.
- Capture Previous Lessons e.g.: from other projects.
- Appoint a Project Management Team.
- Create an Outline of the Business Case.
- Select the Project Approach and assemble Project Brief.
- Create a plan for the Initiation Stage.

The Starting up a Project process can be describe in follow way:

- Appoint the Executive and Project Manager – this is done by the Corporate or Programme Management. It makes sure that the best possible persons are selected and all sides have agreed on related responsibilities and job descriptions. The Executive and Project Management will take immediate ownership of the project.
- Capture Previous Lessons – the project must learn from previous projects, other people and other sources. This is a very important point in PRINCE2 and its even one of the seven principles. The Project Manager will add useful lessons / advice to the Lessons Log for use in this project.
- Appoint a Project Management Team – the Project Manager will create the Roles and Responsibility descriptions, including the estimated effort required for each role. The Executive will appoint the persons.
- Outline the Business Case – the Executive creates an Outline of the Business Case. The Business Case is a very high-level document and will be expanded later into a full Business Case. For now, it addresses value for the business, company objectives, and funding & risk information. Also in this activity, the Project Manager creates the Project Product Description to describe the main output of the project.
- Select the Project Approach and assemble Project Brief – the Project Manager examines how best to approach the project, using all available knowledge, and also assembles the Project Brief document. There will be more about this later.
- Planning an Initiation Stage – the Project Manager creates a plan for the Initiation Stage, which will be the first stage of the project. This plan will be detailed enough to be used as a day-to-day plan by the Project Manager. It will include information such as objectives, deliverables, cost and time. The Executive will appoint the persons role.

2.1.2. Initiating a Project Process (IP)

Initiating a Project process refers just to the process "Initiating a Project." Initiation Stage is bigger and refers to all the work that has to be done in the Initiation process and the first Managing a Stage Boundary process.

As shown in diagram (Fig. 2.2), the Initiating a Project (or IP) process is triggered by the Project Board. This IP process is usually short, especially when compared to the rest of the project. But it is perhaps the most important stage, as it describes what has to be done by the project and therefore should not be rushed.

The purpose of the IP process is to understand the work that needs to be done to deliver the required products and to produce the project plan. So there are a number of good questions to ask about the project and these are the most common:

- What are the reasons for doing the project, the benefits and risks?
- The scope – what is to be done and not to be done?
- When can products be delivered?
- How to ensure that quality will be achieved?
- How risks, issues and changes will be identified and followed up?
- How PRINCE2 will be tailored to suit the project?

Initiating a Project Process consist of 8 Activities:

- Prepare the Risk Management Strategy – this will define how to manage risk during the project.
- Prepare the Configuration Management Strategy – this will define how to manage the products produced during the project.
- Prepare the Quality Management Strategy – this will define how to ensure quality during the project.
- Prepare the Communication Management Strategy – this will define how and when the project will communicate to stakeholders.
- Set Up Project Controls – this will define how the Project Board can control the project and how the Project Manager can control the work done by the teams.
- Create the Project Plan – this covers cost, timescale, risks, quality plan and deliverables.
- Refine the Business Case – this means to complete the Business Case document.
- Assemble the Project Initiation Documentation – this is to collect and assemble documents and information from the documents created so far in the SU and IP processes.

The Project Initiation Documentation is a collection of most of the documents produced so far in both the SU and IP processes.

First of all, there is the project approach and project definition, which contains a lot of information about the project and is extracted from the Project Brief:

- The Project Management Team Structure which includes the Roles Descriptions.
- The Business Case which includes time and cost information from the project plan.
- The four management strategy documents which are Quality, Configuration Management, Risk and Communications.
- The Project Plan which contains information on timescale, cost, resource requirements, products that will be produced, risks, tolerances, controls and quality.
- The Project Controls document which describes how the project will be monitored and controlled, tolerances between the different management levels, and the number of stages.
- How PRINCE2 was tailored to suit the project.

2.1.3. Subsequent delivery stages

Stage Boundary (SB)

Managing a Stage Boundary (SB) after the Initiation Stage is the first Managing a Stage Boundary process and it is normally performed after each Controlling a Stage process or each stage.

The objectives for the Managing a Stage Boundary process are:

- To assure the Project Board that all products in the Stage are produced and approved.
- If it is a large project you can create Lessons Report from the lessons log (optional).
- Create the End Stage Report, to show what has been completed in the current stage compared to the Stage Plan.
- Create the Next Stage Plan.

The main inputs are:

- The Project Initiation Documentation to compare with Initiation Stage Plan.
- The Initiation Stage Plan.
- And of course, all the register files (Quality, Issue, Risk).

The Stage Boundary's outputs are:

- The End Stage Report (a report on the stage just completed, the Initiation Stage).
- The Next Stage Plan.

Authorize the project (DP)

Authorize the project is the 2nd control point and 2nd Activity for the Project Board. The end of the Initiation Stage is the trigger for the "Authorize the project" activity. The Project Board confirms the project's objectives and the scope is clearly defined and understood. They can decide to stop the project, ask for further information, or give authorization for the project to continue.

The "Authorize the project" activity has the following input and outputs.

Inputs:

- Project Initiation documentation.
- Request to Deliver a Project.

Outputs:

- Authorization – authorize the Project so the project can start.
- Approval – approve the Project Initiation Documentation.
- Notification – to the Corporate or Programme Management that the project has started.

Controlling a Stage (CS)

The trigger for the "Controlling a Stage" process comes always from the Project Board Activity "Authorize a Stage or Exception Plan". A Work Package contains information on one or more products to be developed which includes such information as product descriptions, planning data, and constraints. This becomes the agreement between the Project Manager and the Team Leader.

Managing Product Delivery (MP)

The objectives of Managing Product Delivery are to:

- Agree on the details of the work to be done between the Project Manager and Team Leader, and make sure that the Team Leader understands what they need to deliver.
- Do the Work: meaning the Team Manager manages the development of the products and takes the necessary steps to ensure quality for each product.
- Provide regular progress information to the Project Manager using Checkpoint Reports.
- Handing back the completed work to the Project Manager and obtaining approval for each product after the work is done and quality has been checked.

The Managing Product Delivery process can have four outputs, which are: The Team Plan, The Checkpoint Reports, the Quality Register and Completed Work

- Team Plan: This plan is prepared by the Team Manager in the activity "Accept a Work Package" and is used to plan the work that will be carried out by the team members.

- Checkpoint Reports: These are reports from the Regular Team Meetings led by the Team Manager and are given to the Project Manager.
- Quality Register: The Quality Register is updated as each product is tested after development by the testers. The Quality Register is also used by the Project Manager to check on progress.
- Completed Work Package: This is the name given to the group of completed products that are handed back to the Project Manager.

Controlling a Stage (CS)

The Controlling a Stage process has two main outputs, which are inputs to the Project Board Activity "Give ad hoc direction". These are the Highlight Report and the Exception Report. There is also one input from the Give ad hoc direction activity, which is "Guidance and Advice." Here is a bit more about these.

The Highlight Report:

- This is a regular report on the stage progress. It is created by the Project Manager and sent to the Project Board on a time-driven frequency, e.g.: every two weeks.
- The report provides a summary of the stage versus the stage plan, and also information on tolerances, potential issues, products completed, next work packages and corrective actions.

The Exception Report:

- This report is only created if the current stage will not finish according to the plan and within tolerances, so the Project Manager must alert the Project Board.
- The Exception Report provides an overview of why the stage will most likely go out of tolerance, and then includes different options to get the project back on track. It also assesses the impact on the business case, as this issue will most likely increase the cost of the project.
- The Project Manager recommends one of the options in the Exception Report to the Project Board.

Project Manager Day to day activities (CS)

There are eight activities in the Controlling a Stage process. They are divided into three parts that also describe what the Project Manager does:

- Deal with Work Packages.
- Do Monitoring and Reporting.
- Deal with Issues.

The Work Package activities are:

- Authorize a Work Package – meaning assign and agree with the Team Manager so that the Team Manager knows what to do and can create their team plan.

- Review Work Package Status – check on work package progress, so read Checkpoint reports and check the Quality Register.
- Receive Completed Work Packages – which is to receive the completed products back from the Team Manager and confirm that they have been quality-checked and stored, as described in the configuration management document.

The Monitoring and Reporting activities are:

- Review the stage status – continually compare the stage status to the stage plan – checking if the stage is still on track and if anything is likely to affect this.
- Report Highlights – create regular reports to the Project Board to let them know how well the stage is going according to the plan.

The Issue activities are:

- Capture and examine issues and risks – any person can raise an issue and the Project Manager must gather and review them. Reviewing also includes categorizing and assessing the impact of each issue.
- Escalate issues and risks – if there are issues to report or if the stage is expected to go out of tolerance, then create an Exception Report and send it to the Project Board.
- Take corrective action – normally, Taking Corrective Action is used when extra work has to be done to solve an issue and the stage can stay within tolerance.

Managing a Stage Boundary (SB)

The Managing a Stage Boundary process provides information to the Project Board about the current status of the project at the end of each stage. This process happens after all the work in the current stage plan has been completed and before the next stage can begin.

The objectives of the "Managing a Stage Boundary" process are:

- To confirm to the Project Board which products have been produced in the current stage as documented in the stage plan, and also update the Project Plan to show what has been done so far and forecast the planning for the next stage.

To provide the Project Board with information so they can:

- Assess the viability of the project – meaning checking that it still worth doing.
- Approve Stage Completion – which is to approve the stage (that was just done).
- Authorize the start of the Next Stage.

The main outputs of Managing a Stage Boundary are the End Stage Report, the Next Stage Plan and the update to the Project Plan and Business Case. The Exception Plan will be created instead of the Next Stage Plan:

- The End Stage Report provides a detailed report on the results of the current stage by comparing the performance of the stage to the original stage plan used at the beginning of the stage.
- The Next Stage Plan is a detailed day-to-day plan for the next stage and needs to be approved by the Project Board.
- The stage plan for next stage is created near the end of the current stage, so this means that the Managing a Stage Boundary process starts before the end of the Controlling a Stage process.
- The Project Plan is updated to incorporate the actual progress from the current stage, and it should also include the forecast planning for the next stage and should update time and cost data.
- The Business Case – the end of each stage is a good time to update the Business Case and check if the project is still viable and worth doing. The Project Board is also interested to know that the benefits of the project can still be realized within the agreed parameters, which are time, cost, quality, risk and scope.
- The Exception Plan – this plan is created only when the current stage goes beyond its tolerance level (e.g.: taking 15% longer than planned), and the Project Manager must therefore get authorization to complete the current stage.

Authorize a Stage or Exception Plan (DP)

The Authorize a Stage or Exception plan activity is another important control point for the Project Board. They will review the data provided by the Project Manager and decide if the project should continue to the next stage.

The Project Board will therefore do the following:

- Compare results of current stage against stage plan.
- Check performance of project to date (they can use the baselined project plan for this).
- Evaluate the next stage plan.
- Check the risk summary.
- Review the Business Case (they will check if the Business Case is still valid).
- Check that lessons are being learned and that they are used in future stages.

They can choose to give approval for the next Stage Plan. This is the Authorization for the next stage to begin or approve the Exception Plan.

2.1.4. Closing a Project (CP)

Normally a Project closes after all the products have been produced and delivered. The Closing a Project process becomes part of the last stage and the Project Manager will take the necessary action to prepare for project closure, but only the Project Board can actually close a project.

Closing a Project and Premature Close

A clear project end is necessary to avoid wasted resources and not allow the project to drag on. It also provides the opportunity for the Project Board to review the project against the Initial Project Plan.

The Project Manager carries out the work in Closing a Project, and the objectives are:

- Check that all required products have been delivered and accepted.
- Capture lessons learned in the Lesson Report, as this can be valuable for future projects.
- Ensure that the products can be supported after the project is disbanded.
- Hand over products to the customer, as described in the Configuration Management Strategy document.
- Evaluate the project by comparing project objectives with actuals, and write the End Project Report.
- Assess the benefits already realized and plan a review of benefits that will be realized after the project is complete.

Closing a Project Outputs (CP)

The Closing a Project means that the Project Manager provides some documents to the Project Board and other documents to the Operations/Maintenance group who will support the products once the Project is complete.

The documents given to the Project Board are:

- The End Project Report (ERP) – this is written by the Project Manager and compares the project with the Project Initiation Documentation.
- The Lessons Report (LR) – this records useful lessons that were learned during the project and can be applied to future projects.
- Other documents given to the project board are: Project Plan (PP) which has been kept up to date during the project, Benefits Review Plan (BRP) and draft Project Closure Notification.

The follow on actions recommendations (FAR):

- This is a document that includes information on outstanding issues that are taken from the Issue and Risk Logs and requires follow-up action after the project has ended.

- The Project Manager also hands over product information, including the Configuration Item Records (CIR) for each product, to the operations and Maintenance Group.

The Project Manager also creates a draft Project Closure Notification for the Project Board. This will be the notification document that will be sent out later to stakeholders by the Project Board once they have decided to close the project.

Authorize project closure (DP)

PRINCE2 recommends the following actions for the Project Board:

- Review the End Project Report, and compare it to the original plan.
- Confirm who should receive the Follow on Action Recommendations, e.g.: the persons responsible for the maintenance.
- Review the Lessons Report and pass it on so it can benefit future projects.
- Confirm that products have been handed over, and confirm user acceptance and maintenance for each product.
- Review and approve the Benefits Review Plan, as reviewing the benefits will continue to be done after the project shuts down.
- Confirm that the project has met the Business Case by comparing the current Business Case to the original one, comparing the Benefits, Cost, Risks, and Return on Investment.

There are three outputs to the Authorize project closure activity which are:

- Distribute the Lessons Report to the appropriate persons so it is available for future projects. e.g.: give it to the Project Office.
- Distribute the Follow on Recommendations to the persons who will maintain the products after the project.
- The Project Board does is to issue the Project Closure Notification which will announce to all stakeholders that the project will end on a certain date. This is the same Project Closure Notification that was drafted by the Project Manager.

The Project Closure Notification is used to inform people that the project is closing and to therefore submit any costs to the project budget before it is closed.

3. Fundamentals of decision-making and problem solving in project management

3.1. Introduction

Management is often defined as a decision-making process (Davis, 1951). Decision-making is an essential aspect of modern management. It is one of the steps (and the core) in planning, also a part of every managerial function. This clearly suggests that decision-making is necessary in planning, organizing, leading (or motivating) and controlling. The effectiveness of management depends on the quality of decision-making.

To decide means to come to some definite conclusion for follow-up action. Decision is a choice of a course of action among a set of alternatives to achieve a predetermined objective (Terry and Franklin, 1994; Massie, 1964). Every decision-making process produces an outcome that might be an action, recommendation or an opinion. From the aforementioned definition the following features of managerial decision-making can be derived:

- It is a continuous and dynamic process. It is a never ending activity in business management.
- It is always based on rational thinking.
- It is a mental as well as intellectual activity/process and requires knowledge, skills, experience and maturity from decision-maker.
- It is based on reliable information/feedback. The quality of decision-making can be improved with the support of an effective and efficient management information system.
- It is the process followed by deliberations and reasoning.
- It is the choice of the best course among alternatives.
- It is usually purposive i.e. it relates to desired goal.
- It is a time-consuming activity as various aspects need careful consideration before taking final decision.
- Decision-making involves evaluation: the executive must evaluate the alternatives, and should evaluate the results of taken decisions.
- It needs effective communication: the taken decision needs to be communicated to all concerned parties for suitable follow-up actions.
- It leads to commitment. The commitment depends on the nature of the decision: short or long term.
- It is a responsible job as wrong decisions prove to be too expensive for the organization.

People make two types of decisions: instinctive decisions, which are based on immediate perception and intuition, and thoughtful decisions, which are based on our thinking about the consequences. The managerial decisions should be correct to the maximum extent possible. Because of that, scientific decision-making is essential.

A distinction can be made between programmed and non-programmed decisions (Koontz and Weihrich, 2010). A programmed decision is applied to structured or routine problems; it relies primarily on previously established criteria. Routine and well-structured problems, requiring less decision discretion from managers and non-managers, are solved at lower level of the organization hierarchy. Non-programmed decisions are used for unstructured, novel, and ill-defined situations of non-recurring nature. For example strategic decisions are non-programmed, since they require subjective judgments. They are made by upper-level managers. Most decisions are neither completely programmed nor completely non-programmed – they are a combination of both.

Decisions are important as they determine both managerial and organizational actions. A manager has to take a decision before acting or before preparing a plan for execution. Moreover, his ability is very often judged by the quality of decisions he takes.

Decision makers must gather and consider data before making a choice. Problem analysis involves framing the issue by defining its boundaries, establishing selection criteria for alternatives, and developing conclusions based on available information. Analyzing and solving a problem may not result in a decision, although the results are an important ingredient in all decision making process. Problem analysis and solving must be done first, then the information gathered in that process may be used regarding decision making. Problem-solving and decision-making are closely linked, and each requires creativity in identifying and developing options.

Good decision-making requires a mixture of skills: creative development and identification of options, clarity of judgment, decisiveness, and effective implementation.

Decision-making involves a number of steps which need to be taken in a logical manner (Drucker, 2010):

- The managerial problem definition / identification – information relevant to the problem should be gathered so that critical analysis of the problem is possible; the manager should consider problem causes and find out whether they are controllable or uncontrollable.
- The problem analysis – following four factors should be kept in mind: effect of the decision, the scope of its impact, number of qualitative considerations involved and uniqueness of the decision.
- Alternative solutions development – only realistic alternatives should be considered taking into account the existing constraints.
- Selection of the best solution out of the available alternatives – an alternative that seems to be the most rational for solving the problem; the selected alternative must be communicated to those who are likely to be affected by it.

- The decision conversion into action – the manager has to lead to the execution of decision taken.
- Feedback reassurance for follow-up – the manager has to make built-in arrangements to ensure feedback for continuously testing actual developments against the expectations.

In comparison of alternatives people are likely to think exclusively of quantitative factors – they can be measured in numerical terms, such as time or cost. These factors are very important, but the success would be endangered if intangible or qualitative factors were ignored. The qualitative or intangible factors are difficult to measure numerically, such as quality of labour relations, the risk of technological change, or the market conditions. To evaluate and compare the intangible factors in decision-making, managers must first recognize these factors and then determine whether a reasonable quantitative measurement can be given. If not, they should find out as much as possible about the factors, perhaps rate them in terms of their importance, compare their probable influence on the outcome with that of the quantitative factors, and then come to a decision (Koontz and Weihrich, 2010).

3.2. Decisions in project management

Projects such as building a house, constructing new facilities or even designing new products require a great deal of management decision-making. In project management, decisions cannot be random and must be planned in support of project product and organizational objectives. Managerial decisions, based on their specific context and nature, have a significant effect on the organization and require a commitment of fiscal, physical, or human resources.

In project management, most of the decisions are required to consider the triple indicators and objectives:

- Scope and quality (to meet clients' specifications).
- Time (to finish project on schedule).
- Cost (not to exceed the budget).

Project managers are also responsible for successful achieving these additional objectives (Powell and Buede, 2009):

- Stakeholders management (contractors, consultants etc.).
- The project team and resources management (selecting workers, subcontractors, assigning the right people to the right tasks at the right time with the right information).
- The risk management.

Members of the project management teams are responsible for making project management decisions related to the six aforementioned objectives (project, product, organizational, and business goals).

Taking into account the scope and hierarchy level, it is possible to distinguish project management, project, product and organizational decisions. Project management decisions are broad in nature and affect the project, product, and organization. Project and product decisions (narrow in scope) focus on meeting the project requirements – cost, schedule, and product performance (achieving product specifications and customer expectations). Organizational decisions focus on meeting organizational objectives (performance of project team).

Some of the decisions result in short-term success, while the other cause effect long-term success. Because the decision time extent is different (and they are made on different levels in the organization hierarchy), decisions in project management can be classified in three main categories:

- Strategic decisions (broad in scope, affect the entire organization, and usually have long-term consequences, for example: choosing the investment alternative).
- Tactical decisions (less broad in scope, affect middle management, and are usually long-term decisions, driven by strategic decisions and enable achieving strategic goals, for example: selecting subcontractors, suppliers; determining project schedule).
- Operational decisions (narrow in scope, short-term, made during project execution, and driven by strategic and tactical decisions, for example: decision to start, split or defer an activity or to involve additional resources to shorten process duration).

Early decisions impact later decisions in project management. Mistakes due to poor decision-making during the front-end of the project management life cycle can have significant negative effects on the total cost of the product (e.g. building) and users expectations fulfillment. The project management lifecycle provides a framework for the project manager to manage the project in an organized manner. It describes how a project progresses trough the succession of stages – it is a logical sequence of activities needed to accomplish a project goals and objectives. Within the lifecycle, the project transitions from its conception, through feasibility analysis, planning, implementation and control to its termination in a logical sequence that facilitates project decision-making. Many decisions occur in each stage and must be adequately addressed as the project progresses (Powell and Buede, 2009). Examples of these decisions in construction management with supported models and solving methods are show in section 4.

Each lifecycle stage has a set of activities and a prescribed decision gate – the project can only move forward to the next lifecycle stage by meeting the specific requirements. Decision gates serve as a project milestones. The decision-making occurs also at each activity of the stage. Each stage receives available information and resources (inputs). During each stage decisions are made which determine how the inputs are converted by selected actions into outputs. So there are two types of decisions: an activation and conversion type. An activation decision determines that some new activity should begin, based on the progress of other activities and resources availability. A conversion decision allocate available resources, so it establishes that the same set of resources should proceed or continue activity realization. In both cases, reasonable and rational alternatives should be selected for most of these decisions. In Tab. 3.1 the main project management lifecycle stages with respective activities and decision gates are shown.

All decisions (business, economic, social etc.) should be fair and rational. Rational decisions are the best decisions under the available circumstances. Mangers must have a clear understanding of alternative courses by which a goal can be reached under existing circumstances and limitations, mostly very complex in real life decisions. They also must have the information and the ability to analyze and evaluate alternatives in the light of the goals sought. Finally, they must have a desire to come to the best solution by selecting the alternative that most effectively satisfies goal achievement. Decisions must operate for the future, and the future almost invariably involves uncertainties. It is also difficult to recognize all the alternatives that might be followed to reach the goal.

During selection from among alternatives, managers can use three basic approaches: experience, experimentation and research and analysis (Koontz and Weihrich, 2010). Relying only on past experience as a guide for future action can be dangerous, because people do not always recognize the underlying reasons for their mistakes or failures and the lessons of experience may be entirely inapplicable to new problems. Good decisions must be evaluated against future events, while experience belongs to the past. An obvious way to choose from alternatives is to try one or all of them and see what happens. The experimental technique – often used in scientific inquiry – is likely to be the most expensive. Besides, after an experiment has been tried, there still may be doubt about what it proved, since the future may not duplicate the present. This technique, therefore, should be used only after considering other alternatives. One of the most effective techniques for selecting from alternatives is research and analysis. This approach means solving the problem by at first comprehending it. It involves searching for relationships among the more critical of the variables, constraints and goals. Solving a problem requires breaking it into component parts and studying various quantitative and qualitative factors – it is cheaper than experimentation. A major step in the research-and-analysis approach is to develop a model simulating the problem. The most useful simulation is likely to be a representation of the variables in the problem situation by mathematical terms and relationships. Conceptualizing a problem is a major step toward its solution (Koontz and Weihrich, 2010).

Tab. 3.1. Project management lifecycle stages and decisions (Powell and Buede, 2009)

Stage	Activities	Decision gates
Conception	Identify users / stakeholder needs Define the project Define project, product and organizational goals Identify preliminary cost, schedule, and performance risks	Requirements approval for both the project and product
Feasibility analysis	Assess project, product, and organizational feasibility Assess resources capabilities Assess cost, schedule, and performance risks Define cost-benefits Perform risk analysis	Required cost-benefit and risk mitigation measure justification
Planning	Define project tasks (e.g. work packages) Schedule tasks Allocate resources Develop project organization Continue risk analysis	Project management plan approval
Implementation	Mitigate cost, schedule, and performance risks Continue risk analysis	Requirements for the project and product verification and validation
Controlling	Monitor and control project resources, progress and performance Continue risk analysis	Performance measures met
Termination	Measure project success Terminate project Develop lessons learned Identify remaining resources	Project completion approval

A scientific discipline that deals with the application of advanced analytical methods to help to make better decisions is called Operations Research. Employing techniques from mathematical and computer sciences, Operations Research arrives at optimal or near-optimal solutions to even complex problems, supporting decision-making.

3.3. Operations Research for managerial decisions

3.3.1. Introduction

The first formal activities of Operations Research (OR) were initiated in England during World War II. A team of British scientists set out to make scientifically based decisions regarding military operations (e.g. deployment of radar, convoy management, bombing, antisubmarine, and mining operations). After the war, the worked out ideas were adapted to improve efficiency and productivity in the civilian sector (Taha, 2007).

Operations Research (often referred to Management Science) is simply a scientific approach to decision making that seeks the best design and operate a system, usually under conditions requiring the allocation of scarce resources (Winston, 2004). A system is defined as the set of interacting or interdependent components forming an integrated whole (surrounded and influenced by its environment) that work together to accomplish the system' goal. For example, every project organization can be treated as a system whose goal consist of minimizing the time and the cost of construction and maximizing the work quality and user requirements fulfillment. Thus, the methodology of the operations research can be applied to the problems that concern the way of conducting and coordinating the operations (i.e. activities) within organizations (Kulej, 2011). OR is mainly used to handle management problems that were clear-cut, well-structured and repetitive in nature. Typically, those problems were of tactical and operational nature, such as inventory control, resource allocation, projects scheduling etc. In recent years formal approaches have been adopted for the less well-structured strategic planning problems as well.

OR is designated to solve quantitative decision problems, where the factors that influence the decisions can be identified and quantified. The significant features of OR are:

- OR is addressed to managerial decision-making and provides a general systematic process of problem solving.
- OR employs scientific methods for the purpose of solving problems.
- OR attempts to locate the best or optimal solution of the problem under consideration.
- OR is interdisciplinary in nature and often requires team approach to the problem solution (managerial problem have economic, physical, psychological, ecological and engineering aspects).
- Use of computer technology to model the problem and solve the model.

OR involves the construction of decision models (mainly mathematical) that attempt to describe and optimize the system.

It encompasses a wide range of problem-solving techniques and methods applied in the pursuit of improved decision-making and efficiency, such as:

- mathematical programming,
- probability theory,
- statistical methods,
- graph theory,
- simulation,
- queuing theory and other stochastic-process models,
- Markov decision processes,
- econometric methods,
- neural networks,
- expert systems,
- others.

The majority of OR applications usually involve varying degrees of approximations in modeling. The assumed real world is abstracted from the real situation by concentrating on the dominant variables which control the behavior of the real system. A model is defined as a representation or abstraction of an actual object or situation. It shows the relationships (direct or indirect) and interrelationships of action and reaction in terms of cause the effect. In fact, many real-life situations tend to be very complex because there are literally innumerable inherent factors.

Classification of models provides an additional insight into their essentials since they can be described in many ways. Models can be categorized by their types, dimensionality, function, purpose, subject or degree of abstraction. The basic types of models are diagrammatic (e.g. project network), physical (e.g. scale model of the building) or mathematical (Srivastava et al., 2005).

A diagrammatic (analog) model employs graphical symbols to represent system structure – the variables and their interrelationships. They can represent dynamic situations and can depict the characteristics of the event being under study. Examples are flow charts, frequency distributions etc.

A physical (iconic) model is a physical representation of the system either in an idealized form or on different scale. It resembles the thing it represents.

A mathematical (symbolic) model employs letters, numbers and another types of symbols and expressions to represent variables and their interrelationships. It employs mathematical notation to represent the variables and their interrelations and takes the form of mathematical relationships, especially equations.

Mathematical models are often used in operations research because they are easier to manipulate and they yield more accurate results under manipulation compared to the iconic and analog models.

Taking into account various criteria, mathematical models can be categorized as follows:

- Static versus dynamic models. A dynamic model accounts for time-dependent changes in the state of the system, while a static (or steady-state) model calculates the system in equilibrium, and thus is time-invariant.
- Analytical versus numerical. Analytical models use mainly analytical mathematical equations to describe interrelations among variables. To solve the models analytical methods are used. In latter case (when the solution procedure is complex or the interrelationships take form of other expressions than equations or inequalities, e.g. if / than rules) numerical methods are used which are concerned with iterative procedures through the use of numerical computations at each step. The algorithm (or the set of computational rules) is started with trial or initial solution and continued with a set of rules to improve it towards optimality. In case of dynamic numerical models simulations methods are used.
- Explanatory versus predictive. In some situations a model is developed to be a mathematical description of real situation. It helps to understand more about the problem (e.g. shows possible alternatives and helps to evaluate the results of each choice over another) or even enables system optimization (arriving an optimum solution according to the input criteria). Predictive models are aimed at predicting (forecasting) variable values with high accuracy.
- Linear versus nonlinear. If the objective function and constraints are represented entirely by linear equations, then the model is regarded as a linear model. If one or more of the objective functions or constraints are represented with nonlinear equation, then the model is known as a nonlinear model.
- Discrete versus continuous. In discrete model all parameters and variables are treated as discrete; in continuous models they can take continuous values.

Deterministic versus stochastic. In deterministic models all variables and parameters are known and are static. In stochastic models randomness and uncertainty is present. The parameters of the model can be probabilistic (with known probability distribution function), statistical (random but unknown distribution function) or strategic (only with known possible values or value extend) in nature.

3.3.2. The OR methodology of problem solving

The principal phases for implementation OR in practice include (Taha, 2007):

- The problem definition.
- The model construction.
- The model solution.

- The model validation and the results verification.
- The solution implementation.

Problem definition involves defining the scope of the problem under investigation. The aim is to identify three principal elements of the decision problem: description of the decision alternatives, determination of the objective of the study, and specification of the limitations under the modelled system operates (Taha, 2007).

Second phase entails an attempt to translate the problem definition into a **model**. OR models are designed to optimize a specific objective criterion subject to a set of constraints, the quality of the resulting solution depends on the completeness of the model in representing the real system.

The best way to start constructing a model is to identify all the components that contribute to the effectiveness of the system. The next step is to determine whether or not each of these components should be used. To understand the significance of each component in the system, it may be advisable to test all the available data experimentally or by some statistical method. From among the selected variables (components), it is necessary to identify the controllable and uncontrollable variables and to assign a symbol to each element where at least one symbol represents the measure of effectiveness or ineffectiveness (Srivastava et al., 2005).

Constructing a model requires obtaining the data (parameters) to be used in the model as input. Quality of data determines the quality of output. Obtaining correct and relevant data may indeed be a difficult exercise when relatively large problems are involved. A number of sources may be used for collecting data, i.e. company reports and documents, interviews with company personnel etc. (Vohra, 2007).

A mathematical model (mostly used in OR) is defined by a system of equations and related mathematical expressions that describe the essence of a problem. A main elements of a model are the following (Hilier and Lieberman, 2001; Kulej, 2011):

- Decision variables – the variables whose values are under our control and influence on the performance of the system; they represent decisions to be made; its values are to be determined.
- Objective function – the appropriate measure of system performance expressed as a mathematical function of the decision variables.
- Constraints – any restrictions on the values that can be assigned to the decision variables, expressed mathematically, typically by means of inequalities or equations.
- Parameters of the model – the constants (namely, the coefficients and right-hand sides of variables and left-hand sides in equations or inequalities) in the constraints and in the objective function.

Model solution is so far the simplest of all OR phases because it entails the use of well-defined optimization algorithms. A model solution implies determination of specific set of decision variables that would yield a desired level of output. The desired level of output is determined by the principle of choice adopted and represents the optimizing level. Optimization might mean maximizing the level of goal attainment from a given set of resources or cost minimization which will satisfy the required level of goal achievement, or ratio maximization of the goal attainment to cost (Vohra, 2007).

The solutions can be classified as being feasible or infeasible, optimal or non-optimal and unique or multiple.

A model solution (a set of values of the decision variables) is feasible if it satisfies all of the constraints of the problem, whereas an infeasible solution is the one which does not satisfy all the constraints – it is unacceptable one.

A solution is optimal if, in addition to being feasible, it yields the best (maximum or minimum) value of the objective function. The feasible solutions other than the optimal solutions are called non-optimal solutions. In case where more than one objective function is to be optimized simultaneously, for a non-trivial multi-objective optimization problem, it does not exist a single solution that optimizes each objective. Optimal decision need to be taken in the presence of trade-offs between conflicting objectives. Solutions of the multi-objective optimization are called no dominated, Pareto optimal, efficient or no inferior. In such solutions none of the objective functions can be improved in value without degrading some of the other objective values. All Pareto optimal solutions (so called Pareto front) are considered equally good.

If only one optimal solution to a given problem exists, it is called a unique solution. If two or more optimal solutions to a problem exist, which are equally efficient, then it is said that the multiple optimal solutions exist. They provide to a manager a greater flexibility in implementation.

In OR, we do not have a single general technique to solve all mathematical models that can arise in practice. Instead, the type and complexity of the mathematical model dictate the nature of the solution method. The most prominent OR technique is linear programming. It is designed for models with linear objective and constraint functions. Other techniques include integer programming (in which the variables assume integer values), binary programming, dynamic programming (in which the original model can be decomposed into more manageable sub problems), network programming (in which the problem can be modelled as a network), and nonlinear programming (in which functions of the model are nonlinear). Another group consists of queuing and simulations models. These are only a few among many available OR tools (Taha, 2007).

In most OR techniques solutions are determined by algorithms. An algorithm provides fixed computational rules that are applied repetitively to the problem, with each repetition (called iteration) moving the solution closer to the optimum.

Because the computations associated with each iteration are typically tedious and voluminous, it is imperative that these algorithms are executed on the computer (Taha, 2007). The algorithms (methods of solutions for the each kind of model) are executed by commercial or even open source software packages (LINDO/LINGO, CPLEX, Mathematica, MatLab, MathCAD, Excel Solver, LpSolve).

An important aspect of the model solution phase is sensitivity analysis. It obtains additional information about the behavior of the optimum solution when the model undergoes some parameter's changes. Sensitivity analysis is particularly needed when the parameters of the model cannot be estimated accurately – it enables to study the behavior of the optimum solution in the neighborhood of the estimated parameters (Taha, 2007).

Because the solution depends on the input data and the employed model, both need testing. **Model validity** checks whether or not the proposed model predicts the behavior of the system under study adequately. It involves also, testing the structural assumptions of the model to ascertain their validity. Common method for checking the validity of a model is to compare its output with historical output data. The model is valid if, under similar input conditions, it reasonably duplicates past performance (Taha, 2007). The obtained solution should be **verified** and checked for implementation possibility in real life conditions. Such testing comprises of determining the accuracy and completeness of the data used by model.

Implementation of the solution of validated model involves the translation of the results into understandable operating instructions to be issued to the people who will administer the recommended system (Taha, 2007). Models used in OR may be detailed in mathematical terms, but they generally do not consider the human aspects that are significant in implementation of the solution. The impact of a decision may cut across various segments of the organization, and the factors like resistance to change, desire to be consulted and informed, motivation, and so on may come in the way of implementation (Vohra, 2007).

OR methodology is supported by the modern computer-based information systems, i.e. management information systems, decision support systems, expert systems using artificial intelligence. A management information system represents an organized way of managing information and data. It comprises a body of organized procedures for identification, collection, processing, retrieval and dissemination of information. Decision support system is developed to aid management in improving its decision-making. It supports, rather than replaces, managerial judgment. The manager may use of what, if questions, modified data and quickly witness results of such changes. Expert systems are information systems that attempt to support or automate decision-making and act like intelligent and rational decision-makers. It is done by sorting and using knowledge about a specific, limited topic and producing conclusions based on the data that they receive. They mimic the human behavior, are able to think, learn, understand and use common sense (Vohra, 2007).

Mathematical models of many real-life managerial problems are so complex that it is impossible to solve them by any of the available optimization algorithms. In such cases, it may be necessary to abandon the search for the optimal solution and simply seek a good (suboptimal) solution using heuristics, metaheuristics or simulation.

3.3.3. Heuristics and metaheuristics

By problem-solving we typically mean the solution of problems via a search method over a well-defined search space (feasible solution set). Many decision problems can be solved exactly by specific exact methods. However for many problems such exact methods cannot be used. Sometimes such methods are not known. Sometimes methods are known, but are impractical, perhaps because the method is computationally intractable when used on problems of realistic size. Because of such difficulties, many problems are solved using problem-specific heuristic methods with low computational effort, but they do not guarantee finding an optimal solution. Some heuristic techniques aim to be more generic and can be applied to a wide range of problems. One specific strategy, that is commonly adopted in the application of these methods, is to reduce a new problem to an already solved problem in one of these kinds, and then solve it using the known methods (Johnson, 2008).

Many problems are too specialized to be worth the expenditure of effort to create a specific heuristic. Also one of the aims of computer science is to reduce the amount of individual effort which needs to be put into the solution of particular problems. For these reasons the creation of metaheuristics is important. A metaheuristic is a high-level problem-independent algorithmic framework that provides a set of guidelines or strategies to develop heuristic optimization algorithms (Sörensen and Glover, 2013).

Metaheuristics can be seen as general “rules of thumb” for solving a wide range of problems. The source of inspiration for metaheuristics is the abstraction from the natural world. The ways in which natural systems adapt and process information about themselves and their environment can be abstracted and used as the basis of a computational metaheuristic, for example in Genetic and Evolutionary Algorithms, swarm search methods such as Ant Colony Optimization and Particle Swarm Optimization, Simulated Annealing, problem-solving with Artificial Immune Systems, Ant Colony Optimization and Tabu Search (Johnson, 2008).

Metaheuristic frameworks are defined in general terms, metaheuristic algorithms can be adapted to fit the needs of most real-life optimization problems in terms of expected solution quality and allowed computing time, which can greatly vary across different problems and different situations. Also metaheuristics do not put any demands on the formulation of the optimization problem (like requiring constraints or objective functions to be expressed as linear functions of the decision variables) (Sörensen and Glover, 2013).

Metaheuristics evaluate potential solutions and perform a series of operations on them in order to find different, better solutions. Based on the way in which solutions are manipulated, three fundamental classes of metaheuristics can be distinguished (Sörensen and Glover, 2013):

- local search metaheuristics – making small changes to a single solution,
- constructive metaheuristics – constructing solutions from their constituting parts,
- population-based metaheuristics – iteratively combining solutions into new ones.

Many metaheuristic algorithms combine ideas from different classes – they are called hybrid metaheuristics.

Metaheuristics operate on a representation or solution encoding of an object that can be stored in computer memory and can be conveniently manipulated by the different operators employed by the metaheuristic.

The operating framework of metaheuristics will be detailed shown on Evolutionary Algorithm used for project schedule optimization (Jaśkowski and Sobotka 2006).

Evolutionary algorithms work as computer systems for solving problems according to the rules observed in the evolution of live organisms. The rules involve system structure, and ways of their functioning and adapting to existing conditions. A characteristic feature of this approach in solving optimization problems is creating a population of individuals representing solutions in a form of a chromosome. As in nature, better-adapted individuals – better solutions from the point of view of an objective function – stand a better chance of survival and development. Evolutionary algorithms are classified as methods based on artificial intelligence i.e. algorithms acting like human behavior.

The evolutionary algorithms are used to solve optimization problems in many branches of industry. A number of examples of their application may be found in construction, such as the optimization of structures, engineering and design, selection of equipment for earth-moving operations. Many studies show that evolutionary algorithms have a considerable potential for efficient solving of many project scheduling problems, for example to facilitate the time-cost optimization and processes modes selection or to the optimization of resource allocation and levelling.

Applying optimization methods to project scheduling is one of the conditions for the rationalization of the construction industry. This approach proved to be appropriate for solving scheduling problems and relatively simple in computation.

The successive steps of evolutionary algorithm are shown in Fig. 3.1 and described below. In Tab. 3.2, basic notions used in evolutionary algorithms description are explained.

Step 1. Initiation. Initiation consists in creating initial population – a specified number of individuals (chromosomes). In project scheduling individuals' representation can be used in the form of genes' string containing information about methods of carrying out processes, values of processes priority or processes start dates.

Initial population is created randomly. Particular genes assume values chosen randomly with equal probability from their values interval or set.

Genes are modified in consecutive steps of the algorithm until a solution that meets the optimization objective is obtained.

Step 2. Individual assessment. Evolutionary algorithms are used to look for the best adapted individuals for which the fitness function value is the highest. The fitness function corresponds to the maximized objective function in mathematical model of the problem. In case of minimized objective function, it is necessary to convert it into maximized fitness function. In both cases, formula used to calculate fitness function values should include penalties for individuals not meeting existing constraints and do not fit to the feasible solution set.

Step 3. Protection of the best individual. The individual (chromosome) from the initial population for which the fitness function value is the best is **remembered**. The best individual protection (so–called exclusive strategy) is a special additional reproductive procedure. The best adapted individual, among all of former generations, does not always pass to a new population. Exclusive strategy is used as the protective step against the loss of that individual. If the best individual from the current generation is worse than the best from the previous generation, then the latter replaces the worst individual in the current population.

Tab. 3.2. The notions used in the evolutionary algorithm description (Jaśkowski and Sobotka, 2006)

Notion	Notions explanation
Population	Set of individuals (solutions)
Individuals	Solutions encoded as chromosomes (strings of bits – genes, with information about the ways of carrying out particular processes and processes priorities values)
Chromosomes	String of genes
Gene	Also called a feature, mark, detector – is a single element of a genotype (chromosome in particular); in the study genes encode the method of carrying out a given process and the value of process priority
Genotype	A given individual's group of chromosomes

Phenotype	A set of values corresponding to a given genotype (time values for completing project for a given solution)
Allel	Value of a given gene
Locus	Position of a given gene in a chromosome
Fitness function	It is the amount of adaptation (fitness) of a given individual in population; it enables the selection of individuals best adapted in accordance with an evolutionary rule of surviving „the strongest"
Generation	A successive iteration in the evolutionary algorithm

Step 4. Checking the termination condition. The action of the algorithm can be stopped in two cases:

- after performing a specified number of iterations (when the number of current generation is greater than the maximum value assumed),
- when, after some number of iterations, there are no better solutions than in previous generations.

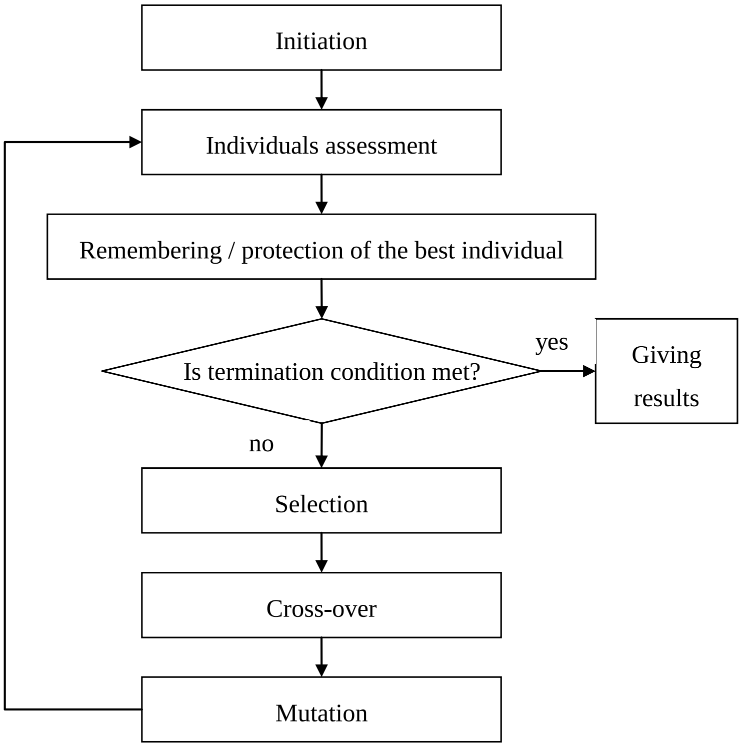


Fig. 3.1. Steps of evolutionary algorithm (Jaśkowski and Sobotka, 2006)

If the termination condition is not met, a selection of individuals is carried out as the next step.

Step 5. Selection procedure. Chromosomes selection consists in choosing these individuals that will take part in producing offspring for the next generation. Chromosomes having the highest value of fitness function are the most likely to produce new individuals. The simplest method – roulette wheel can be used in the process of selection (Michalewicz, 1996). Selection runs as follows:

- entire fitness of population is calculated as the sum SUM of fitness function values of all individuals,
- for each individual *i* relative fitness *FITNESSREL*[*i*] is calculated, corresponding to the probability of chromosome selection for reproduction:

$$FITNESSREL[i] = \frac{FITNESS[i]}{SUM}, \tag{3.1}$$

- and then total fitness *FITNESSTOT*[*i*] (cumulative distribution function of selection probability) is calculated by recurrent dependence:

$$\begin{aligned} &FITNESSTOT[0] = FITNESSREL[0] \\ &FITNESSTOT[i] = FITNESSTOT[i-1] + FITNESSREL[i], \end{aligned} \tag{3.2}$$

- a random variable *r* within $\langle 0,1 \rangle$ is generated; an individual for which the condition:

$$\begin{aligned} &FITNESSTOT[j-1] \le r < FITNESSTOT[j] \\ &(individual\, j = 0,\ when: r < FITNESSTOT[0]) \end{aligned}, \tag{3.3}$$

is met, is selected for a new parental generation.

The last step is repeated as many times as the population size.

Step 6. Cross-over. The task of cross–over is to recombine chromosomes by exchanging strings of genes between parents' chromosomes.

The simplest method is called one–point cross–over (Michallewicz, 1996). The procedure is carried out in two stages:

- For each chromosome from parental population a random variable y within $\langle 0,1 \rangle$ is generated. If y < PCROS, where PCROS is crossover probability (system parameter), then a given chromosome is selected for recombination. Selected chromosomes are then paired.
- For each pair of chromosomes (parents) a random number POINT is generated, defining the point of "crossing" chromosomes. Strings of genes in parents' chromosomes ahead of the point of crossing are not changed, only genes behind that point are exchanged between parents.

Step 7. Mutation. Mutation consists in a random change of one or more genes of the selected chromosome, with probability equal to mutation frequency

PMUTAT. For each chromosome in a population and each gene in a chromosome, a random variable z within $\langle 0{,}1 1\rangle$ is generated. If $z<PMUTAT$, a given gene j undergoes mutation i.e. takes any value (selected randomly) within its variability interval.

Calculation of the fitness function value for each individual in a new generation, the best individual protection, selection procedures, cross–over, mutation are repeated until the termination condition of algorithm is met.

Then the result of algorithm's action is given i.e. the solution to the problem – the best methods of carrying out processes and / or start and finish dates of the processes. The best solution corresponds to the individual having the highest value of the fitness function.

3.3.4. Simulations

Solving practical problems of business operations and selecting the best options is a complex task – even if the decision environment is treated as deterministic. From the point of decision making, construction may be considered as an especially challenging branch of industry, regardless of country, technology level or economic conditions, it is prone to considerable operational risk. Thus, the assumption of deterministic character of construction projects may lead to wrong decisions, and many researchers propose tools or methodologies aimed to improve construction planning.

For the optimization of complex management processes and systems the stochastic simulation is recommended and used by many researchers, especially in combination with optimization algorithms.

Many construction processes are of cyclic nature, with operations repeated in the same sequence what results from method of their execution. Duration of such repeated operations is usually a little different in each cycle. This is due to a variety of factors affecting productivity of the resources and changing conditions of work. Thus, cyclic construction processes are stochastic and examined by means of simulations or tools of statistical analysis. The results of such analysis are the basis for planning the works with respect to composition of machine sets or worker crews, estimating the process time, and harmonizing the work. If the systems actually operate, information on their performance is possible to be collected on site and analyzed by means of statistical methods. In the case of systems at the planning stage, computer simulations provide input for the analysis.

Simulation is a technique used to imitate operation of a real-life complex system as it evolves over time by means of a dynamic model (Winston, 2004). In the case of computer simulation, the real-life system is modelled by means of a computer program.

Computer simulation is the use of a model to understand and experiment with a system. Simulation model mimics the changes that occur through time in the real system (Pidd, 2003). It usually takes the form of a set of assumptions about the operation of the system, expressed as mathematical or logical relations between the objects of interest in the system. Simulation can be seen as a sampling experiment on the real system, with the results being sample points. Once a model is built, it can be used repeatedly to analyze different polices, parameters or designs. However, it must be emphasized that simulation is not an optimizing technique – it is often used to analyze "what if" type of questions (Winston, 2004).

Before simulation tests are conducted, a model of the real-life system has to be built. Simulation models have been classified as static or dynamic, deterministic or stochastic, and discrete, continuous or hybrid (Banks et al., 2001).

A static simulation model represents a system at a particular point in time. We usually refer to a static simulation as a Monte Carlo simulation. Dynamic simulation models represent systems that change as time advances (e.g. simulation model of an inventory system for a one-week time period). In deterministic models randomness is not included and they, therefore, have a known set of inputs and a unique set of outputs (e.g. model, which uses average values as input variables and therefore, the outputs are consequently deterministic). a stochastic simulation model has one or more random variables as inputs, which lead to random outputs (e.g. queuing system, where customers arrive following a random distribution of arrivals and service times vary according to a statistical distribution and as a result waiting times vary) (Tako, 2008).

Depending on the character of the model's state variables and how the time is handled in the system, simulation models are:

- continuous – when state variables change continuously (i.e. the amount of water flowing through a pipe),
- discrete – when state variables change in distinct time-steps, or
- hybrid.

There are three popular simulation approaches used in Operational Research:

- Discrete-Event Simulation (DES),
- System Dynamics (SD), and
- Agent-Based Simulation (ABS).

DES involves modeling of systems which consist of discrete entities going through specific states, which change at discrete points in time. These points in time are the ones at which state changes (or events) occur (Pidd, 2003; Tako, 2008). Entities (e.g. customers, machines, products etc.) are objects or components whose behavior is tracked through the model as the simulation proceeds. Entities go through a number of states, which represent their progression in the system. An entity remains in a state for a period of time and whenever its state changes, an event occurs. Entities are given attributes, which can be thought of as properties of each specific entity. Another important element in DES models are activities (e.g. service, inter-arrival times). An activity takes a specific amount of time, which involves the time needed for an entity to change from one state to another. Before entering an activity, entities wait in queues (or buffers), until the activity center becomes available (Tako, 2008).

System Dynamics studies dynamic behavior of complex systems over time. A central concept in the SD paradigm is that of feedback, a closed cause and effect chain, where information about the result of an action is fed back to generate further action. Analyzed systems in SD simulations are made up of flows (rates) and stocks (levels). Stocks are defined as an accumulation of resources through time (e.g. materials, machines, people or information). Rates or flows consist of the decision, action or change that affects resources flowing between levels. They directly control the increase or decrease of resource levels (Tako, 2008).

In Agent-Based Simulation another – decentralized and individual-centric (as opposed to system level) – approach in modeling of analyzed systems is used. Agent-based modeling is a way to model the dynamics of complex systems composed of autonomous, interacting agents to observe the collective effects of agent behaviors and interactions. Agents (which can be people, companies, projects, vehicles, products, etc.), have behaviors, often described by simple rules, and interactions with other agents, which in turn influence their behaviors, learn from their experiences, and adapt their behaviors. An agent has its capability to act autonomously, that is, to act on its own without external direction in response to the situations it encounters. Agents are endowed with behaviors that allow them to make independent decisions. Typically, agents are active, initiating their actions to achieve their internal goals, rather than merely passive, reactively responding to other agents and the environment. A typical agent-based model has three elements: a set of agents and their attributes and behaviors (decision-making heuristics, rules or adaptive processes, reactions, states), a set of agent relationships and methods of interaction, and the agents' environment (agents interact with their environment in addition to other agents).

There are three basic modelellinging strategies for defining the concept of model analysis and the way of its creation (Abduh et al., 2010). These are:

- process interaction strategy (PI) – that focuses on transaction flows inside the systems,
- activity scanning strategy (AS) – that identifies processes and conditions required for their completion, and
- event scheduled strategy (ES) – based on modeling events that are likely to occur or whose occurrence has been planned.

In practice, these strategies are used in combinations. In the case of construction processes, a combination of AS and ES strategies is recommended, and referred to the three-phase activity scanning method.

The commonly used method to conduct simulation experiments is Monte Carlo. Monte Carlo method rely on repeated random sampling to obtain numerical results. It enables probability and risk analysis done by generating values of a number of different random variables (e.g. service and interarrival times) from the specified probability distributions in order to determine the different outcomes (e.g. mean queue length). By using Monte Carlo simulations, decision makers are able to determine the range of possibilities and their probability of occurrence for any choice of actions.

A simulation study consists of several distinct stages. The initial stage requires an explicit statement of the objective of the study (description of the problem, question to be answered, the hypothesis to be tested, alternatives to be considered, performance criteria, model parameters and state variables). The next stage is the development of the model (to represent the essential features of the system under study by mathematical or logical relations) and collection of data. The model should be translated to a form in which it can be analyzed on the computer. This usually involves developing a computer program for the model (and choice of the programming language). At the verification stage the program is checked whether it works properly. Next, the model is validated to determine whether it realistically represents the system being analyzed and whether the results from the model will be reliable. Then the model is used to conduct the experiments to answer the questions at hand. It enables proper designing of the experiment (e.g. determination of the replications number). The data generated by the simulation experiments must be collected, processed, and analyzed (whether they are realistic and statistical reliable). Finally, a decision must be made whether to perform any additional experiments (Winston, 2004).

The main practical problems of using simulations for analyzing construction processes are related with (Abduh et al., 2010):

- limited access to input (lack of statistical data on construction activities' times with respect to distribution types and parameters),
- lack of modeling expertise (the existing software requires from the user much more than basic computer skills, sometimes the user has to translate a graphic model into a computer program using specified programming language, the simulation reports have to be interpreted), and
- software accessibility (costly licenses).

Construction practitioners prefer widely available software and universal systems facilitating calculations (like spreadsheets) to single-purpose specialized systems, regardless of their commercial or in-house origin (Abduh et al., 2010).

3.4. Multi criteria decision making

An owner evaluates bid proposals for a construction works taking into account several criteria, for example costs, project duration, building durability, contractor's experience. Similarly follows a contractor who intends to purchase a construction equipment. When machine have similar technical specification choice is made on the basis of not only the purchase price, but also operating costs. The contractor pays attention to service, multifunctionality and durability of the equipment. The owner on the design stage must select the solution which is a compromise between the price and the utility properties (e.g. thermal insulation of external wall, durability or visual values). All those situations can be described in the same way: the best compromise choice must be made among the set of alternatives/variants (design solutions, contractors/subcontractors, offers) $A = \{a_1, ..., a_n\}$ evaluated using set of criteria $C = \{c_1, ..., c_m\}$. Evaluation of alternatives i using criterion j is denoted as a_{ij}. The importance of the criteria is usually different therefore often criteria have assigned weights $W = \{w_1, ..., w_m\}$. The most often weights are determined to fulfill condition $\sum_{j=1}^{m} w_j = 1$.

Decision maker comparing alternatives must express the preferences and state if (Greco, 2005):

- a_r is preferred (at least as good as) to a_s or a_s is preferred to a_r,
- a_r is indifferent to a_s,
- a_r is incomparable to a_s.

Multi attribute/criteria decision making process comprise following problems:

- Selection – choice of one or subset of the best variants from the set of alternatives a (e.g. subcontractor or supplier selection problem, choice of construction method, selection construction equipment to earth works).
- Classification (sorting) – the assignment of alternatives into predefined homogenous groups according to the decision maker's preference (e.g. division of concept designs on the accepted for further analysis, rejected and sent for complement).
- Ranking – ordering from the best to the worst from the point of view of set of criteria (e.g. order of negotiations with subcontractors).

Criteria can be classified as quantitative (measurable) and qualitative (incommensurable). Ratings for quantitative criteria can be expressed in some natural scales and units e.g. cost in €, mass in kilograms or warranty in years. For description of qualitative criteria a predefined set of linguistic terms can be applied (e.g. insufficient solution, good, very good, perfect) – nominal scales. In many multi-attribute decision making methods (MADM) qualitative criteria are transformed into quantitative. The most commonly ordinal, interval and ratio scales are used in this purpose. Using ordinal scale the increasing or decreasing preferences order of alternatives is obtained. For example assigning alternative a_r rating 3, a_s rating 2 and a_q – 1, can only be stated that alternative a_r is better than a_s and a_s is better than a_q from the point of view of an analyzed criterion. Decision maker does not express the degree of his/her preferences fulfillment by several alternatives, we cannot tell how much alternative a_r is better than a_s, or if the difference between alternatives a_r and a_s is the same as between a_s and a_q. This difficulty can be eliminated using an interval scale. An interval scale provide a common and constant unit of measurement, which allows to indicate the exact distances between alternatives. In the case of qualitative criteria the start point of the scale is determined by rating of the worst alternative and the end corresponds to rating of the best. Rating an intermediate alternative express the distance (preferences of decision maker) between that criterion and the worst and the best alternative. Often the worst evaluation has assigned value 0, whereas the perfect value has 100 points assigned.

The ratio scale has all the properties of an interval scale (unity) and also has a natural (absolute) zero point, which means absence of the attribute. Ratings of any pair of alternatives allows to express the distance between them and how much one of an analyzed alternative is better than the other. The ratio a_{rj}/a_{sj} shows how many times a_r is preferred to a_s in j criterion.

For interval and ratio scales both addition and multiplication can be applied for aggregation final score.

If higher values of ratings are assigned to better alternatives from the point of view of a criterion, then such criteria belong to the „profit" category (benefit type criteria). Otherwise – when higher values of ratings are assigned to worse alternatives, a criterion belongs to „cost" category. Whether a criterion is profit or cost type depends on the decision situation. a project budget for the owner belongs to „cost" criteria category, whereas for the contractor the same criteria is defined as benefit type, because the price increase can lead to higher his/her profit.

Variants evaluation should be performed to fulfill decision maker requirements. The criteria should be the most objective and measurable. In the case of using many criteria, the objective evaluation of variants is difficult, especially that part of criteria is quantitative and part is qualitative. That problem can be effectively solved only by application of objective multi-attribute decision making methods. They allow to apply many criteria, also contradictory to each other. Variety of applied methods and procedures to aid decision making testifies about problem complexity and about difficulty in formulation of universal solutions. The method should be appropriate to solve multi faced problem. Application of multi-attribute decision making methods, in order to support the decision making process requires:

- To define criteria (and their weights) precisely describing preferences of the decision maker; a set of criteria should be defined based on experts' experience and knowledge; good solution is to apply ready-made standards.
- To evaluate alternatives against criteria defined both quantitative using commonly shared scales of measurement and qualitative which subjective ratings – it is necessity to formulate proper interval, ratio or ordinal scale.
- To choose appropriate multi-criteria decision aid method characterized by confirmed reliability.
- To predict risk of incorrect evaluations (overrated or rarely underrated) usually based on data received only from the bid proposal form.

According to Pareto method (Deb, 2002) alternative a_r is deemed to dominate over alternative a_s with respect to a set of „profit" category criterion $C = \{c_1, \ldots, c_m\}$ if and only if $\exists c_t \in C$ for which $a_{rt} > a_{st}$ and for other criteria $j \neq t$, $a_{rj} \geq a_{sj}$.

An alternative is called non-dominated, Pareto optimal or Pareto efficient if none of the other alternatives cannot be higher rated according to one criterion without a worse rating for any other criterion. In 1909 Vilfredo Pareto studying population income and wealth problem found out that group's situation cannot be improved without making another group's situation worse. Using Pareto optimum concept allows to classify alternatives as non-dominated and dominated and to limit set of alternatives for further analysis using multi criteria optimization.

4. Decision problems and methods in managing construction projects

4.1. Selection problems – examples and methods

4.1.1. Ordinal ranking methods in multi criteria decision making

Review of ranking methods

Advantage of ordinal ranking methods is that there is no necessity to express importance of criteria (assessing weights) and standardization of criteria. Ordinal methods were invented in the eighteenth century to improve reaching a collective decision (social choice theory), especially to select the best candidate in elections. Voters can be treated as multiple criteria.

In 1770 Jean Charles de Borda (Lansdowne, 1996) proposed to recognize as the best alternative with the highest value of the Borda Count:

$$BC(a_i) = \sum_{j=1}^{m} (n - n_{ij}), \quad i = 1, 2, \ldots, n, \tag{4.1}$$

where n_{ij} – rank of alternative i under criterion j.

The Borda Count Method can be modified to consider importance of criteria. Aggregated score of alternative, called SAR (Simple Additive Ranking), is calculated as:

$$SAR(a_i) = \frac{1}{n} \sum_{j=1}^{m} w_j (n - n_{ij}), \quad i = 1, 2, \ldots, n, \tag{4.2}$$

with constraints:

$$\sum_{j=1}^{m} w_j = 1, \tag{4.3}$$

$$w_j \geq 0, \tag{4.4}$$

where w_j – weight of criterion j.

In Condorcet procedure alternative a_r is preferred over a_s if and only if $a_{rj} > a_{sj}$ in more than 50% of criteria. Making pairwise comparison for all alternatives can select a Condorcet winner – the alternative which is preferred to all others. A Condorcet winner will not always exist.

Copeland's method (Saari and Merlin, 1996), is natural extension of the Condorcet winner. In pairwise comparison a_r to a_s, alternative a_r receives score:

$$v_{rs} = \begin{cases} 1 & -\text{if } a_r \text{ is prefered over } a_s \\ 1/2 & -\text{if } a_r \text{ and } a_r \text{ are tied} \\ 0 & -\text{if } a_s \text{ is prefered over } a_r. \end{cases} \tag{4.5}$$

Ranking alternatives is crated based on the Copeland score:

$$CP(a_i) = \sum_{s \neq i} v_{is}, \quad i = 1, 2, \ldots, n, \ \ s = 1, 2, \ldots, n. \tag{4.6}$$

In the Bernardo method (Lansdowne, 1996; *Hwang* and Lin, 1987) ranking of alternatives is determined by maximum agreement between overall ranking and rankings for each criterion. An agreement matrix $\mathbf{P} = [p_{rs}]$ with entries p_{rs} which represent number of rankings where alternative r is placed in s position. A binary decision variables x_{rs} decide, whether alternative r is placed in s position in overall ranking. To achieve consistency in final ranking with the agreement matrix we must solve binary problem:

$$\max : z = \sum_{r=1}^{n} \sum_{s=1}^{n} x_{rs} p_{rs} \ , \tag{4.7}$$

subject to:

$$\sum_{r=1}^{n} x_{rs} = 1, \quad s = 1, 2, \ldots, n, \tag{4.8}$$

$$\sum_{s=1}^{n} x_{rs} = 1, \quad r = 1, 2, \ldots, n, \tag{4.9}$$

and

$$x_{rs} \in \{0, 1\}, \ \ r = 1, 2, \ldots, n, s = 1, 2, \ldots, n. \tag{4.10}$$

In the Arrow and Raynaud's ranking procedure (Lansdowne, 1996; Munda, 2008), the first step is to create outranking matrix $\mathbf{A} = [q_{rs}]$. An element q_{rs} indicates number of criteria for which alternative a_r is ranked higher than a_s.

In step k of algorithm for each row of the matrix (a square matrix of order n) the maximum value of entries is identified and next the minimum value of them is chosen (when some alternatives are tied, one of them is selected arbitrary). This alternative corresponding to this value is placed $(n - k + 1)$th position of final ranking. If $r < n$ the row and column related to that alternative are removed. A new comparison matrix (order $n - 1$) is obtained for step $k + 1$ of algorithm. The procedure is being repeated until all alternatives are ranked.

Others algorithms based on ordinal ranking of criteria e.g. Cook-Seiford Social Choice Function, Köhler's primal and dual algorithms or the Arrow-Raynaud's dual algorithm were detailed described by Lansdowne (1996).

An example of using ordinal ranking methods for construction equipment selection

A contractor intends to buy a new excavator. The four offers $\{a_1, a_2, a_3, a_4\}$ are evaluated using following criteria: purchase cost (c_1), operating cost (c_2), productivity (c_3), service availability (c_4). To judge alternatives, order of preference was created for each criterion:

$c_1 : a_3 \succ a_2 \succ a_1 \succ a_4$,

$c_2 : a_1 \succ a_3 \succ a_2 \succ a_4$,

$c_3 : a_4 \succ a_2 \succ a_1 \succ a_3$,

$c_4 : a_3 \succ a_1 \succ a_2 \succ a_4$.

Calculated values of the Borda Count according to Eqn. (4.1) are:

$BC(a_1) = (4-3)+(4-1)+(4-3)+(4-2) = 7$,

$BC(a_2) = (4-2)+(4-3)+(4-2)+(4-3) = 6$,

$BC(a_3) = (4-1)+(4-2)+(4-4)+(4-1) = 8$,

$BC(a_4) = (4-4)+(4-4)+(4-1)+(4-4) = 3$.

According to the Borda Count method, the order of preference is: $a_3 \succ a_1 \succ a_2 \succ a_4$, that means that a_3 is preferred over another alternatives.

In Condorcet method, by making pairwise comparison of alternatives for all criteria it can be determined that:

- a_1 is preferred over a_2 respecting 2 criteria (a_2 is preferred over a_1 2 times),
- a_1 is preferred over a_3 respecting 2 criteria (a_3 is preferred over a_1 2 times),
- a_1 is preferred over a_4 respecting 3 criteria (a_4 is preferred over a_1 1 times),
- a_2 is preferred over a_3 respecting 1 criteria (a_3 is preferred over a_2 3 times),
- a_2 is preferred over a_4 respecting 3 criteria (a_4 is preferred over a_2 1 times),
- a_3 is preferred over a_4 respecting 3 criteria (a_4 is preferred over a_3 1 times).

Outracking relations based on pairwise comparison are as follow:

$a_1 \succ a_4,\ a_2 \succ a_4,\ a_3 \succ a_4, a_3 \succ a_2$.

The Condorcet winner does not exist:

- alternative a_1 is preferred only over a_4,
- alternative a_2 is preferred only over a_4,
- alternative a_3 is preferred over a_2, and a_4 but is tied with a_1,

- alternative a_4 is not preferred any time.

Copeland scores (Eqn. (4.6)) based on pairwise comparison:

$CP(a_1) = \frac{1}{2} + \frac{1}{2} + 1 = 2$, $CP(a_2) = \frac{1}{2} + 0 + 1 = 1\frac{1}{2}$,

$CP(a_3) = \frac{1}{2} + 1 + 1 = 2\frac{1}{2}$, $CP(a_4) = 0 + 0 + 0 = 0$.

According to Copeland method order of preference is: $a_3 \succ a_1 \succ a_2 \succ a_4$.

In Bernardo method the agreement matrix is as follows:

$$\mathbf{P} = \begin{bmatrix} 1 & 1 & 2 & 0 \\ 0 & 2 & 2 & 0 \\ 2 & 1 & 0 & 1 \\ 1 & 0 & 0 & 3 \end{bmatrix}.$$

According to Eqn. (4.7), z should be maximized:

$$z = x_{11} + x_{12} + 2x_{13} + 0x_{14} + 0x_{21} + 2x_{22} + 2x_{23} + 0x_{24} + 2x_{31} + x_{32} + 0x_{33} + x_{34} + x_{41} + 0x_{42} + 0x_{43} + 3x_{44},$$

under constraints:

$x_{11} + x_{21} + x_{31} + x_{41} = 1$, $x_{21} + x_{22} + x_{23} + x_{24} = 1$,

$x_{31} + x_{32} + x_{33} + x_{34} = 1$, $x_{41} + x_{42} + x_{43} + x_{44} = 1$,

$x_{11} + x_{12} + x_{13} + x_{14} = 1$, $x_{12} + x_{22} + x_{32} + x_{42} = 1$,

$x_{13} + x_{23} + x_{33} + x_{43} = 1$, $x_{14} + x_{24} + x_{34} + x_{44} = 1$,

$x_{11}, x_{12}, x_{13}, x_{14} \in \{0, 1\}$, $x_{21}, x_{22}, x_{23}, x_{24} \in \{0, 1\}$,

$x_{31}, x_{32}, x_{33}, x_{34} \in \{0, 1\}$, $x_{41}, x_{42}, x_{43}, x_{44} \in \{0, 1\}$.

Solving equations we have: $x_{13}, x_{22}, x_{31}, x_{44}$ are equal 1 and other $x_{rs} = 0$. Obtained preference raking of alternatives is: $a_3 \succ a_2 \succ a_1 \succ a_4$.

Using Arrow-Raynaud method the pairwise comparison matrix was created: $\mathbf{A} = \begin{bmatrix} 0 & 2 & 2 & 3 \\ 2 & 0 & 1 & 3 \\ 2 & 3 & 0 & 3 \\ 1 & 1 & 1 & 0 \end{bmatrix}$, the maximum values of each row of the matrix were selected: $\begin{bmatrix} 3 \\ 3 \\ 3 \\ 1 \end{bmatrix}$.

The worst alternative is a_4 and its position in order of preference is $4-1+1=4$.

In the next step the row 4 and column 4 are deleted, so matrix a has the form $\mathbf{A} = \begin{bmatrix} 0 & 2 & 2 \\ 2 & 0 & 1 \\ 2 & 3 & 0 \end{bmatrix}$, the maximum values of each row: $\begin{bmatrix} 2 \\ 2 \\ 3 \end{bmatrix}$.

The worst alternative (chosen arbitrary between a_1 and a_2) is a_1 and its position in order of preference is $4-2+1=3$.

In the next step the row 1 and column 1 are deleted, so matrix a has the form $\mathbf{A} = \begin{bmatrix} 0 & 1 \\ 3 & 0 \end{bmatrix}$, the maximum values of each row: $\begin{bmatrix} 1 \\ 3 \end{bmatrix}$.

The worst alternative is a_2 and its position in order of preference is $4-3+1=2$. Remaining alternative a_3 is preferred according to Arrow-Raynaud method.

4.1.2. Rank ordering criteria weighting methods

The weights can be determined subjectively by decision maker, but there are many simple and effective criteria weighting methods based on criteria ranking. The most popular are rank sum, rank reciprocal and rank exponent method (Malczewski, 1999). Ranking order of criteria c_j $(j=1, 2, \ldots, m)$ is determined in respect to decision maker's preference. Number 1 is assigned to the first-ranked, 2 to second-ranked, …, m to the last ranked criterion. This ranking is like an individual preference list. So m_j is rank of j-th criterion $(j=1, 2, \ldots, m)$ in preference criteria order.

In the rank sum weight method a rank is weighted $(m-m_j+1)$ and normalized by sum of all weights:

$$w_j = \frac{(m-m_j+1)}{\sum_{k=1}^{n}(m-m_k+1)}, \quad j=1, 2, \ldots, m. \tag{4.11}$$

Inverse (or reciprocal) weights are calculated by standardization of reciprocal of a criteria rank:

$$w_{j=} \frac{1/m_j}{\sum_{k=1}^{m} 1/m_k}, \quad j=1, 2, \ldots, m. \tag{4.12}$$

In the rank exponent method the decision maker specified the weight of the most important criterion *p* on a 0-1 scale. Weights are derived based on formula:

$$w_{j=}\frac{\left(m-m_j+1\right)^p}{\sum_{k=1}^{m}\left(m-m_j+1\right)^p},\quad j=1,2,\ldots,m\ . \tag{4.13}$$

For $p = 0$ weights are equal, for $p = 1$ results in rank sum weights.

4.1.3. Multi criteria utility functions

Multi criteria utility theory assumes that utility function $U(a_i)$ can be defined, which expresses set of criteria influence on final evaluation of an alternative. Aggregation of alternatives' ratings for all criteria allows to state that a_r is preferred to a_s if and only if $U(a_r) > U(a_s)$.

The most commonly used aggregation function is weighted sum of ratings in form of:

$$U(a_i)=\sum_{j=1}^{m} w_j r_{ij},\quad i=1,2,\ldots,n\ , \tag{4.14}$$

where r_{ij} are standardized ratings and transformed to profit category. Standardization of ratings scales to interval $[0,1]$ is performed using procedure:

- for profit category criteria:

$$r_{ij}=\frac{a_{ij}-a_{j\min}}{a_{j\max}-a_{j\min}}\ , \tag{4.15}$$

- for cost category criteria:

$$r_{ij}=\frac{a_{j\max}-a_{ij}}{a_{j\max}-a_{j\min}}\ , \tag{4.16}$$

where $a_{j\max}$ – the maximum, whereas $a_{j\min}$ – the minimum value of rating against criterion j.

Standardizing ratings' scales can be performed using formulas:

- for profit category criteria:

$$r_{ij}=\frac{a_{ij}}{a_{j\max}}\ , \tag{4.17}$$

- for cost category criteria:

$$r_{ij} = \frac{a_{j\min}}{a_{ij}}. \tag{4.18}$$

4.1.4. Analytic Hierarchy Process (AHP)

<u>Decision-making with the AHP</u>

In Analytic Hierarchy Process (AHP) – originally developed by T.L. Saaty (2013) – a decision maker is asked how one factor (alternative, criterion) is more important than another. Relative dominance $a_{ij} = w_i / w_j$ is made by pairwise comparisons of factors, using scale:

- 1 – equal importance (two activities contribute equally to the objective),
- 3 – moderate importance of one over another (experience and judgment slightly favor one activity over another),
- 5 – essentials or strong importance (experience and judgment strongly favor one activity over another),
- 7 – very strong importance (an activity is favored very strongly over another; its dominance demonstrated in practice),
- 9 – extreme importance (the evidence favoring one activity over another is of the highest possible order of affirmation).

Intermediate values 2, 4, 6, 8 can be used in particular case of doubts referring to relative dominance of factors. When factor i is less important than j the following transformation is applied:

$$a_{ji} = \frac{1}{a_{ij}}, \quad a_{ij} > 0, \quad i, j = 1, 2, ..., n. \tag{4.19}$$

A decision maker makes $n(n-1)/2$ judgments located in matrix $\mathbf{A}$:

$$\mathbf{A} = \begin{bmatrix} 1 & a_{12} & \cdots & a_{1n} \\ 1/a_{12} & 1 & \cdots & a_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ 1/a_{1n} & 1/a_{2n} & \cdots & 1 \end{bmatrix}.$$

Matrix $\mathbf{A}$ is called a positive reciprocal pairwise comparison matrix.

Pairwise comparison matrix $\mathbf{A}$ is consistent if for all judgments $a_{ij}a_{jk} = a_{ik}\ (i, j, k \ldots n)$. Due to the human nature rarely matrix comparison is consistent. For example a decision maker states that factor 1 is of moderate importance over 2, factor 3 is of strong importance over 2 and simultaneously can be stated that factors 1 and 3 are of equal importance than

$a_{12} = 3, a_{23} = 1/5, a_{13} = 1$ and $a_{12}a_{23} = 3/5 \neq a_{13} = 1$ so judgments are not perfectly consistent.

Number of compared factors on the one level of analysis (criteria respect to the main goal – level 1 and priorities of alternatives respect to each criterion – level 2) should be lower or equal to 9. When number of factors is large it is difficult to express relative preferences. It affects in inconsistency of judgments in the pairwise comparison and cause that each weights would be small what can lead to misshape results.

In AHP method a priority vector is derived from the pairwise comparison matrix $\mathbf{A}$ by solving a system of homogeneous linear equations:

$$\mathbf{Aw} = \begin{bmatrix} 1 & a_{12} & \cdots & a_{1n} \\ 1/a_{12} & 1 & \cdots & a_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ 1/a_{1n} & 1/a_{2n} & \cdots & 1 \end{bmatrix} \begin{bmatrix} w_1 \\ w_2 \\ \vdots \\ w_{n1} \end{bmatrix} = \lambda \begin{bmatrix} w_1 \\ w_2 \\ \vdots \\ w_n \end{bmatrix} = \lambda \mathbf{w}, \tag{4.20}$$

where $\mathbf{w}$ is an eigenvector (of order n) and λ is an eigenvalue of matrix $\mathbf{A}$. The normalized eigenvector is also called priority vector. It expresses relative weights of factors.

The eigenvector can be derived from the characteristic function of $\mathbf{A}$:

$$(\mathbf{A} - \lambda \mathbf{I})\mathbf{w} = 0, \tag{4.21}$$

where $\mathbf{I}$ is the identity matrix (matrix with 1 on the main diagonal and 0 elsewhere).

This linear system has a nonzero solutions if and only if the determinant

$$\det(\mathbf{A} - \lambda \mathbf{I}) = 0. \tag{4.22}$$

This determinant:

$$\begin{vmatrix} a_{11} - \lambda & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} - \lambda & \cdots & a_{12} \\ \cdots & \cdots & \cdots & \cdots \\ a_{n1} & a_{n2} & \cdots & a_{nn} - \lambda \end{vmatrix},$$

is called a characteristic polynomial of matrix $\mathbf{A}$. This polynomial of degree n can be written in form: $\det(\mathbf{A} - \lambda \mathbf{I}) = c_0 \lambda^n + c_1 \lambda^{n-1} + \cdots + c_{n-1}\lambda + c_n$. His roots are the eigenvalues of matrix $\mathbf{A}$.

To obtain the weights the principal (maximum) eigenvalue $\lambda_{\max}$ and the corresponding eigenvector of the pairwise comparisons matrix should be determined. In the ideal case, when matrix is consistent $\lambda_{\max} = n$. The human nature causes that there are some disturbances in a comparison matrix, so it becomes inconsistent and $\lambda_{\max} > n$.

Several methods have been developed to approximate the principal eigenvector and largest eigenvalue $\lambda_{\max}$, for example: normalization of the column sum method, arithmetic or geometric mean method, eigenvector method, least square method, logarithmic least squares method or weighted least squares method (Kou et al. 2013). For a consistent pairwise comparison matrix weights can be calculated as normalized arithmetic mean as follow:

- normalizing matrix by dividing each number in a column of matrix $\mathbf{A}$ by its column sum:

$$b_{ij} = \frac{a_{ij}}{\sum_{i=1}^{n} a_{ij}}, \tag{4.23}$$

- calculating the vector of priority by averaging across the rows:

$$w_i = \frac{\sum_{j=1}^{n} b_{ij}}{n}. \tag{4.24}$$

One of the popular methods for deriving weights is calculating geometric means of the rows. The normalized geometric means:

$$w_i = \frac{\left(\prod_{j=1}^{n} a_{ij}\right)^{1/n}}{\sum_{k=1}^{n}\left(\prod_{j=1}^{n} a_{ik}\right)^{1/n}}, \tag{4.25}$$

are very close to the eigenvector corresponding to the largest eigenvalue of the pairwise comparison matrix. Weights determined by the geometric mean of the rows and the columns are the same.

The priorities can be obtained by raising the matrix to large powers and summing each row and dividing each sum by the total sum of all the rows (Saaty, 2013). The power method is a simple way to determine value of principal eigenvector with assumed precision ε. For every iteration k approximation of eigenvector $\mathbf{w}^{(k)}$ is calculated. Iterations are accomplished when reaching assumed accuracy in difference of approximations of eigenvector $\max\left|w_i^{2k} - w_i^{k}\right| < \varepsilon \ (\forall i,\, i = 1, 2, \ldots, n)$. a vector of weights is the vector from the last iteration. For successive iteration k its approximation $\mathbf{w}^{(k)}$ is obtained as follows:

- calculate matrix $\mathbf{A}^{2k}$,
- calculate the sum of each row:

$$Z_i = \sum_{j=1}^{n} a_{ij} , \tag{4.26}$$

- calculate the total sum of all the rows:

$$Z = \sum_{i=1}^{n} Z_i , \tag{4.27}$$

- calculate approximation of the eigenvector:

$$w_i^{(k)} = \frac{Z_i}{Z} . \tag{4.28}$$

The principal eigenvalue can be calculated as:

$$\lambda_{\max} = \frac{\sum_{j=1}^{n} a_{ij} w_j}{w_i} \ \forall i \in \{1, 2, ..., n\} . \tag{4.29}$$

When $\mathbf{w}$ is in normalized form $\left(\sum_{j=1}^{n} w_j = 1 \right)$, we obtain:

$$\lambda_{\max} = \sum_{j=1}^{n} \lambda_{\max} w_j = \sum_{i=j}^{n} \left(\sum_{i=1}^{n} a_{ij} \right) w_j = \sum_{i=1}^{n} \sum_{j=1}^{n} a_{ij} w_j . \tag{4.30}$$

The consistency of pairwise comparison matrix is measured using the Consistency Index defined as follows:

$$CI = \frac{\lambda_{\max} - n}{n-1} . \tag{4.31}$$

Saaty introduced a Random Consistency Index (*RI*), which is average *CI* of randomly generated 500 reciprocal matrixes with dimension n using scale $\{1/9, 1/8, \ldots, 1/2, 1, 2, \ldots, 8, 9\}$ (Tab. 4.1).

Tab. 4.1. Random Consistency Index (*RI*)

n	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
RI	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

A Consistency Ratio (CR):

$$CR = \frac{CI}{RI}, \tag{4.32}$$

allows to estimate inconsistency of matrix $\mathbf{A}$. When $CR \le 0.1$ matrix is sufficiently consistent. In case $CR > 0.1$ the inconsistency is not acceptable and subjective judgment should be revised.

In AHP method, the main goal, criteria and alternatives create multi-level hierarchical structure (Fig. 4.1). Decision-making process was replaced by consecutive sub-problems solving, defined at the same level. Calculations on each level of hierarchy are repeated according to the same rules, pairwise comprising, with respect to the element in the immediate upper level (for criterion and alternatives). The aim of the calculation is to determine weights (importance) of the criteria to achieve the main goal, and then statement, to what degree alternatives meet the requirements defined by criterions. Decomposition of selection the best alternative cause that on each level a relatively small number of comparisons is made including the impact of only one factor (criteria to the main goal, a preference for each alternative on each criterion). It is easier for decision maker to define relative dominance of alternatives. In case of quality criterions, pairwise comparison of relative dominance of alternatives replaces necessity of quantification of alternatives ratings. AHP method is especially useful, when the number of quality criteria is high, and ratings depend on subjective feelings of decision maker.

A decision maker should perform sensitivity analysis to find out how factors affect the main goal.

For aggregation of a final evaluation the linear additive utility function is applied:

$$\mathrm{U}(\mathrm{a_i}) = \sum_{j=1}^{m} w_j v_i^j, \; i = 1, 2, \ldots, n, \tag{4.33}$$

where w_j – local priority of criterion *j* in respect to the main goal, v_i^j – local priority of alternative *i* in respect to criterion *j*.

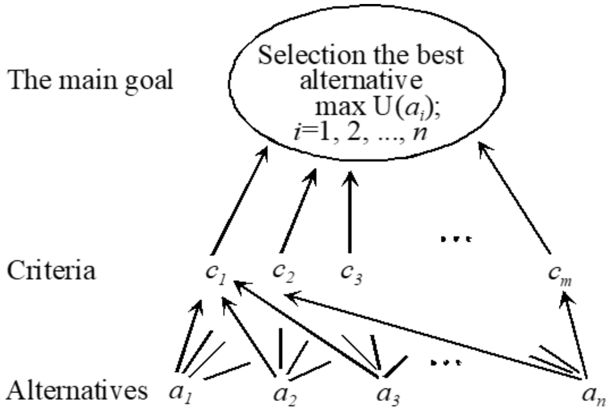


Fig. 4.1. Hierarchical tree for the AHP methodology

The final score determine a ranking of alternatives to achieve the main goal.

The algorithm of the final ranking of alternatives in AHP method is as follows:

- Developing a hierarchical structure of a decision problem (definition of the main goal, determining a list of acceptable alternatives and identifying criteria for evaluation alternatives).
- Defining the importance of criteria to the main goal:
  - Creating pairwise comparison matrices.
  - Determining the relative dominance of criteria.
  - Measuring consistency of the pairwise comparison matrices.
- Defining the preference of alternatives in respect to criteria:
  - Creating pairwise comparison matrices of alternatives for each criterion.
  - Determining the relative preference of alternatives for each criterion.
  - Measuring the consistency of pairwise comparison matrices.
- Analysis of results:
  - Calculating the final score of alternatives.
  - Determining the final ranking of alternatives.
  - Discussing and approving the final results.

A case study of supplier selecting using AHP method

The choice of criterions of supplier ratings

The right choice of supplier can influence in high degree on effectiveness of whole construction project. The choice of the right supplier can reduce the risk of exceeding of a deadline, budget overrun, risk associated with defects and malfunctions and as an effect additional costs for correcting defective works. In comparison to other economic sectors, in construction industry clients (owners) are more endangered on effects of wrong choice, because the final result of the investment and construction activity is the work of all participants of the project: designer, contractor and producer and also the supplier of building materials. In the literature many supplier selection criteria were described (Dickson, 1996). Thiruchelvam and Tookey (2011) presented 36 criteria the most often presented in the literature in years 1966–2010. Those criteria also depend on cultural conditions. For example on the German market for supplier choice a key role play lead time and customer service. Important, though not to such a great degree, are reliability and flexibility of a provider. Attention is also paid to environmental aspects. In Sweden availability is a feature more important than price, because delays in construction could lead to a huge penalty, therefore local suppliers are preferred. Ukrainian owners attach the greatest importance to the price, for this reason they prefer cheaper domestic materials. In this case, a cooperation between owner and supplier becomes easily. On the Russian market great importance has recognizability of the product (brand). Czechs whereas prefer local producers of building materials.

The most commonly used criteria for evaluating suppliers are: price, quality, potential and financial statement. Decisive choice criterion of the supplier selection is primarily the price. This is due to the fact that this is measurable and no doubt fully objective. Choice of supplier only because of the price can cause delay of some construction works or make it impossible to complete a *project* on time, the increased cost due to crews or construction equipment idle time, low quality of construction works whether the need for correction of defective works to assure owners requirements. Therefore, there is a need to implement the principles of testing the credibility of the suppliers and the procedures for selection and concluding contracts.

The price is closely related to location criterion, which influence on the cost of materials. The purchase cost of an item is the unit of purchase price from an external source including transportation costs. Cost of delivery is usually between 8 and 12% of the materials price. Location criterion will have a decisive influence on supplier of heavy building materials choice. Heavy building materials, in the lack of the clear definition of them, are usually considered as aggregate, basic materials (e.g. brick), precast concrete elements and ready concrete mix, for which delivery cost is high in relation to their value. A small distance of supplier significantly reduces the transportation time, enables close coordination of delivery data with the progress of construction works, what as a consequence reduces amount of materials stored in a construction site. This is particularly important in case of construction projects located in center of cities, where are limited areas of construction site or there are limitations of delivery sizes or delivery dates (e.g. the delivery can take place only at certain times of the day).

During the realization of complex construction projects there are also incorporated rare and hardly available materials, custom prefabricated elements (e.g. precast stadium construction). Sometimes they have high value (e.g. aluminum facades) or are not easy to approach on the local market. The contractor must look for vendors throughout the whole country. The right choice of supplier may shorten the period of delivery time or provide a higher quality.

One of the most frequently used criterion in the supplier evaluation is the quality of offered materials. Building materials must be approved for application in construction in accordance with the requirements of the specific country. In the case of buildings of significant value, it happens that a construction manager additionally requires research results, or the whole book of factory production control, and even perform tests for products on their own. Requirements for the properties of construction products and necessary requirements for their storage, transport, delivery terms and control are determined by the construction manager in the technical specification for execution and acceptance of construction works. These requirements are formulated on the basis of the relevant standards. The offer must therefore be evaluated in relation to fulfill minimum requirements described in specifications.

Potential of the suppliers is associated with the ability to deliver materials in a specific time, in ordered quantity, meeting the specified properties. The progress of the construction works may be disturbed by many factors negatively affecting the efficiency of construction works. The main source of the risk is the weather. Planning in the construction industry is burdened with high risk, because of this construction schedules quickly become outdated. The supplier must closely cooperate with construction manager and flexibly adjust the delivery size and date to continuously updated working schedules. The supplier must have an efficient management system, suitable equipment, sufficient number of concrete mixer trucks and adequate capability of a concrete plant, but above all, good financial condition.

In the supplier selection process may also be helpful implementation of the prequalification procedure of the suppliers, whereby those suppliers are eliminated, who do not meet the basic requirements. Knowledge of building materials market helps the contractor to keep a register of suppliers that facilitates and accelerates access to a group of potential tenderers. Large number of potential competitors applying for the order enables the elimination of inappropriate suppliers and shortening procurement process. The register should be periodically updated and supplemented with new potential vendors.

Example of AHP application to the supplier selection problem

The works manager must select the supplier of ready mixed concrete for the project located in the center of a big city. Due to the limited setting time (time from mixing of the ingredients till the concrete was *poured, compacted and finished must take place before the concrete reaches initial setting)* the number of potential suppliers is few. Providing a ready mixed concrete in the center of the city is difficult because of the conditions in motion. Thus, the criterion of location is more important than the others. Suppliers produce a ready mixed concrete according to the specifications, so the supplied product has very similar characteristics and quality criterion is not under consideration. Apart from the price important criterion is the potential of the concrete mixes manufacturer, understood as the ability to customize the size and delivery time to the progress of construction works (e.g. concreting on Saturdays or in the afternoon hours). Significant from the point of view of the contractor is the date and terms of payment. Deferment of payment means that for the supplied ready-mixed concrete can be paid after receiving the payment from the owner for completed works, in the worst case, shorten the loan term of works in progress. Mentioned in the literature criterion of "financial statement" in this case is irrelevant because it is relatively easy to change supplier of ready mix concrete without negative impact on the progress of construction works. In analyzed case the problem is choosing the best candidate from three potential tenderers $\{a_1, a_2, a_3\}$ using criteria: price (c_1), localization (c_2), payment terms (c_3) and potential (c_4).

The comparison of criteria with respect to the goal

As a result of pairwise comparisons it was accepted that localization has strong importance over price and payment terms and equal importance with potential. The potential has moderate advantage over the terms of payment and price. Comparing importance of the price due to payment terms it was assumed, that the price has moderate importance, due to its influence on the financial liquidity of the company. Comparison matrix can be presented in form:

$$\mathbf{A} = \begin{bmatrix} 1 & 1/5 & 3 & 1/3 \\ 5 & 1 & 5 & 1 \\ 1/3 & 1/5 & 1 & 1/3 \\ 3 & 1 & 3 & 1 \end{bmatrix}.$$

Values of criteria's weights are calculated by using power method.

Iteration I of power method k:=1.

Calculate matrix:

$$\mathbf{A}^2 = \begin{bmatrix} 1 & 1/5 & 3 & 1/3 \\ 5 & 1 & 5 & 1 \\ 1/3 & 1/5 & 1 & 1/3 \\ 3 & 1 & 3 & 1 \end{bmatrix} \begin{bmatrix} 1 & 1/5 & 3 & 1/3 \\ 5 & 1 & 5 & 1 \\ 1/3 & 1/5 & 1 & 1/3 \\ 3 & 1 & 3 & 1 \end{bmatrix} = \begin{bmatrix} 4.0000 & 1.3333 & 8.0000 & 1.8667 \\ 14.6667 & 4.0000 & 28.000 & 5.3333 \\ 2.6667 & 0.8000 & 4.0000 & 0.9778 \\ 12.000 & 3.2000 & 20.000 & 4.0000 \end{bmatrix},$$

and the following sum of each row: $Z_1(1) = 15.200$, $Z_2(1) = 52.000$, $Z_3(1) = 8.444$, $Z_4(1) = 39.200$ and sum of all rows $Z(1) = 114.844$. Normalized values of the eigenvectors are:

$$w_1(1) = \frac{15.200}{114.844} = 0.132\,,\ w_2(1) = 0.453\,,\ w_3(1) = 0.074,\ w_4(1) = 0.341\,.$$

Iteration II of power method k:=2.

$$\mathbf{A}^4 = \begin{bmatrix} 79.2889 & 23.0400 & 138.6667 & 29.8667 \\ 256.0000 & 75.0222 & 448.0000 & 97.4222 \\ 44.8000 & 13.0844 & 79.2889 & 17.0667 \\ 196.2667 & 57.6000 & 345.6000 & 75.0222 \end{bmatrix}, \ \mathbf{w}(2) = \begin{bmatrix} 0.137 \\ 0.444 \\ 0.078 \\ 0.341 \end{bmatrix},$$

hence the difference of approximations of normalized eigenvectors is:
$\mathbf{w}(2) - \mathbf{w}(1) = \begin{bmatrix} 0.005 & -0.009 & 0.004 & 0.000 \end{bmatrix}^T$.

Iteration III of power method k:=3.

$$\mathbf{A}^8 = \begin{bmatrix} 24259.0657 & 7090.0243 & 42633.2918 & 9219.9443 \\ 78694.7793 & 22999.9249 & 138299.1644 & 29909.3965 \\ 13803.5200 & 4034.3072 & 24259.0657 & 5246.3187 \\ 60514.6074 & 17686.5280 & 106350.3644 & 22999.92494 \end{bmatrix},$$

$\mathbf{w}(3) = \begin{bmatrix} 0.137 \\ 0.444 \\ 0.078 \\ 0.341 \end{bmatrix}$ and the difference of approximations of normalized eigenvectors is: $\mathbf{w}(3) - \mathbf{w}(2) = \begin{bmatrix} 0.000 & 0.000 & 0.000 & 0.000 \end{bmatrix}^T$.

It can be considered that values of weights of criteria which determines the choice of ready concrete mix supplier are:

- price (c_1) $w_1 = 0.137$,
- localization (c_2) $w_2 = 0.444$,
- payment terms (c_3) $w_3 = 0.078$,
- potential (c_4) $w_4 = 0.341$.

System of equations (Eqn. (4.20)) allows to calculate λ_{max} the largest eigenvalue of the pairwise comparison matrix. It takes the form:

$$\begin{bmatrix} 1 & 1/5 & 3 & 1/3 \\ 5 & 1 & 5 & 1 \\ 1/3 & 1/5 & 1 & 1/3 \\ 3 & 1 & 3 & 1 \end{bmatrix} \begin{bmatrix} 0{,}137 \\ 0{,}444 \\ 0{,}078 \\ 0{,}341 \end{bmatrix} = \lambda_{max} \begin{bmatrix} 0{,}137 \\ 0{,}444 \\ 0{,}078 \\ 0{,}341 \end{bmatrix}.$$

Value of λ_{max} is calculated according to Eqn. (4.30):

$$\lambda_{max} = 0.137 \cdot (1 + 5 + 1/3 + 3) + 0.444 \cdot (1/5 + 1 + 1/5 + 1) +$$
$$0.078 \cdot (3 + 5 + 1 + 3) + 0.341 \cdot (1/3 + 1 + 1/3 + 1) = 4.186.$$

The consistency index has a value:

$$CI = \frac{\lambda_{max} - n}{n - 1} = \frac{4.186 - 4}{4 - 1} = 0.062,$$

while the consistency ratio is:

$$CR = \frac{CI}{RI} = \frac{0.062}{0.89} = 0.070 < 0.1.$$

Pairwise comparison matrix was defined in a correct way.

Estimating priorities of alternatives (suppliers) with respect to criteria

For price of 1m^3 ready concrete mix criterion suppliers criterion was compared using the evaluation scale. It was stated that supplier a_1 has strong importance over supplier a_2 and moderate importance over a_3, and supplier a_3 moderate importance over a_2. Comparison matrix takes the form:

$$\mathbf{A} = \begin{bmatrix} 1 & 5 & 3 \\ 1/5 & 1 & 1/3 \\ 1/3 & 3 & 1 \end{bmatrix},$$

and local priority of suppliers in respect to the price criterion are: $[0.637 \quad 0.105 \quad 0.258]^T$, and $CR = 0.034 < 0.1$.

For other alternatives:

- localization criterion (c_2) $\mathbf{A} = \begin{bmatrix} 1 & 1/3 & 3 \\ 3 & 1 & 5 \\ 1/3 & 1/5 & 1 \end{bmatrix}$, $\mathbf{v}^{(2)} \begin{bmatrix} 0.258 \\ 0.637 \\ 0.105 \end{bmatrix}$, and $CR = 0.033 < 0.1$,
- payment terms criterion (c_3) $\mathbf{A} = \begin{bmatrix} 1 & 3 & 3 \\ 1/3 & 1 & 1 \\ 1/3 & 1 & 1 \end{bmatrix}$, $\mathbf{v}^{(3)} \begin{bmatrix} 0.600 \\ 0.200 \\ 0.200 \end{bmatrix}$,

  and $CR = 0.000 < 0.1$,
- potential criterion (c_4) $\mathbf{A} = \begin{bmatrix} 1 & 1/5 & 1 \\ 5 & 1 & 3 \\ 1 & 1/3 & 1 \end{bmatrix}$, $\mathbf{v}^{(3)} \begin{bmatrix} 0.156 \\ 0.659 \\ 0.185 \end{bmatrix}$,

  and $CR = 0.025 < 0.1$.

Final evaluation

Final evaluation represents meeting of contractor's expectations with suppliers' taking into account all criteria:

$$\mathrm{U}(\mathrm{a}_1) = 0.137 \cdot 0.637 + 0.444 \cdot 0.258 + 0.078 \cdot 0.600 + 0.341 \cdot 0.156 = 0.3018,$$

$$\mathrm{U}(\mathrm{a}_2) = 0.137 \cdot 0.105 + 0.444 \cdot 0.637 + 0.078 \cdot 0.200 + 0.341 \cdot 0.659 = 0.5375,$$

$$\mathrm{U}(\mathrm{a}_3) = 0.137 \cdot 0.258 + 0.444 \cdot 0.105 + 0.078 \cdot 0.200 + 0.341 \cdot 0.185 = 0.1606.$$

In the accepted assessment system order of preference of suppliers is the following: $\mathrm{a}_2 \succ \mathrm{a}_1 \succ \mathrm{a}_3$.

4.1.5. TOPSIS method

Decision-making using TOPSIS method

In TOPSIS method (**T**echnique for **O**rder **P**reference by **S**imilarity to **I**deal **S**olution) final evaluation rely on measurement of similarity to the ideal alternative, whose ratings for all criteria receive the most beneficial values. Criteria can belong to profit and cost categories.

Steps in TOPSIS method (Yousefzadeh, 2013):

- calculating normalized ratings:

$$r_{ij} = \frac{a_{ij}}{\sqrt{\sum_{i=1}^{n} a_{ij}^2}}, \tag{4.34}$$

where a_{ij} - criterion rating j for alternative i,

- calculating weighted ratings according to dependence:

$$v_{ij} = w_j r_{ij}, \tag{4.35}$$

- defining the ideal A^+ and negative ideal A^- point, derived from weighted ratings:

$$A^+ = \left\{v_1^+, v_2^+, ..., v_{m1}^+\right\}, \tag{4.36}$$

where $v_j^+ = \left((\max_i v_{ij} \middle| j \in C_1), (\min_i v_{ij} \middle| j \in C_2)\right), i = 1, 2, ..., n$ and

$$A^- = \left\{v_1^-, v_2^-, ..., v_{m1}^-\right\}, \tag{4.37}$$

where $v_j^- = \left((\min_i v_{ij} \middle| j \in C_1), (\max_i v_{ij} \middle| j \in C_2)\right), i = 1, 2, ..., n$,

while v_j^+ and v_j^- are coordinates of the ideal and negative ideal point in space of ratings of criteria, C_1 and C_2 are subsets of criteria belonging to profit and cost categories,

- calculating Euclidean distance from each alternative to the ideal:

$$S_i^+ = \sqrt{\sum_{j=1}^{m} \left(v_{ij} - v_j^+\right)^2}\ , \tag{4.38}$$

and the negative ideal point:

$$S_i^- = \sqrt{\sum_{j=1}^{m} \left(v_{ij} - v_j^-\right)^2}\ , \tag{4.39}$$

- calculating relative closeness to the ideal point:

$$PI_i = \frac{S_i^-}{S_i^- + S_i^+}, \tag{4.40}$$

- ranking of alternatives in descending order according to evaluation PI_i.

The formula (Eqn. (4.40)) states that from two alternatives alike distant from the negative ideal point, higher final evaluation will obtain alternative closer to segment connecting the ideal and negative ideal solutions– minimum value $S_i^- + S_i^+$. Therefore alternative with values of ratings of all criteria close to average is better than alternative with extreme values of rating – a few close to the best, other to the worst ratings. Alternatives, which obtained the same evaluation PI belong to curve $PI \cdot S^+ - (1 - PI) \cdot S^- = 0$. The idea of TOPSIS method was presented in Fig. 4.2.

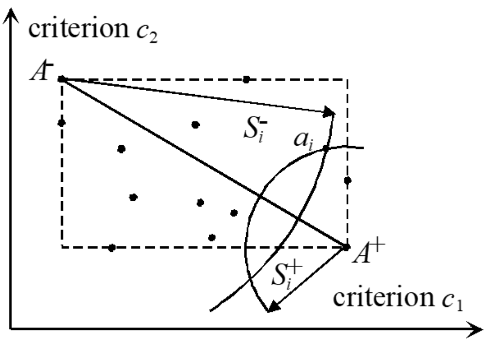


Fig. 4.2. Evaluation of alternatives using TOPSIS – Euclidean distance to the positive ideal and negative ideal solution in 2 – D space; attribute 1 – profit type, attribute 2 – cost type

<u>Example of using TOPSIS method in construction management</u>

There is problem of choosing the best offer on window frames for a residential house. Evaluation criteria were ranked from the most to the least important: c_1 – price, c_2 – thermal transmittance, c_3 – warranty and c_4 – visual value. Four joinery manufacturers made proposals (Tab. 4.2). Criterion „visual value” is subjectively rated using interval scale 1-100. Subjective ranking order for criteria is: c_1, c_2, c_3, c_4.

Tab. 4.2. Evaluating product alternatives under multiple criteria

Alternative	Price [€]	Thermal transmittance [W/m²K]	Warranty [years]	Visual value [points]
1	15000	0.8	5	50
2	17000	0.6	3	80
3	16000	0.7	7	70
4	20000	0.5	4	90

The rank sum weights are calculated according to Eqn. 3.14:

$$w_1 == \frac{(4-1+1)}{4+3+2+1} = 0.4,\ w_2 = 0.3,\ w_3 = 0.2,\ w_4 = 0.1 .$$

Normalized ratings based on Eqn. 3.37 are:

$$r_{11} = \frac{15000}{\sqrt{(15000)^2+(17000)^2+(16000)^2+(20000)^2}} = 0.438,\ r_{21} = 0.497,\ r_{31} = 0.468,\ r_{41} = 0.585 ,$$

$$r_{12} = \frac{0.8}{\sqrt{(0.8)^2+(0.6)^2+(0.7)^2+(0.5)^2}} = 0.606,\ r_{22} = 0.455,\ r_{32} = 0.531,\ r_{42} = 0.379 ,$$

$$r_{13} = \frac{5}{\sqrt{(5)^2+(3)^2+(7)^2+(4)^2}} = 0.502,\ r_{23} = 0.302,\ r_{33} = 0.704,\ r_{43} = 0.402 ,$$

$$r_{14} = \frac{50}{\sqrt{(50)^2+(80)^2+(70)^2+(90)^2}} = 0.338,\ r_{24} = 0.541,\ r_{34} = 0.473\ r_{44} = 0.608 .$$

Weighted ratings are calculated according to Eqn. 3.38:

$$v_{11} = 0.4 \cdot 0.438 = 0.175,\ v_{21} = 0.199,\ v_{31} = 0.187,\ v_{41} = 0.234 ,$$

$$v_{12} = 0.3 \cdot 0.606 = 0.181,\ v_{22} = 0.137,\ v_{32} = 0.159,\ v_{42} = 0.114 ,$$

$$v_{13} = 0.2 \cdot 0.502 = 0.100,\ v_{23} = 0.060,\ v_{33} = 0.141,\ v_{43} = 0.080 ,$$

$$v_{14} = 0.1 \cdot 0.338 = 0.034,\ v_{24} = 0.054,\ v_{34} = 0.047,\ v_{44} = 0.061 .$$

Criteria “warranty” and “visual values” are profit but “price” and “thermal transmittance” belongs to cost category, so coordinance of the ideal point are:

$$A^+ = \{0.175, 0.114, 0.141, 0.061\} ,$$

and for the negative ideal point:

$$A^- = \{0.234, 0.181, 0.060, 0.034\} .$$

Distances from alternatives to the ideal point are:

$$S_1^+ = \sqrt{(0.175-0.175)^2 + (0.181-0.114)^2 + (0.100-0.141)^2 + (0.034-0.061)^2} = 0.083,$$

$S_2^+ = 0.088,\ S_3^+ = 0.049,\ S_4^+ = 0.085.$

Distances from alternatives to the negative ideal point are:

$$S_1^- = \sqrt{(0.175-0.234)^2 + (0.181-0.181)^2 + (0.100-0.060)^2 + (0.034-0.034)^2} = 0.071,$$

$S_2^- = 0.060,\ S_3^- = 0.097,\ S_4^- = 0.075..$

Relative closeness alternatives to ideal point (Eqn. (3.43)) is:

$$PI_1 = \frac{0.071}{0.071+0.083} = 0.461,\ PI_2 = 0.405,\ PI_3 = 0.664,\ PI_4 = 0.469.$$

Descending order of alternatives according to evaluations PI_i is $a_3 \succ a_4 \succ a_1 \succ a_2$. Alternatives a_1 and a_4 are very similar.

4.2. Construction project planning with processes uncertain durations

4.2.1. PERT method

PERT network analysis

A variety of factors (e.g. climate conditions, employee motivation or leader skills of a construction manager) influence on the duration of construction projects, as well as the duration of particular tasks the project scope may be broken down into. These factors' frequency and impact depend on the project-specific, contractor-specific and location-specific conditions. A project may contain many, even thousands of activities with unique uncertainty (Hinze, 2012). Program Evaluation and Review Technique (PERT) incorporates random nature of activity durations into Critical Path Method (CPM). PERT was developed in 1958 and since then it has been a commonly used tool aiding planning of construction projects. Its popularity comes from the fact that accepted assumptions made it possible to simplify the analysis of networks under uncertainty with random activities durations.

In CPM, technical and organizational conditions of a construction project are represented in the form of an activity-on-node network, where nodes represent events (points in time) and arcs activities. A precedence relation between activities is presented as a directed graph (digraph) $G = (N, A)$, where N is a set of nodes and A is a set of ordered pairs of nodes called arcs (Demeulemeester and Herroelen, 2002). An activity connecting a predecessor event i and a successor event j is denoted as ij. The traditional precedence relation without time lag between activities ij and uv depends on the fact that activity uv starts immediately after finishing ij and is symbolically represented by $ij \prec uv$. Each activity has its own duration and requires resources (working crews, construction equipment and materials or money). Dummy activities are introduced into the network (they not consume time and resources) to model complicated technological and organizational dependencies between construction project activities.

In the network there is only one start node, which does not have any immediate predecessor and one end node without any successors. The number *i* of nodes (events) cannot be duplicated and the network should not contain cycles. In a properly constructed precedence network each node belongs to a path connecting the start node and the end node. A network is analyzed in a forward pass and in a backward pass. Forward pass determines the earliest start time and the earliest completion time for each activity in the network. Backward pass determines the latest start time and the latest completion time for each activity (Badiru, 2011).

The earliest time of occurrence for the start event, which is the date of starting a construction project is equal 0 (unless otherwise stated). For other events *j* the earliest event date t_j^0 is calculated as follow:

$$t_j^0 = \max\{t_i^0 + t_{ij}\}, \tag{4.41}$$

where t_i^0 – the earliest date of events *i* which are immediate predecessors of *j* $(i \prec j)$, t_{ij} – duration of activity ij.

The project completion time is computed as an early finish time for the end node. For the end node it is assumed that the earliest and latest dates are equal, so the latest date t_i^1 for other events i is calculated as follows:

$$t_i^1 = \min\{t_j^1 - t_{ij}\}, \tag{4.42}$$

j is successor to all events i.

For all network activities ij we can calculate (Hillier and Lieberman, 2001, Hinze, 2012; Kerzner, 2003; Ravindran, 2008):

- the earliest starting time: $t_{ij}^{0S} = t_i^0$, (4.43)
- the earliest finish time $t_{ij}^{0F} = t_i^0 + t_{ij}$, (4.44)
- the latest starting time $t_{ij}^{1S} = t_j^1 - t_{ij}$, (4.45)

- the latest finish time $t_{ij}^{1F} = t_j^1$, (4.46)
- the total float $z_{ij} = t_j^1 - \left(t_i^0 + t_{ij}\right)$. (4.47)

Activities with the total float equal 0 are critical. They form a critical path (the longest path in the network) which determine the minimum project completion time. Total float time is the amount of time by which an activity may be delayed from its earliest starting time without delaying the completion time of the project.

The authors of PERT assumed that the duration of a process (a task/activity of a network model) is a beta random variable *T*. The beta distribution with the range $\left[t_a, t_b\right]$has a density function of the form (Hinze, 2012; Law and Kelton, 1999):

$$f(t) = \frac{\left(t - t_a\right)^{\alpha-1}\left(t_b - t\right)^{\beta-1}}{\mathrm{B}(\alpha, \beta)\cdot\left(t_b - t_a\right)^{\alpha+\beta-1}}, \quad t_a < t < t_b; \alpha, \beta > 0, \tag{4.48}$$

and the beta function is defined by:

$$\mathrm{B}(\alpha, \beta) = \int_0^1 s^{\alpha-1}(1-s)^{\beta-1} ds, \tag{4.49}$$

where a and *b* are location parameters, and a and β are shape parameters.

Some possible shapes of a beta distribution are shown in Fig. 4.3. The mean, also called the expected value $E(T)$ of a random beta variable, is:

$$E(T) = \frac{\alpha \cdot t_b + \beta \cdot t_a}{\alpha + \beta}, \tag{4.50}$$

and the variance $D^2(T)$ will be calculated as follows:

$$D^2(T) = \frac{\alpha \cdot \beta \cdot \left(t_b - t_a\right)^2}{(\alpha + \beta + 1)\cdot(\alpha + \beta)^2}, \tag{4.51}$$

whereas the mode is given by the formula:

$$m = \frac{t_a(\beta - 1) + t_b(\alpha - 1)}{\alpha + \beta - 2}; \quad \alpha, \beta > 1. \tag{4.52}$$

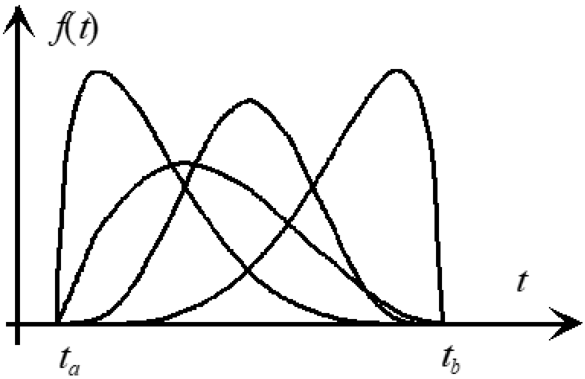


Fig. 4.3. An example of different shapes of a beta distribution

As observed in real life, the distribution function of a process duration is usually unsymmetrical and positively skewed (Fig. 4.4).

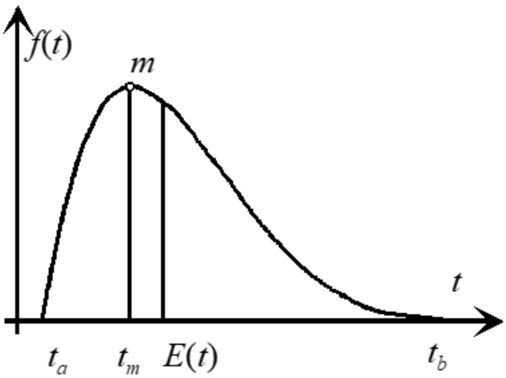


Fig. 4.4. Unsymmetrical and positively skewed a beta distribution of a process duration

In PERT method it was assumed that the mean and variance of the random variable of an activity duration are equal (Hillier and Lieberman, 2001; Malcolm et al., 1959; Ravindran, 2008):

$$E(T) = \frac{t_a + 4t_m + t_b}{6}, \tag{4.53}$$

$$D^2(T) = \frac{(t_b - t_a)^2}{36}, \tag{4.54}$$

where: t_a – optimistic time (optimistic estimation of process duration), t_b – pessimistic time, and t_m – the most likely time $(t_a < t_m < t_b)$.

It is assumed for the optimistic time that during construction work only small difficulties will occur. For the pessimistic time obstacles difficult to surmount may occur. Manager performs all of the estimations at the most likely duration (Kerzner 2003).

Creating a reliable construction schedule depends mainly on the time estimation accuracy. Standard production rates are often the basis for planning the duration of construction processes. However they do not include site specific conditions, changes in construction methods, changes of productivity caused by different experience of working crews or weather impact on activity duration, etc. To determine the process duration, historic data from previously completed construction projects can be applied. This might be too costly, time consuming and in some cases unjustified. Due to the unique character of construction projects and processes, statistical data may be of little use in the future. Application of regression and forecasting methods is risky when extrapolation outside the range of available data is performed. Estimated activities duration can be generated by simulation or derived from heuristic assumptions (Ravindran, 2008).

Group decision making methods are commonly used to evaluate time and resources for activities. That problem is collectively analyzed by a decision team including experienced engineers in special meetings. The experts' evaluation depends on their own working practice (Demeulemeester and Herroelen, 2002). Even experienced construction managers may make their evaluation on the basis of the worst case in career, which can lead to overestimations of an activity duration. The project owner's experts can have a tendency to estimate too optimistically, whereas a contractor tries to incorporate the highest level of risk within time estimation and this evaluation can be overrated.

Estimation of duration parameters should be performed separately and potential resources conflicts should not be taken into account. Time estimation should not include random factors like fire or strike (Demeulemeester and Herroelen, 2002).

In PERT method it was assumed that project completion time is a random variable with a normal distribution, as the sum of independent random variables of critical (constituting a critical path) activities duration. This assumption is based on the Central Limit Theorem:

If $E(X_1), E(X_2), \ldots, E(X_n)$ are expected values and $D^2(X_1), D^2(X_2), \ldots, D^2(X_n)$ are variances of identically distributed random variables $X_1, X_2, \ldots, X_n$ and if the number of random variables increase indefinitely $n \to \infty$, then distribution of random variable $X = X_1 + X_2 + \cdots + X_n$ converges to the normal distribution with the mean:

$$E(X) = E(X_1) + E(X_2) + \cdots + E(X_n), \tag{4.55}$$

and variance:

$$D^2(X) = D^2(X_1) + D^2(X_2) + \cdots + D^2(X_n). \tag{4.56}$$

On the basis of the Central Limit Theorem a random variable of time (date) on which an event $i\ (i = 1, 2, \ldots, m)$ can take place has a normal distribution with the mean and variance:

$$E(T_i) = \sum_{(i,j)\in L_i} E(T_{ij}),\ i = 1, 2, \ldots, m, \tag{4.57}$$

$$D^2(T_i) = \sum_{(i,j)\in L_i} D^2(T_{ij}),\ i = 1, 2, \ldots, m, \tag{4.58}$$

where the mean/variance of random variables T_{ij} of activity durations belonging to the longest path L_i from start to this event (corresponding node) are summed.

When a few paths on the same length occur in the network, the path with the highest variance is selected for the further analysis. The longest path, connecting the start and end nodes, is called a critical path. Its length determines the entire project duration.

Using transformation:

$$U_i = \frac{T_i - E(T_i)}{\sqrt{D^2(T_i)}},\ i = 1, 2, \ldots, m, \tag{4.59}$$

we get the standard normal distribution (a normal distribution with mean 0 and variance 1) of event i occurring.

The probability of the date of an *event* i being earlier than the deadline t_i^d defined for this event is equal to the probability that the standard normal distribution is less than or equal u_i (Hillier and Lieberman, 2001; Ravindran, 2008):

$$P(T_i \le t_d) = P(U_i \le u_i),\ i = 1, 2, \ldots, m, \tag{4.60}$$

where:

$$u_i = \frac{t_i^d - E(T_i)}{\sqrt{D^2(T_i)}},\ i = 1, 2, \ldots, m. \tag{4.61}$$

This probability is obtained from the table containing values of the cumulative standard distribution *U*.

For calculating the probability that the date of event i is in a time window $\left[t_a, t_b\right]$ it is necessary to solve the equation:

$$P\left(t_a \le T_i \le t_b\right) = P\left(T_i \le t_b\right) - P\left(T_i \le t_a\right),\ i = 1, 2, \ldots, m. \qquad (4.62)$$

The probability of an activity occurring on a critical path is called the criticality index. A construction manager must pay attention to activities with large criticality indexes since they have a great impact on the deadline of the entire project.

The assumption of a normal distribution for completion time of the entire project is true in situation where summed random variables are independent and where the start date of any activity takes place at the end of exactly one predecessor. The event date is determined by the longest path (the path with the highest sum of expected values of activities durations) connecting the start with this event, whereas influence of other paths on this event date is negligible. Influence of those paths can be important, especially when their length does not differ significantly from the longest path (for mean durations), and variances are higher than the variance of path included in calculations. The project duration determined in an accurate way can be even 25% longer than duration calculated according to PERT method.

<u>An example of using PERT method to project scheduling</u>

The precedence diagram of an example single storey building construction is shown in Fig. 4.5. For all activities optimistic, pessimistic and most likely estimates of their durations are given (Tab. 4.3). Based on Eqn. (4.53) and (4.54) the mean and variance of activity durations were calculated. Using Eqn. (4.41) and (4.42) the earliest and latest times for all events (Tab. 4.4) were determined using the mean of variables. It is a basis to calculate the total float of activities using Eqn. (4.47). Data are collected and presented in Tab. 4.4.

The critical path connects nodes: $1-2-3-4-5-8-10-11-12$ and the date of project completion is variable T_P normally distributed with the mean:

$$E\left(T_P\right) = E\left(T_{1,2}\right) + E\left(T_{2,3}\right) + E\left(T_{3,4}\right) + E\left(T_{4,5}\right) + E\left(T_{5,8}\right) + E\left(T_{8,9}\right) + E\left(T_{9,10}\right) + E\left(T_{10,11}\right) + E\left(T_{11,12}\right) =$$
$$4.33 + 23.67 + 17.17 + 9.17 + 0.00 + 9.50 + 12.17 + 14.17 + 12.33 = 102.51 \text{ days},$$

and variance:

$$D^2\left(T_P\right) = D^2\left(T_{1,2}\right) + D^2\left(T_{2,3}\right) + D^2\left(T_{3,4}\right) + D^2\left(T_{4,5}\right) + D^2\left(T_{5,8}\right) D^2\left(T_{8,9}\right) +$$
$$D^2\left(T_{9,10}\right) + D^2\left(T_{10,11}\right) + D^2\left(T_{11,12}\right) =$$
$$1.00 + 2.78 + 1.36 + 0.69 + 0.00 + 1.36 + 2.25 + 1.36 + 1.00 = 11.80.$$

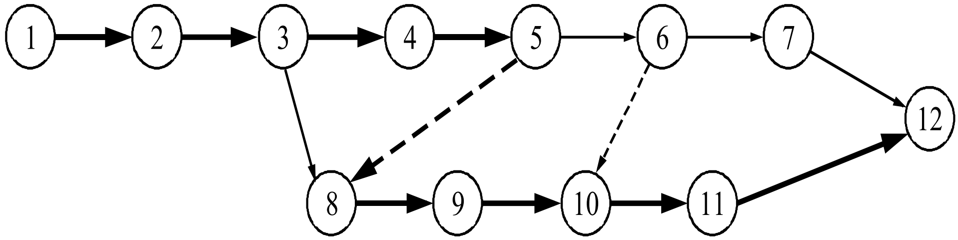


Fig. 4.5. Activity-on-node representation of an example construction project

Tab. 4.3. List of project activities and their parameters

ID	**Activity**	t_a **[days]**	t_m **[days]**	t_b **[days]**	$E(T_{ij})$ **[days]**	$D^2(T_{ij})$ **[days]**	**Total float [days]**
1 – 2	Earthworks	2	4	8	4.33	1.00	0.00
2 – 3	Foundations, walls and slabs	20	23	30	23.67	2.78	0.00
3 – 4	Roof framing	14	17	21	17.17	1.36	0.00
4 – 5	Roofing	7	9	12	9.17	0.69	0.00
5 – 6	Installation of exterior windows and doors	9	11	16	11.50	1.36	10.17
6 – 7	Finishing exterior walls	11	14	20	14.50	2.25	13.67
7 – 12	Side walk and landscape	7	8	12	8.50	0.69	13.67
3 – 8	Partition walls	16	19	25	19.50	2.25	6.84
8 – 9	Interior plastering	7	9	14	9.50	1.36	0.00
9 – 10	Sand cement screed and resilient layer	8	12	17	12.17	2.25	0.00
10 – 11	Interior painting	11	14	18	14.17	1.36	0.00
11 – 12	Floor finishing	10	12	16	12.33	1.00	0.00

The probability that construction project completion time will be shorter than the deadline $t_d = 106$ days can be calculated as follows:

$$P(T_P \le t_d) = P\left(U \le \frac{t_d - E(T)}{\sqrt{D^2(T)}}\right) = P\left(U \le \frac{106.00 - 102.51}{\sqrt{11.80}}\right) = P(U \le 1.02) = 0.85.$$

Tab. 4.4. The earliest and latest time for events of the example network

Node	**Earliest time [days]**	**Latest time [days]**
1	**0.00**	**0.00**
2	**4.33**	**4.33**
3	**28.00**	**28.00**
4	**45.17**	**45.17**
5	**54.34**	**54.34**
6	65.84	76.01
7	80.34	94.01
8	**54.34**	**54.34**
9	**63.84**	**63.84**
10	**76.01**	**76.01**
11	**90.18**	**90.18**
12	**102.51**	**102.51**

The probability that the completion project time is in the range of $[100, 110]$ days can be computed as follows:

$$P(t_a \leq T_P \leq t_b) = P(T_P \leq t_b) - P(T_P \leq t_a) = P(T_P \leq 110) - P(T_P \leq 100) =$$

$$P\left(U \leq \frac{110 - 102.51}{\sqrt{11.80}}\right) - P\left(U \leq \frac{100 - 102.51}{\sqrt{11.80}}\right) =$$

$$P(U \leq 2.18) - P(U \leq -0.73) = P(U \leq 2.18) - (1 - P(U \leq 0.73)) =$$
$$0.98 - (1 - 0.77) = 0.75.$$

4.2.2. Monte Carlo simulation for PERT network analysis

As popular tool as PERT method used for planning of construction projects under uncertainty is Monte Carlo simulation. Advantage of the simulation method is possibility to analyze networks consisting of activities whose duration is described by any probability distributions, without any additional simplifying assumptions. Simulation method allows to model any time, resource and precedence constraints. Such limitations exist in the implementation of construction projects, while cooperating with each other a large number of designers, subcontractors and suppliers.

Due to the unique character of construction project it is mostly assumed that activities duration are PERT-beta, triangular and uniform distributions.

The triangular distribution with lower limit t_a, upper limit t_b and mode t_m where $t_a < t_b$ and $t_a \le t_m \le t_b$ has a density function (Fig. 4.6):

$$f(t) = \begin{cases} \dfrac{2(t - t_a)}{(t_m - t_a)\cdot(t_b - t_a)} & \text{dla } t_a \le t \le t_m \\ \dfrac{2(t_b - t)}{(t_b - t_m)\cdot(t_b - t_a)} & \text{dla } t_m \le t \le t_b \end{cases} . \tag{4.63}$$

The expected value and variance of the triangular distribution are:

$$E(T) = \frac{t_a + t_m + t_b}{3} , \tag{4.64}$$

$$D^2(T) = \frac{t_a(t_a - t_m) + t_b(t_b - t_a) + t_m(t_m - t_b)}{18} . \tag{4.65}$$

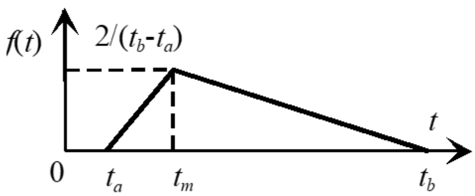


Fig. 4.6. The probability density function of the triangular distribution with lower limit t_a, upper limit t_b and mode t_m

The triangular distribution is simple and easy to interpret, even for people not related to the modeling of construction processes. Sometimes the triangular distribution is called „lack of knowledge" distribution. The lower limit t_a, upper limit t_b and the mode t_m are the same as optimistic, pessimistic and most likely times in PERT.

In cases when only the lower t_a and upper limit t_b of an activity duration can be easily estimated, while it is difficult to estimate the mode a uniform distribution may be used. The probability density function of the continuous uniform distribution (Fig. 4.7) is:

$$f(t) = \begin{cases} \dfrac{1}{t_b - t_a} & \text{for } t_a \le t \le t_b \\ 0 & \text{for } t < t_a \text{ or } t > t_b \end{cases} . \tag{4.66}$$

The mean and variance of the uniform distribution are:

$$E(T)=\frac{1}{2}(t_a+t_a), \tag{4.67}$$

$$D^2(T)=\frac{1}{12}(t_b-t_a)^2. \tag{4.68}$$

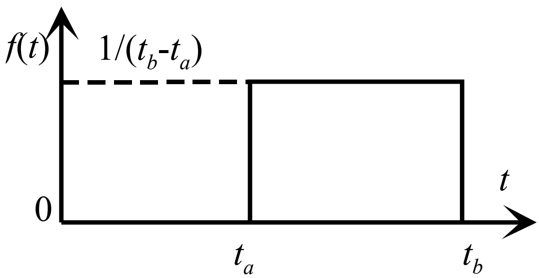


Fig. 4.7. The probability density function of the uniform distribution with the lower t_a and upper limit t_b

A goal of Monte Carlo simulation in a construction project planning is determining the mean (expected value), variance or type and others parameters of a probability distribution events $i\,(i=1,2,\ldots,m)$ times of a network. The network is analyzed repeatedly. In each replication $k\,(k=1,2,\ldots,n)$ duration times are drawn for each activity from the appropriate distributions and then earliest times t_{ik}^0 for all events are calculated using CPM algorithm. Each simulation trial allows to make observations t_{ik}^0 of event times. The data t_{ik}^0 obtained from running simulation are examined and usually grouped and presented as a histogram of an output probability distribution, what facilitates to find the distribution that the best fits the data. Collecting simulation outputs allows to estimate the mean and variance of event times T_i^0. Random variables T_{ij}^0 (random sample of size n for each event times) are corresponding to randomly selected observations t_{ij}^0.

An unbiased estimator of the true population mean $\mu=E(T_i^0)$ is the sample mean (Singh, 2009):

$$\hat{\mu}_i=\frac{1}{n}\sum_{k=1}^{n}T_{ik}^0,\ i=1,2,\ldots,m. \tag{4.69}$$

An unbiased estimator of the variance $\sigma_i^2 = D^2\left(T_i^0\right)$ is the sample variance:

$$\hat{\sigma}_i^2 = \frac{1}{n-1}\sum_{k=1}^{n}\left(T_{ik}^0 - \hat{\mu}_i\right)^2, \; i = 1, 2, ..., m. \tag{4.70}$$

The means $E\left(T_i^0\right)$ and variances $D^2\left(T_i^0\right)$ are unknown then variables:

$$\hat{T}_i = \frac{\hat{\mu}_i - E\left(T_i^0\right)}{\hat{\sigma}_i \big/ \sqrt{n}}, \; i = 1, 2, ..., m, \tag{4.71}$$

have a Student's *t*-distribution with $n - 1$ degrees of freedom.

From tables containing values of the Student's t distribution with $n-1$ degrees of freedom can be obtained t_α critical values for assumed significance level α that:

$$P\left\{-t_\alpha < \hat{T}_i < t_\alpha\right\} = 1 - \alpha, \; i = 1, 2, ..., m. \tag{4.72}$$

Hence the confidence interval for the mean $E\left(T_i^0\right)$ will be calculated as follows:

$$P\left\{\hat{\mu}_i - t_\alpha \frac{\hat{\sigma}_i}{\sqrt{n}} < E\left(T_i^0\right) < \hat{\mu}_i + t_\alpha \frac{\hat{\sigma}_i}{\sqrt{n}}\right\} = 1 - \alpha, \; i = 1, 2, ..., m. \tag{4.73}$$

and the length confidence interval for event time i is equal:

$$d_i = 2t_\alpha \frac{\hat{\sigma}_i}{\sqrt{n}}, \; i = 1, 2, ..., m. \tag{4.74}$$

The most commonly used significance level is $\alpha = 0.05$. The $1-\alpha$ confidence level is the probability of selecting such range that the true value of the parameter will be in that range. The higher the value of significance level, the wider the confidence interval, and therefore less accurate the parameter estimation. Designing simulation experiments should be aimed to minimize the length of confidence intervals. One of the primary ways of narrowing the confidence interval is to increase the number of replications but this extends the simulation tests. Usually small number of n_1 initial replications is performed to evaluate a length d_{1i} of confidence intervals for event times (Chung, 2004):

$$d_{1i} = 2t_\alpha \frac{\hat{\sigma}_i}{\sqrt{n_1}}, \; i = 1, 2, ..., m, \tag{4.75}$$

where $\hat{\sigma}_i$ is the standard deviation estimator – see Eqn. (4.70).

When the precision level d_i for each activity was arbitrary selected, using the deviation estimator derived from n_1 initial replications, number n_2 of simulation runs must comply:

$$d_i = 2t_\alpha \frac{\hat{\sigma}_i}{\sqrt{n_2}} = \frac{d_1\sqrt{n_1}}{\sqrt{n_2}}, \; i = 1, 2, ..., m, \tag{4.76}$$

and then number of required replications:

$$r_2 = \frac{d_{i1}^2}{d_i^2} n_1, \; i = 1, 2, ..., m. \tag{4.77}$$

The precision level must be obtained for all estimating event times of a network. In many cases a number of replications is determined in such way, that the length of confidence interval was small fraction (e.g. 10%) of estimated time (the relative precision approach).

For drawing values from a distribution of variable there are random numbers needed. Numbers are random when each number in a given random sequence occurs with the same frequency. Random numbers generated by using algebra equations are called "pseudo-random". They are obtained by using pseudo-random generators. The most known the congruential generator is based on the recursive relation (Singh, 2009):

$$x_{r+1} = (ax_r + b) \cdot (\text{mod } m), \; r = 1, 2, \ldots, \tag{4.78}$$

where: numbers a – multiplier and *c* – increment are given integers, the starting integer value x_1 is known as the seed, and the *m* is a large integer.

A repetition period of random numbers of exactly *m* can be achieved with appropriate choices of *a*, *b* and *m*. Period should exceed the amount of numbers which are needed in the planned simulation experiment, because that's the point where the sequence repeats. The pseudo-random numbers are reproducible (the order of their occurrence is predictable). It helps in verification of a simulation program and the identical sequence of numbers facilitate to compare variants in "what-if" analysis.

The uniform distribution on the interval (0, 1) is obtained by standardization range of generated number by dividing random number by period *m*. Sampling values from a continuous random variable *T* with a probability density function *f*(*T*) and cumulative distribution function *F*(*T*) enables solving the equation (the inverse transform method) (Law and Kelton, 1999; Singh, 2009):

$$T = F^{-1}(U). \tag{4.79}$$

Number u_i is sampling from the uniform distribution and solving Eqn. (4.79) enables to return number t_i (Fig. 4.8).

A variety of efficient algorithms to generate the various continuous and discrete random variables was elaborated (Law and Kelton, 1999). They are in-built in simulation packages for analysis construction projects in random conditions. In some of them e.g. @RISK (Palisade) for generating values with beta distribution it is required to identify four parameters $[t_a, t_b, \alpha, \beta]$: lower limit t_a, upper limit t_b and shape α, β parameters. Basing on optimistic, pessimistic and most likely estimations we must determine α and β shape parameters.

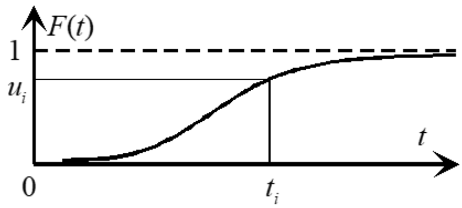


Fig. 4.8. Generating random variable *T* with cumulative distribution function *F*(*T*)

Comparing the mean of beta distribution (Eqn. (4.43)) to the PERT mean (Eqn. (4.46)) and the beta variance (Eqn. (4.44)) to the PERT variance (Eqn. (4.47)) we get system of equations which allows to determine unique shape parameters. Davis (2008) proofs that:

$$\alpha = \left(\frac{2(t_b + 4t_m - 5t_a)}{3(t_b - t_a)} \right) \left[1 + 4 \left(\frac{(t_m - t_a) \cdot (t_b - t_m)}{(t_b - t_a)^2} \right) \right], \tag{4.80}$$

$$\beta = \left(\frac{2(5t_b - 4t_m - t_a)}{3(t_b - t_a)} \right) \left[1 + 4 \left(\frac{(t_m - t_a) \cdot (t_b - t_m)}{(t_b - t_a)^2} \right) \right]. \tag{4.81}$$

4.3. Project performance monitoring and prediction

4.3.1. Earned Value

In the course of a project, information on its status (behind or ahead of schedule?; over or under budget?), the scale of current variances from the plan, and the reasons for such variances provide a key input for the project control decisions (Burke 2006).

Earned Value is a tool that uses information on cost, schedule and work performance to establish the current status of the project. Although it is based on a simplified model of a project (S-curves of cumulated as-planned and actual cost – Fig. 4.9), it proved useful and became a standard in project management (PMBOK 2009).

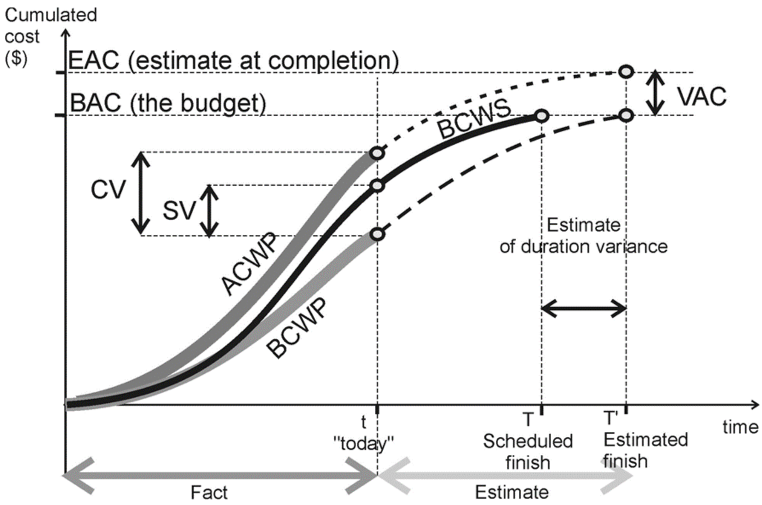


Fig. 4.9. Earned Value curves

The analysis requires the following input (Burke 2006):

- *BCWS* – Budgeted Cost of Works Scheduled – the project schedule – a baseline for the analysis, represented as cumulated planned costs related to time of their incurrence.
- *BCWP* – Budgeted Cost of Work Performed – a measure of physical progress of works expressed by cumulated planned cost of works actually done related to time, it is also called Earned Value.
- *ACWP* - Actual Cost of Work Performed – cumulated actual cost works actually completed so far, related to time.
- *BAC* – Budget at Completion – total as-planned cost of the whole project, it equals *BCWS* at the planned finish.
- *T* – as-planned duration of the project.

On this basis, simple indicators of the project's status can be calculated. The purpose of it is to detect any deviation as soon as possible, so that there is enough time to asses if the deviation is dangerous for the project and, if necessary, to take corrective actions. Therefore, the method requires a disciplined approach to the collection of data on cost and progress of tasks. Fig. 4.9 presents the idea of the method.

PC – Percentage Complete – compares the planned cost of work completed so far to the total planned cost of the project:

$$PC = \frac{BCWP}{BAC}\,. \tag{4.82}$$

CV – Cost Variance – is a measure of deviation between planned and actual cost of works done until the date of progress check. It is expressed in monetary units. If negative, it indicates that the project is over budget:

$$CV = BCWP - ACWP\,. \tag{4.83}$$

To capture the scale of deviation, it is often expressed as a fraction of the budgeted cost of works performed:

$$CV\% = \frac{CV}{BCWP} \cdot 100\%\,, \tag{4.84}$$

or as *CPI* – Cost Performance Index – that compares the planned and actual value of works done (if less than 1, it indicates that the project has consumed more money than planned, if greater than 1, there have been savings):

$$CPI = \frac{BCWP}{ACWP}\,. \tag{4.85}$$

SV – Schedule Variance – is a measure of deviation between the actual progress and the planned progress of works. Though it is interpreted as time deviation, it is expressed in monetary units. If negative, it indicates that less work has been done than scheduled:

$$SV = BCWP - BCWS\,. \tag{4.86}$$

To address any distortion caused by the relative value of activities, deviation from the schedule is expressed as a fraction of BCWS:

$$SV\% = \frac{SV}{BCWS}\,. \tag{4.87}$$

SPI – Schedule Performance Index – compares the planned cost of works done with planned cost of works planned:

$$SPI = \frac{BCWP}{BCWS}\,. \tag{4.88}$$

Earned Value allows the manager to extrapolate current trends of project development to predict their likely final effect by calculating estimated cost of completing the project. Such extrapolation is usually not meant as a reliable forecast, but to illustrate the possible scale of cost deviation and to urge the manager to take actions.

EAC – Estimate at Completion – is calculated at the date of reporting progress to serve as an estimate of the effect of deviations cumulated from the project's start on the total project cost, so it informs how much the project is going to be in the end, if the cost performance index *CPI* stays the same:

$$EAC = \frac{BAC}{CPI}\,. \tag{4.89}$$

EAC is not necessarily based on the assumption that future costs are going to follow the today's cost pattern. Other scenarios can be considered but, as the method rests upon a simplified model of a project, linear extrapolation is claimed to be adequate. The general *EAC* formula allows for a number of simple scenarios (Christensen 1994):

$$EAC = ACWP + \frac{BAC - BCWP}{PF}\,, \tag{4.90}$$

i.e. *EAC* is a sum of costs already committed and the reminder of the budget adjusted by a factor (*PF*) that reflects the relationship between the project's future and its past. This can be project-specific. Scenarios often assumed are as follows (Christensen 1994):

- The cost of remaining task is going to be as planned, i.e. future costs are not related to current costs, *PF*=1, so:

$$EAC = BAC + CV\,. \tag{4.91}$$

- The cost of remaining tasks is going to stay in proportion to current *CPI* as in Eqn. (4.89).
- The cost of remaining tasks will be related to current tendencies of both schedule and cost performance, so the *PF* is a Critical Ratio (*CR*), called sometimes a Schedule Cost Ratio (*SCR*):

$$SCI = CPI \cdot SPI\,. \tag{4.92}$$

4.3.2. Illustration of Earned Value calculations

Fig. 4.10 presents a fragment of a construction project's schedule. Tab. 4.5 contains input collected by the end of the 12th week of the schedule, and Earned Value status indicators calculated on their basis.

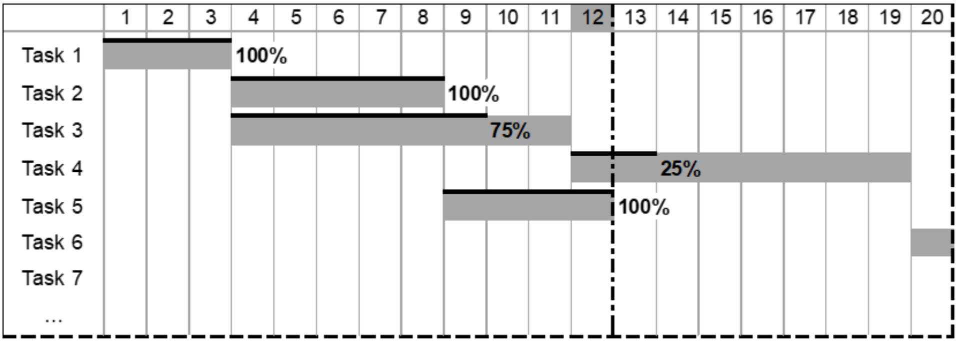


Fig. 4.10. Project schedule – example

Tab. 4.5. Results of Earned Value calculations – example

Item	***BAC*** **[PLN]**	***BCWS*** **[PLN]**	***PC*** **[%]**	***ACWP*** **[PLN]**	***BCWP*** **[PLN]**	***CV*** **[PLN]**	***CPI*** **[–]**	***SV*** **[PLN]**	***SPI*** **[–]**	***EAC*** **[PLN]**
Project	**4800**	1887.5	38	1790	1825	35	1.02	-62.5	0.97	4707.9
Task 1	**400**	**400**	**100**	**400**	400	0	1.00	0	1.00	
Task 2	**500**	**500**	**100**	**510**	500	-10	0.98	0	1.00	
Task 3	**600**	**600**	**75**	**400**	450	50	1.13	-150	0.75	
Task 4	**700**	**87.5**	**25**	**190**	175	-15	0.92	87.5	2.00	
Task 5	**300**	**300**	**100**	**290**	300	10	1.03	0	1.00	
Task 6	**300**	**0**	**0**	**0**	0	0	**-**	0	-	
Task 7	**800**	**0**	**0**	**0**	0	0	**-**	0	-	
…	…	**0**	**0**	**0**	0	0	**-**	0	-	

The input, marked bold in Table 4.5, comprises:

- A budget of the whole project (*BAC*) broken down into particular tasks.
- Actual Percentage Complete (*PC*) of each task as measured or estimated in the course of inspection (represented by black lines over schedule bars and values above them in Fig. 2).
- Actual Costs of Works Performed (*ACWS*), as measured or estimated in the course of inspection.
- Budgeted Costs of Works Scheduled (*BCWS*) read from the baseline schedule; according to the baseline, by the end of week 12, Task 3 should have been completed, so its *BCWS* = *BAC*, but Task 4 should be about 1/8 complete, so its *BCWS* = 0.125 *BAC*).

The above input is used to calculate the project performance indicators. First, Budgeted Cost of Work Performed is calculated for each task (as the product of observed percentage complete and the task's budget), and the whole project's *BCWS, BCWP, ACWP* are calculated as sums of values of all tasks.

Then, the progress of the whole project, calculated according to Eqn. (4.82), is: $PC = \frac{BCWP}{BAC} = \frac{1825}{4800} = 38\%$.

The project's *CV*, *CPI*, *SV*, and *SPI* are calculated on the basis of its *BCWS*, *BCWP* and *ACWP*. One can observe that Tasks 2 and 4 proved more expensive than planned (their *CV* is negative, and *CPI* smaller than 1), but there were some economies made on Tasks 3 and 5; the overall effect after week 12 is savings of PLN 35. If the project was to proceed with current cost performance, its total costs would drop from the planned PLN 4800 to PLN 4707.9 (*EAC* calculated according to Eqn. (4.89)).

As for the schedule performance measures, the results indicate that Task 3 is behind schedule (its *SV* is negative, and *SPI* smaller than 1), and Task 4 is more advanced than planned; as with this method positive schedule variances compensate the negative ones, the whole project is considered behind schedule in terms of scope of works by PLN -62,5.

4.3.3. Earned Value and inferences on project delay

It is worth remembering that *SV* (expressed in monetary units) and *SPI* are considered to be measures of schedule deviation, but they are in fact the measures of difference between the cost of work planned and work done. In practice they are only indirectly and approximately related to the project's time scale.

The Earned Value model of a project is linear. This does not distort cost variances and *EAC* estimates, as total cost is a simple sum of costs of tasks. Regardless of the task relationships and timing, if each task cost was raised by, say, 5 percent, the total cost would be also 5 percent greater than the initial budget. Therefore, Eqn. (4.89) is correct.

As for the schedule, the problem is more complex due to precedence relationships between tasks. As there are usually both critical and non-critical tasks in the schedule, and delay of a single task does not necessarily mean that the project finish date is going to be affected. The earned value model does not allow for this fact and each task deviation is reflected in the project's *SV* and *SPI*. Similarly, if some tasks were behind schedule and some ahead, the overall *SV* might equal 0 and indicate that the project was on schedule, even if there are actually serious delays.

Another drawback of the simplified model comes from the following fact: completed tasks cease to affect the project's schedule variance - their *SV* is always 0 (*SPI* = 1) and their *BCWP* becomes equal to *BCWS*, no matter if the tasks have been delayed or shifted to earlier of later dates. So, there are two interpretations of a task's $SV = 0$ ($SPI = 1$): the task runs according to the plan, or the task is fully completed. This quality is shared by single tasks and the whole project (Fig. 1: at the end of the project, $BCWP = BCWS = BAC$). Therefore, at a certain stage of project development (usually the last third of its duration) *SV* and *SPI* cannot be considered reliable measures of schedule deviation – either in terms of time or in terms of completed scope of works (Vandevoorde and Vanhoucke 2006). And yet another shortcoming of the Earned Value's simplified model: the assumption that the time variance stays in proportion to *SV* is wrong (Corovic 2007). This is illustrated in Fig. 4.11.

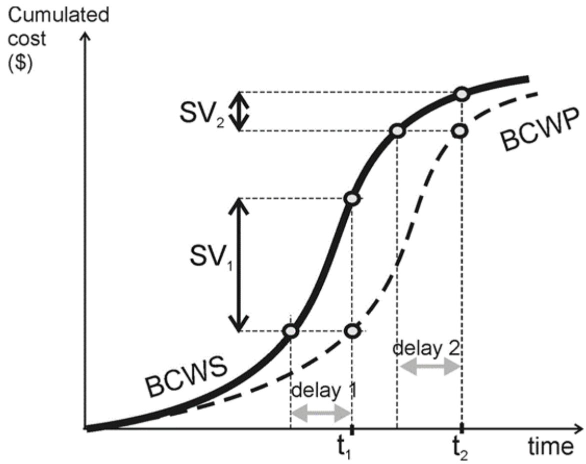


Fig. 4.11. Lack of relationship between Schedule Variance and delay

4.3.4. Earned Schedule

The literature on the subject argues that Earned Value method cannot (and has not been intended to) substitute more detailed analyses of project schedules. However, as it proved useful in cost management, a similar simple tool for schedule analysis is being looked for.

Earned Schedule (Lipke 2009, Henderson 2007) uses the same input (*BCWS, BCWP*) as Earned Value, and just like in the case of the latter method, S-curves are considered to be adequate (though simplified) models of the project's development over time. However, schedule variances $SV(t)$ is to be calculated "horizontally" and expressed in time units (Fig. 4.12). $SV(t)$ is to inform directly on how many time units the project is ahead or behind the plan.

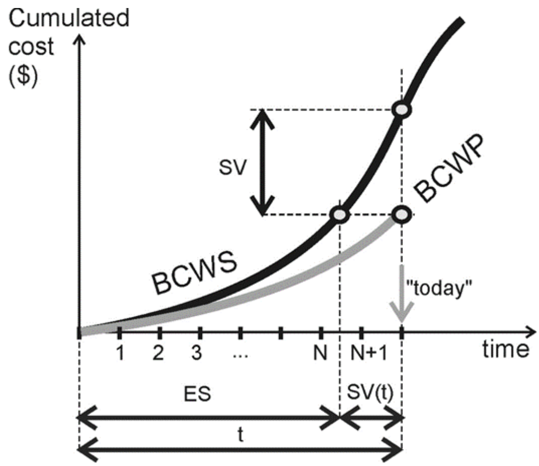


Fig. 4.12. Schedule variance according to Earned Schedule approach

SV(*t*) is a geometric distance between *BCWS* and *BCWP* measured horizontally along the time scale (Lipke 2009):

$$SV(t) = N + \frac{BCWP - BCWS_N}{BCWS_{N+1} - BCWS_N} - t\ , \tag{4.93}$$

where *N* is a number of units of time from the project start to the moment of analysis whose *BCWS* is lower than the current *BCWP* at the moment of the analysis, *BCWP* is measured at the moment of analysis (*t*), $BCWS_N$ and $BCWS_{N+1}$ are budgeted costs of works scheduled at the *N*th and at the (*N*+1) unit of time.

A website (www.earnedschedule.com/Calculator.shtml) created by the author of the Earned Schedule method, Walt Lipke, provides spreadsheets for calculating *SV*(*t*) on the basis of *BCWS* and *BCWP* data measured at consecutive units of time.

Having established the time variance *SV*(*t*) one can calculate the "earned schedule" (*ES*), i.e. the time when, according to the baseline plan, the works actually done should have been ready (see Fig. 4.12):

$$ES = t - SV(t)\ . \tag{4.94}$$

The method of extrapolating current project performance trends to roughly estimate the actual duration is similar to Earned Value's approach to extrapolating *EAC* (Eqn. (90)):

$$T' = t + \frac{T - ES}{PF}\ , \tag{4.95}$$

so actual duration is the sum of time already consumed (*t*) and the time that remained from the planned duration adjusted by a factor (*PF*) depending on the assumed relationship between the project's current and future performance. If one assumes that the rate of progress is going to follow current pattern and stay in proportion to current *SPI*(*t*):

$$SPI(t) = \frac{ES}{t}\,, \tag{4.96}$$

$$T' = t + \frac{T - ES}{SPI(t)} = \frac{T}{SPI(t)}\,. \tag{4.97}$$

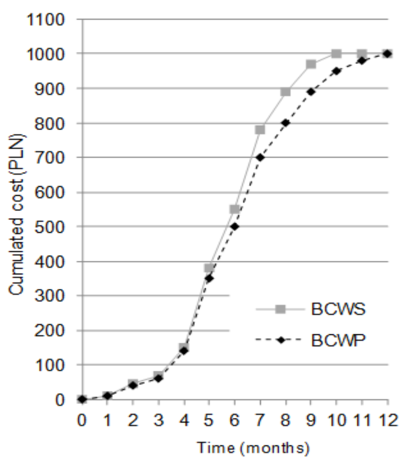
4.3.5. Illustration of Earned Schedule application

Tab. 4.6 presents *ex-post* data on consecutive monthly checks of a notional project whose budget was PLN 1000 and planned duration was 10 months. The project was completed with a two months delay. Basing on *BCWS* and *BCWP* records, schedule variances were calculated using Earned Value and Earned Schedule approach, so, respectively, according Formula 5 and Formula 12. The development of these measures of schedule deviation over time was compared in Fig. 4.13.

The results of calculations speak clearly in favor of Earned Schedule: schedule deviation *SV*(*t*) reflects the logic of project development: as the actual progress is steadily carried away from the plan, the time variance *SV*(*t*) grows and there is no distortion towards the project finish date – quite contrary to *SV* development showing first a growing negative deviation from the plan, and later considerable improvement – the latter despite the fact of the actual delays still growing.

Tab. 4.6. Example – ex-post analysis of schedule variance development by Earned Value and Earned Schedule

Month	BCWS [PLN]	BCWP [PLN]	SV [PLN]	SV(t) [month]
1	10	10	0	0.00
2	45	40	-5	-0.14
3	69	60	-9	-0.38
4	150	140	-10	-0.12
5	380	350	-30	-0.13
6	550	500	-50	-0.29
7	780	700	-80	-0.35
8	890	800	-90	-0.82
9	970	890	-80	-1.00
10	1000	950	-50	-1.25
11	1000	980	-20	-1.67
12	1000	1000	0	-2.00



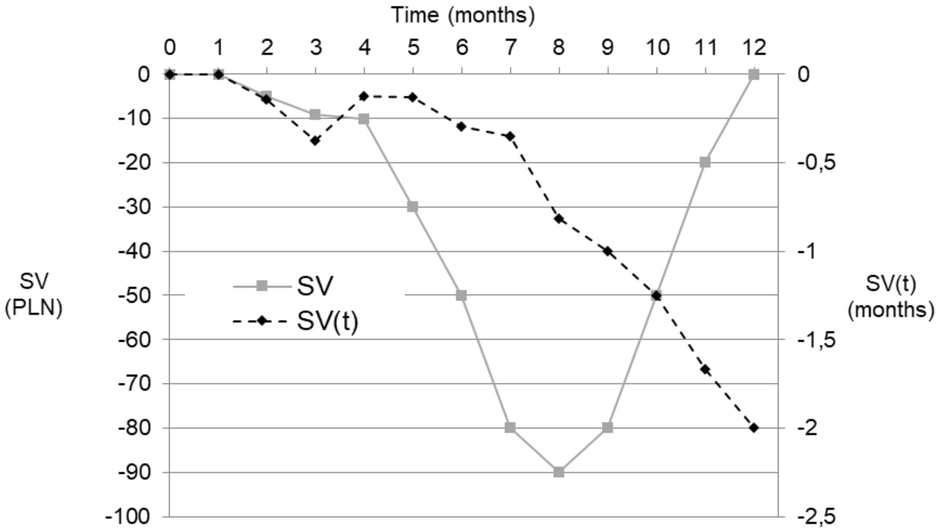


Fig. 4.13. Development of schedule variations in the example

4.3.6. Summary and conclusions

Many organizations worldwide adopted Earned Value as a standard management tool. It is described in practically all management handbooks and incorporated into management software. However, if to be implemented, the method should be used according to its purpose: it is not a tool for forecasting. Instead, it facilitates progress monitoring, determination of project status (on time? to budget?), and identification of potentially negative occurrences. Its simple idea can be – and has been – developed into whole management systems that *provide supporting data for forecasting of estimated costs; and foster discipline in incorporating changes to the baseline in a timely manner* (Department of Defense 2015). The method evolves constantly, expanded by new sets of performance measures and guidelines for more reliable forecasting of the likely further development of the project (Lipke 2009).

5. Risk Management

The risk (R) is a measure of the probability and consequence of not achieving a defined project goal (Kerzner, 2003). This definition directly indicates that risk is synthesis of two independent factors' influences:

- L – A probability (likelihood) of occurrence of certain event.
- I – Impact of the event occurring if the risk is realized.

Therefore, it can be described as follows:

$$R = f(L, I)\,. \tag{5.1}$$

Origin of the risk is the hazard (H). Part of the future, unfavorable events may be overcome by proper safeguards (S). This results in the second definition of risk (Kerzner, 2003):

$$R = f(H, S)\,. \tag{5.2}$$

The risk gets bigger with hazard and decreases with safeguard. Prophylactic is important, because "proper risk management is proactive rather than reactive" (Kerzner, 2003). For instance, if some datum whose schedule will be overrun exists, the project manager should implement turnaround plan immediately. Otherwise he may expose project to loss or failure because valuable time was wasted and applying of proper action will be problematic.

Risk management has two principal tasks (Project Risk Management, 2014):

- Increase likelihood and impact of opportunities occurrence.
- Decrease likelihood and impact of risks occurrence.

Risk management process is composed of the following stages:

- Risk planning.
- Risk assessment:
  - risk identification,
  - risk analysis.
- Risk responses planning.
- Risk Monitoring and control.

5.1. Risk planning

As it was pointed out earlier risk management is proactive rather than reactive, hence risk planning process should be implemented. This is an interactive strategy and set of methods for identifying and analyzing risk issues, expanding risk handling plans and monitoring how risk should be excluded or minimized (Kerzner, 2003). It is the process the aim of which is to (Kerzner, 2003):

- Develop and organize the strategy documents.
- Find out methods risk management.

- Arrange the resources.

The following components of risk planning can be specified:
- Inputs.
- Tools and Techniques.
- Outputs.

The inputs of risk planning process are as follows (Project Risk Management, 2014):
- Project Management Plan.
- Project Charter.
- Stakeholder register.
- Enterprise Environmental Factors.
- Organizational Process Assets.

There are three the most popular tools and techniques that can be used (Project Risk Management, 2014):
- Analytical Techniques.
- Expert Judgment.
- Meetings.

The Risk Management Plan (RMP) is the major output of risk planning. "Aim of RMP is to ensure that the risk management protocol that is used on the project is commensurate with both the risks and importance of the project to the organization" (Project Risk Management, 2014). It is worth noting that knowledge, experience, knowing tools and inside-out techniques, used by risk managers who prepared RMP, are factors of great significance, influencing quality output.

5.2. Risk issues assessment

The risk analysis is the process, which consists in assessing (evaluating) values of factors influencing on outcome of decision making in risk and uncertainty conditions (Edwards and Bowen, 1999). The more intricate and longer project is, the bigger is the risk factors impact. This is because probability of risks occurrence and their effects is more difficult to evaluate (Jaśkowski, 2015).

The risk assessment issue is composed of identifying and analyze stages. It is time-consuming and hard phase, but elaborate execution is demanded. This is because quality of assessment has a significant impact of all project's success.

5.2.1. Risk identification

The risk identification is major step of risk management process. "It is describing the competiveness conditions and the clarification of risk and uncertainly factors (Rutkauskas 2008; Zayed 2008), recognition of potential sources of risk and uncertainty events responsibilities" (Zavadskas, 2010). This stage aims to identify all potential risk sources. This step is absolutely essential despite the fact that we never recognize all risk issues. “This is because identifying risk involves detailed examination of the project, its components and its strategy, which helps the project manager and the project team to understand better the complexity of the project, its design, the site on which be erected, and likely influence of a range of external environmental factors” (Uher, 2003). This way project manager may identify possible weaknesses and opportunities, which may occur.

There is no fixed-register of risk factors (Jaśkowski and Biruk, 2010), but numerous tools for risk identification exists. The most widespread classification split these approaches into (Uher, 2003):

- Bottom-up.
- Top-down.

The bottom-up identification attempts to link different components in logical and reasonable way. The following bottom-up tools can be specified (Uher, 2003):

- A checklist method, which is analyzing a company’s former database risks.
- A financial statement method, which bases on such analyzing of account statement that would divulge sources of economic loss and theirs degree. Method’s weakness is scanning the project only on the financial side.
- A flow chart approach, which rely on showing significant elements of the process in the graphical way and then examination of it.
- Brainstorming approach, which involves project experts taking part in structured workshop.
- A scenario-building approach, which consists in creating two scenarios: optimistic and pessimistic. Both outlines have to be collated to descry potential risk’s sources.
- Influence diagram approach, which is comprehensive assessment of cause-effect relationships among project variables.

A top-down methods result in holistic view of a project from which potential sources of risk are extracted. There are two the most popular techniques that can be used (Uher; 2003):

- A case-based approach, which is case study of former similar project.
- An aggregate or bottom-line approach, which is subjective assessment of amount of risk and its impact on the project formulated by the top company’s management.

Above-mentioned tools are tasked with spying risk, which can be divided into the following classification from contractor's point of view (Zavadskas, 2010; Constructing Excellence 2006; Potts, 2008):

- External:
    - Political risk:
        - Changes in government laws of legislative system, regulations and policy.
        - Improper administration system.
    - Economic risk:
        - Inconstancy of economy in the country.
        - Repayment situation in the manufacture sphere.
        - Inflation.
        - Delayed funding.
        - Client who do not commit.
    - Social risk:
        - Inexperienced client.
    - Weather risk:
        - Extremely abnormal weather's conditions.
- Project:
    - Time risk:
        - Delay at construction, technology and for all works.
    - Cost risk:
        - The opportunity cost of product rises due to neglecting of management.
    - Work quality:
        - Deflective work.
        - Ultimate client failing to sufficiently acknowledge and reward quality and value for money.
    - Construction risk:
        - Construction delay.
        - Changes in the work and construction technology.
    - Technological risk:
        - Design errors.
        - Lack of technologies.
        - Management errors.
        - Shortage of the qualified labour.
- Internal:
    - Resource risk:
        - Material suppliers unable to meet delivery and/or cost target.
        - Faulty materials or equipment.
        - Equipment suppliers unable to meet delivery and/or cost target.
    - Project members risk:

        - Team member turnover.
        - Staffing build up.
        - Poorly trained or inadequately trained workforce.
        - Motivation, cooperation and team communication issues.
        - Coordination problems.
        - Poor guidance for operatives.
        - Staff accidents and injuries.
    - Construction site risk:
        - Contamination or unusual ground condition.
    - Documents and information risk:
        - Contradiction in documents.
        - Poor tender documents.
        - Non-standard contract documentation.
        - Pretermissions.
        - Legality.
        - Communication.

There are the following risk's sources from the investor's point of view (Godfrey, 1996; Potts, 2008):

- Political:
    - Government policy.
    - Public opinion.
    - Change in ideology.
    - Dogma.
    - Legislation.
    - Disorder (war, terrorism, riots).
- Environmental:
    - Contaminated land or pollution liability.
    - Nuisance (e.g. noise).
    - Permissions.
    - Public opinion.
    - Internal/corporate policy.
    - Environmental law or regulations.
- Planning:
    - Permission requirements.
    - Policy and practice.
    - Land use.
    - Socio-economic impacts.
    - Public opinion.
- Market:
    - Demand (forecasts).
    - Competition.
    - Obsolescence.

    - Customer satisfaction.
    - Fashion.
- Economic:
    - Treasury policy.
    - Taxation.
    - Cost inflation.
    - Interest rates.
    - Exchange rates.
- Financial:
    - Bankruptcy.
    - Margins.
    - Insurance.
    - Risk share.
- Natural:
    - Unforeseen ground condition.
    - Weather.
    - Earthquake.
    - Fire or explosion.
    - Archeological discovery.
- Project:
    - Definition.
    - Procurement strategy.
    - Performance requirements.
    - Standards.
    - Leadership.
    - Organization (maturity, commitment, competence and experience).
    - Planning and quality control.
    - Program.
    - Labour and resources.
    - Communication and culture.
- Technical:
    - Design adequacy.
    - Operational efficiency.
    - Reliability.
- Human:
    - Errors.
    - Incompetence.
    - Ignorance.
    - Tiredness.
    - Communication ability.
    - Culture.
    - Work in the dark or at night.

- Criminal:
  - Lack of security.
  - Vandalism.
  - Theft.
  - Fraud.
  - Corruption.
- Safety:
  - Regulations.
  - Hazardous substances.
  - Collisions.
  - Collapse.
  - Flooding.
  - Fire and explosion.

5.2.2. Risk analysis

"The purpose of risk analysis is to measure the impact of identified risks on a project" (Uher, 2003). According as obtainable data, the following risk analyze methods can be specified (van Westen, 2011):

- Qualitative.
- Quantitative.

Comparison between qualitative and quantitative methods is summarized in Tab. 5.1.

Qualitative methods

The result of using these techniques is qualitative description of risk using linguistic scale. These methods are employed, when acquired information does not allow to estimate risk's magnitude. This kind of assessment is often utilized for simple and straightforward approach. Appropriate application of qualitative methods allow to exchange subjective data for **trustworthy** and reliable risk evaluation. The following analysis techniques are the most popular (Project Risk Management, 2014):

- Risk Probability & Impact Assessment – studies the likelihood of each specific risk occurrence, whereas risk impact assessment investigates the possible influence on a project objectives.
- Risk/tolerability matrix – see description below.
- Risk Data Quality Assessment – involves inspecting the level of risk understanding and the accuracy, reliability, quality and integrity of the collected data regarding it.
- Risk Categorization – The risk breakdown structure is the common way to help to structure and organize all identified risks into appropriate categories, and these will help to pick up all uncertain aspects of the project.

- Risk Urgency Assessment – indicates priority risks, which requires immediate responses.
- Expert Judgment – Based on experts knowledge and experience; it points out impact of common risks on project and particular steps to be taken.

Tab. 5.1. Differences between qualitative and quantitative approaches (www.passionatepm.com, 2011)

Qualitative	**Quantitative**
Risk-level	Project-level
Subjective evaluation of probability and impact	Probabilistic estimates of time and cost
Quick and easy in application	Time consuming

Uncomplicated way to depict risk is application of simple risk/tolerability matrix (Fig. 5.1). Matrix distinguishes low/medium/high probable events, which impact on project course may be low/medium/high. In effect chart has nine fields, which has its own level of probability and impact. The most important fields are embedded in the main diameter of matrix and in the figure 1 they are highlighted by bright color. There are events, which:

- May assess significant impact and low probability level. For example, you always have to consider investor's bankruptcy with regard to great effect of these events, even so it's less probable.
- May assess medium impact and medium likelihood level. For instance, you always have to bear in mind wrong exploration of ground conditions.
- Have small impact and in all probability would happen. Delay in building material delivery, overrunning deadline, worse weather conditions than expected, often occur during construction process, but their cumulative impact on project cannot be neglected.

Other fields can be split into two groups:

- Located over the main diameter. These fields contain almost certain, major events, which shouldn't take place. If such events occur, enterprises have to take necessary steps immediately (Staniec, Zawiła-Niedźwiedzki., 2008).
- Located under the main diameter. This area includes rare, insignificant events which have not been submitted for analysis, because potential profit probably would be lower than incurred expenses.

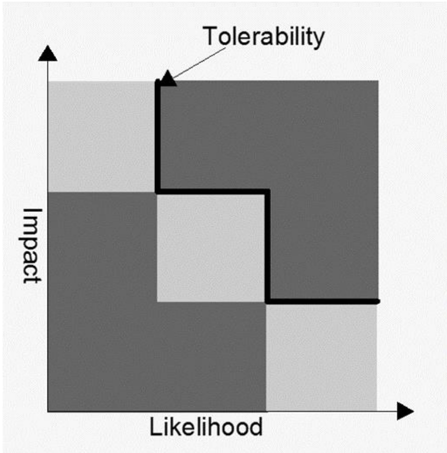


Figure 5.1. Simple risk/tolerability matrix (The Orange Book, 2004)

The risk is caused by a lack of knowledge of future events. Future, positive events are called opportunities, whereas unfavorable events are defined as risks (Kerzner, 2003).

Quantitative methods

Quantitative risk analysis attempts to find numerical assessment of probabilities for the potential consequences of risk. The major feature of stochastic process is that the result cannot be predicted with certainty (Uher, 2003). Quantitative methods are usually used for project risk management e.g. risk analysis in construction project. The ultimate choice of method is contingent of type of problem, the available experience, expertise and the capability of the computer software and hardware (Uher, 2003). There is a wide range of quantitative analysis techniques (Project Risk Management, 2014):

- Sensitivity analysis – involves examining the project to find out how outline is responsive to severity of particular risks. The outcomes of sensitivity analysis are showed shown in graphical way e.g. spider diagrams, which clearly point out crucial areas for risk management team. Fundamental weakness of this kind of analysis is independent dealing with particular risks.
- Probability analysis – in contrast to sensitivity analysis, probability evaluation doesn't consider particular risks in isolation, but it treats problem of risk assessing comprehensively and holistically. Probability analysis is a statistical method, which is often used with Monte Carlo simulation. A pivotal constituent of probability evaluation is the model, which should take into consideration diverse variables, reflecting complex nature of risk.

- Calculating risk allowances:
  - Expected monetary value analysis (EMV) – establishing expected monetary allowance need to multiply likelihood by impact for each risk (like formula 1). Each identifying risk should be assessed into three categories (or more): optimistic, most likely and pessimistic. Evaluation have to incorporate two rules: the most likely outcome must have the highest value, and total value of probability must equal 1 (Potts, 2008). Its main fault is independently treated source of risks. Tab. 5.2. shows example of using EMV method.
  - Decision trees – are employed for more complex problems for which the likelihood of events depend on previous events. It has graphical form of flow diagram. Example of using decision tree is shown in the Fig. 5.2.

Tab. 5.2. The Expected Monetary Value analysis for one identified risk

	Likelihood	**Impact [€]**	**Allowance [€]**
Optimistic outcome	0.1	10 000 saving	-1 000
Most likely outcome	0.6	40 000 extra	24 000
Pessimistic outcome	0.3	90 000 extra	30 000
Expected monetary value			53 000

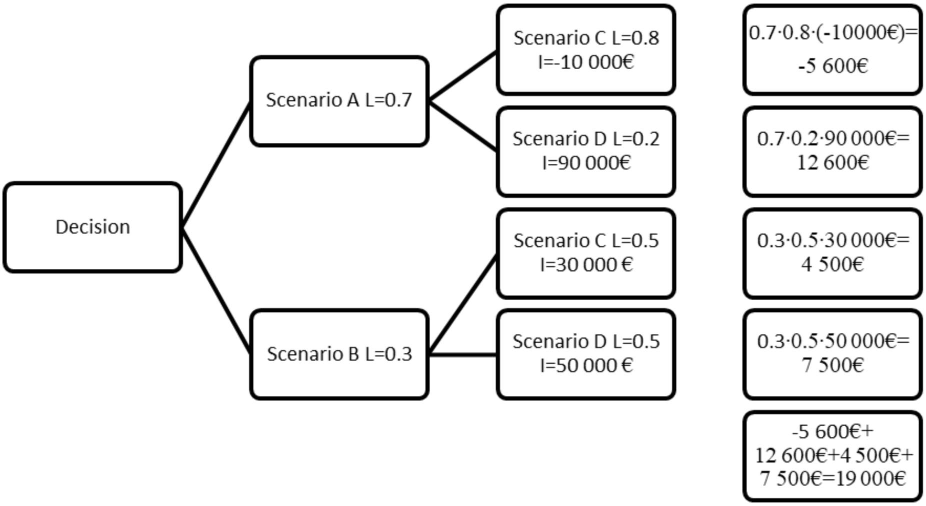


Fig. 5.2. Decision tree as risk analysis form

- Tornado diagram – shows the projects sensitivity (e.g. cost, duration) in graphical way. It displays risks impact on particular factor. Example of using Tornado diagram is shown in the Fig. 5.3.

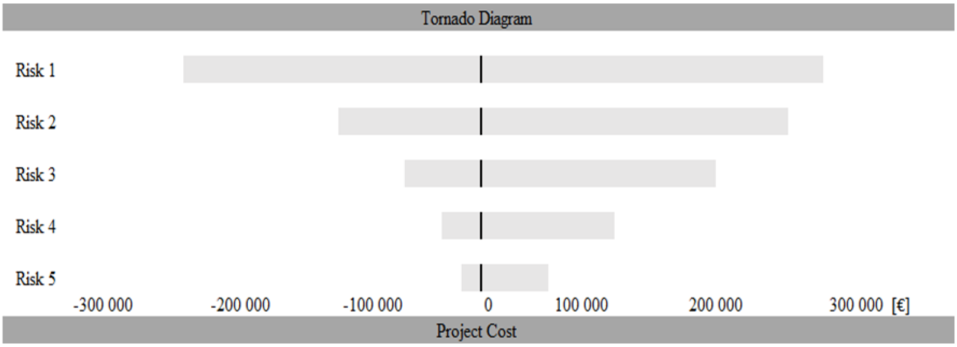


Fig. 5.3. Tornado diagram (Project Risk Management, 2014)

- Modeling & simulation – for computing the whole effects for example by using the Monte Carlo analysis (Reincke, 2006-2009).
- Expert judgment – support an optimistic, realistic and pessimistic probability and impact value for each risk (Project Risk Management, 2014).

Case study

An example to show simulation of analysis methodology was created. A system of methods used in this sample is like methodology used by Dawood (Dawood, 1998). Testing project was studied for the sake of time duration. Risk analysis involves exemplary construction project, which consists of nine activities as shown in the Fig. 5.4.

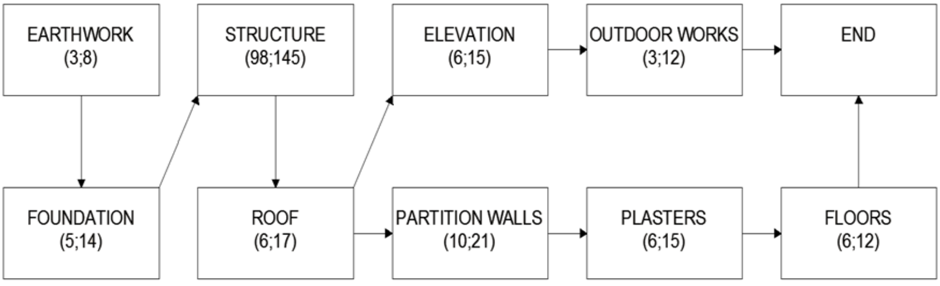


Fig. 5.4. Network of exemplary project (in brackets minimum and maximum duration, respectively)

The five risk factors affecting duration of project activity were created. They are given in the Tab. 5.3. (together with their probability distribution types). In the Fig. 5.5. the exemplary probability distribution with regard to weather conditions is presented.

Tab. 5.3. Risk factors and their probability distributions

Risk factors	**Kind of distribution**	**Values of distribution**
Weather	Triangular	0, 0.8, 1
Soil	Triangular	0, 0.9, 1
Productivity	Triangular	0, 1
Equipment	Triangular	0, 0.6, 1
Delay of materials	Triangular	0, 0.6, 1

The impact of risk factors on project activities is located in the Tab. 5.4. Obviously, this impact should be obtained as the outcome of comprehensive research, but as it was mentioned formerly, the aim of this paper is only showing the methodology.

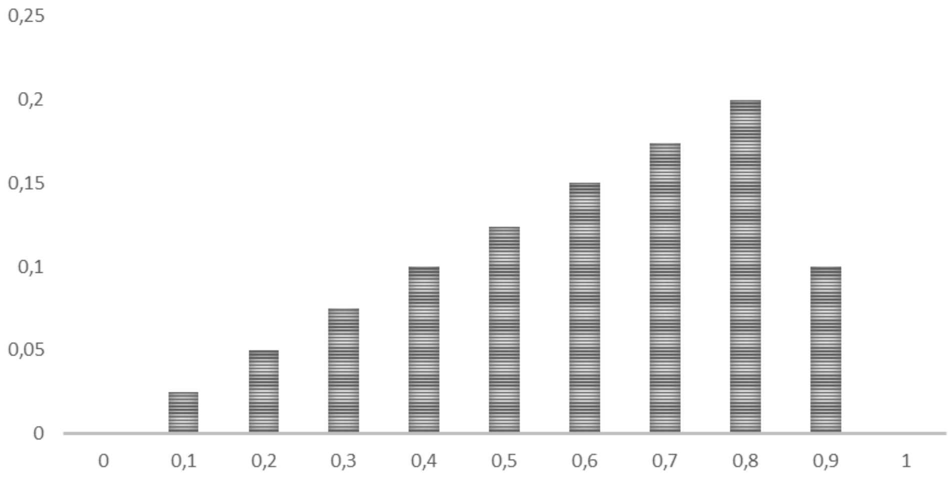


Fig. 5.5. Distribution of weather

Calculations depend on drawing five numbers (for all risk factors) with given probability. These values are multiplied by activity's impact coefficients and possible time span for every activities. This procedure was repeated 1000 times.

Simulation results are presented in figures 6–12. Theoretical timespan of the project is 134-232 days, but the least received outcome is 160 days and the highest one – 220 days. Average project time duration is 192 days with probability 4.2%, but the most probable outcome is 194 days (5.7%). Median amounts to 192 days. Likely project time span (probability more than 1%) is 176-208 days and this range is 33% of theoretical duration.

Tab. 5.4. Impact of risk factors on project activities

Activity/ Risk factor	Weather	Soil	Productivity	Equipment	Delay of materials delivery
Activity 1	0.4	0.4	0.1	0.1	0
Activity 2	0.4	0.2	0.15	0.1	0.15
Activity 3	0.3	0	0.2	0.25	0.25
Activity 4	0.4	0	0.2	0.15	0.25
Activity 5	0.35	0	0.3	0.05	0.3
Activity 6	0	0	0.4	0.25	0.35
Activity 7	0	0	0.4	0.2	0.4
Activity 8	0	0	0.4	0.2	0.4
Activity 9	0.35	0.05	0,35	0.2	0.05

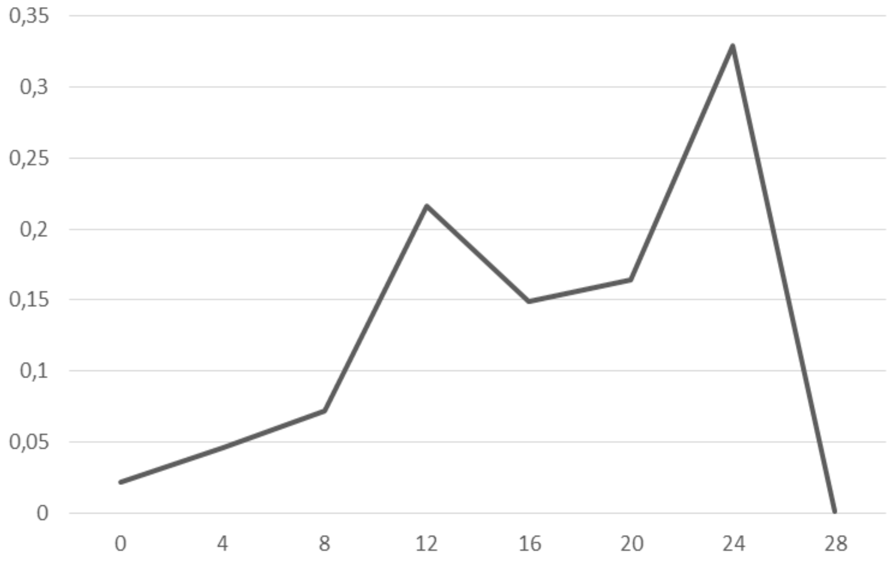


Fig. 5.6. Weather impact on project duration [days]

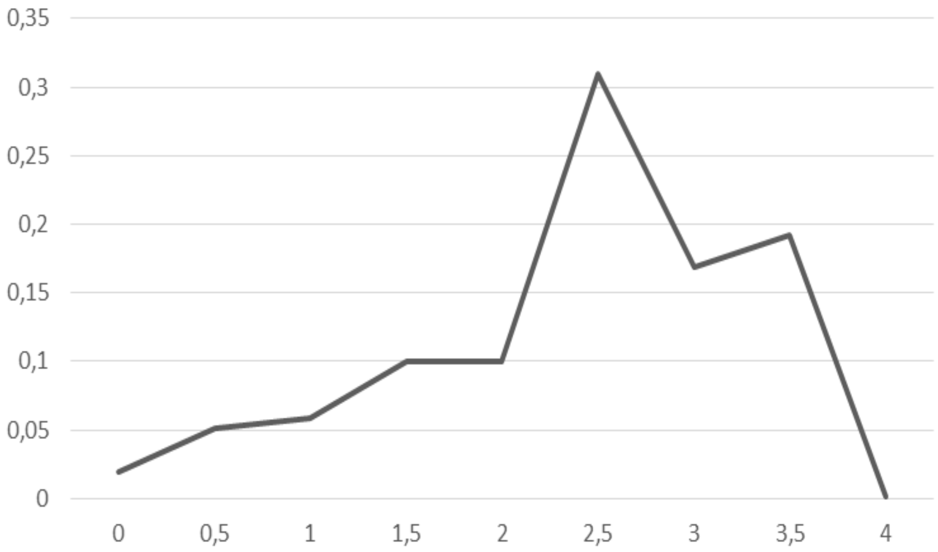


Fig. 5.7. Soil impact on project duration [days]

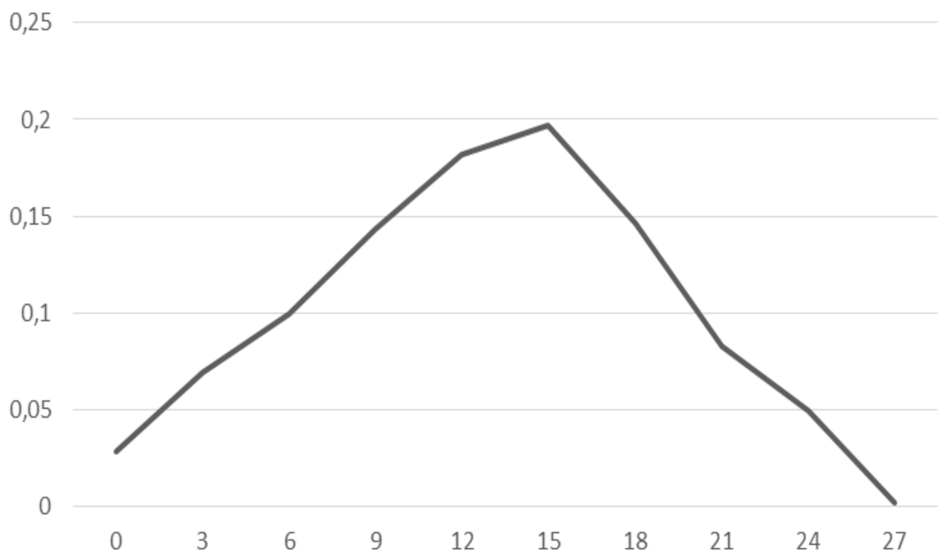


Fig. 5.8. Impact of materials delivery delay on project duration [days]

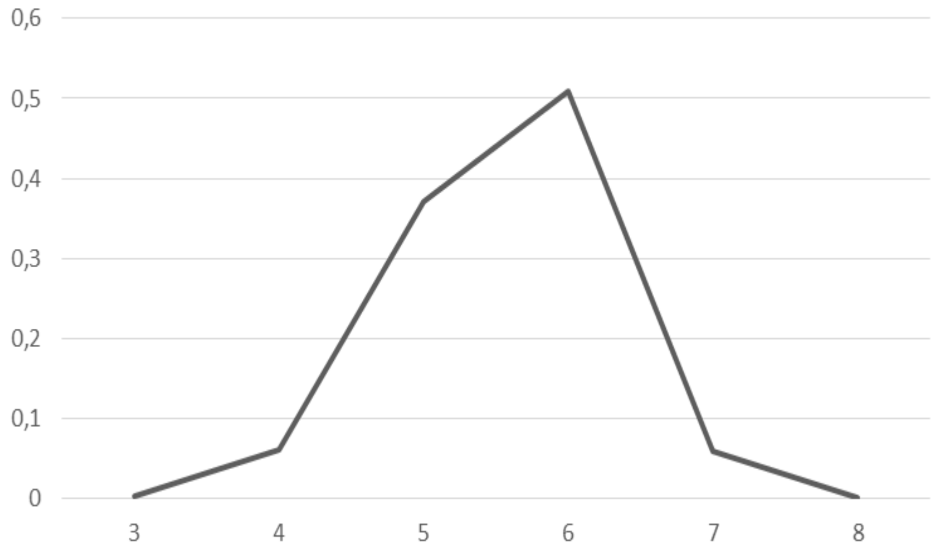


Fig. 5.9. Earthwork duration [days]

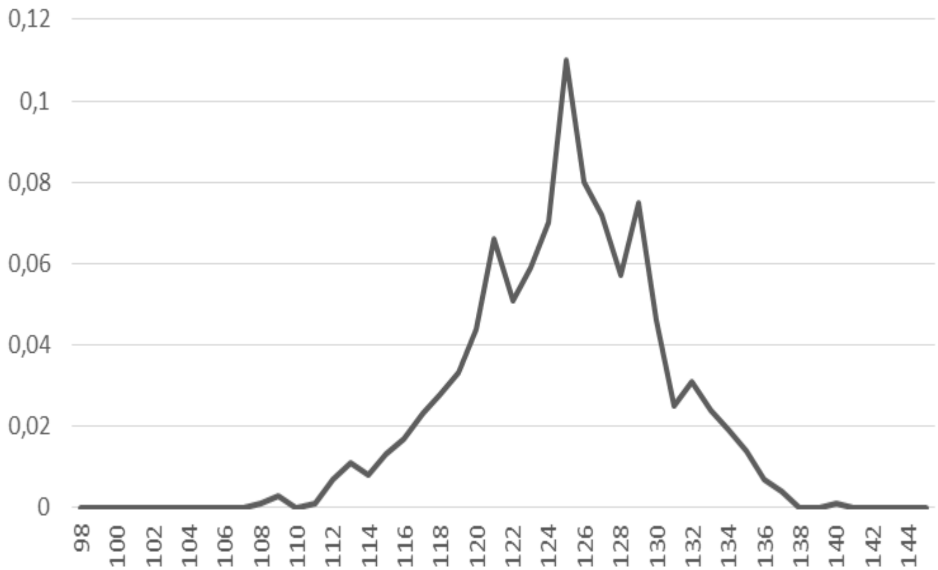


Fig. 5.10. Structure work time duration [days]

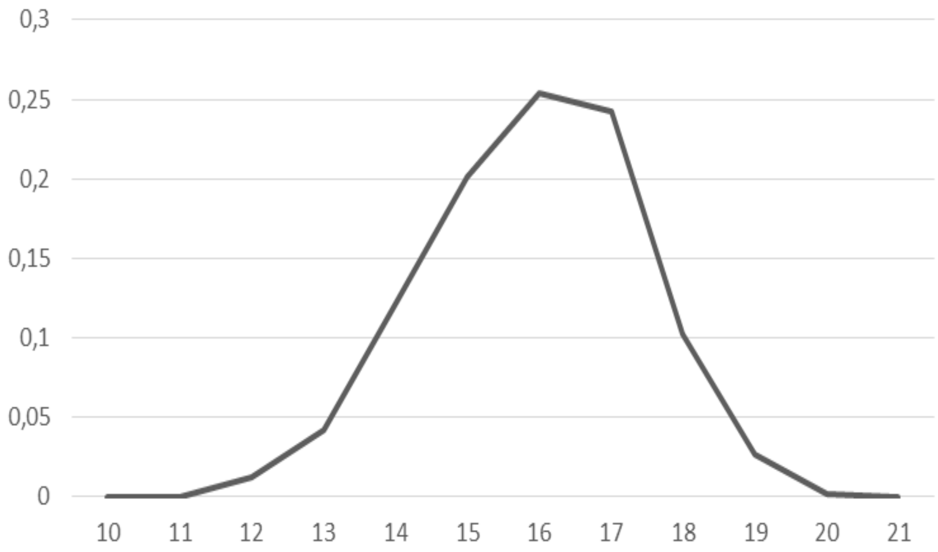


Fig. 5.11. Time duration of partition walls making [days]

Fig. 5.12. Possible time duration of all construction project [days]

5.3. Plan risk response

None of the construction projects can be deprived of risk. Risk may be managed, minimized, transferred, avoided, accepted, but it can never be ignored (Tauron et al., 2011).

The aim of risk response is to change uncertainty into the project's benefits by reducing threats and using opportunities (Orange Book, 2004). It's essential that responses are suitable for risks, cost effective in reference to the project aims and pragmatic within the project context (Project Risk Management, 2014). The risk response strategies are following (Project Risk Management, 2014; The Orange Book, 2004; De Marco, 2011; Potts, 2008):

- Strategies for negative risks:
  - Avoidance – is the most simplistic and the most popular method to minimize risks. This strategy assumes decreasing either probability of threats or its impact.
  - Transfer – demands shifting threats to other stakeholder. This third party company may be insurer who takes risks (obviously for proper premium). Other possibility is handed over risks to subcontractor on the basis of fixed-price contract.
  - Mitigate – "involves a range of activities designed to reduce project risk. These activities include scheduling risky tasks out of the project critical path, allocating resources in order to minimize negative impacts, as well as holding frequent update meetings on important project aspects among others" (De Marco, 2011).
  - Acceptance – is the least recommendable response and it is based on accepting full risk. This strategy is usually chosen in two following cases:
    - Impact or probability of risk is low.
    - Effort (cost, time, resources) of taking other strategies is on unaccepted high level.
- Strategies for positive risks:
  - Exploiting – "examples of directly exploiting responses include assigning an organization's most talented resources to the project to reduce the time to completion or provide lower cost than originally planned" (Project Risk Management, 2014).
  - Sharing – opportunities are divided among partners or team members who are able to gain more from the project. That makes that every partnership member is able to catch the benefit of the project.
  - Enhancing – depends on adding extra resources to reduce the processing time.
  - Acceptance – "accepting an opportunity is being willing to take advantage of it if it comes along, but not actively pursuing it" (Project Risk Management, 2014).

5.4. Risk control

Risks control includes following activities (Project Risk Management, 2014):

- Identified risks tracking.
- Residual risks monitoring.
- Identification of new risks.
- Effectiveness evaluation of risk handling process.

“Risk control is not a problem-solving technique, but rather, a proactive technique to obtain objective information on the progress to date in reducing risks to acceptable levels” (Kerzner, 2003). There are six tools supporting risk control process (Project Risk Management, 2014):

- Risk Reassessment – Risk Management Plan should be regularly refurbished. “The amount and detail of repetition depends on how the project progress relative to its objective” (Project Risk management, 2014). This process incorporates aspects as follow:
  - Recognizing New Risks.
  - Closing Threats that are no longer applicable.
  - Keeping under observation existing risks to figure out if any further steps are required.
- Risk Audit – the purpose of this is to assess the effectiveness of the risk management process. A risk audit investigates the project overall as well as regard to individual risks.
- Variance and Trend Analysis – which measures overall project performance. This evaluation should indicate potential time or cost overruns. The most widespread variance and trend analysis is earned value method.
- Technical Performance Measurement – is next way to indicate whether your progress is on track. This tool should point out the degree of technical risk faced by the project. Project should be measured in a quantitative way with following exemplary benchmark:
  - Response times.
  - Number of defects.
- Reserve Analysis – “compares the contingency reserves remaining to the amount of risk remaining at any time in the project in order to determine if the remaining reserve is adequate” (Project Risk Management, 2014). It is able to release some project reserve from the project, or ask for more, depending on how the project is going.
- Meetings – project’s risk, its deviation, upshifts and downshifts should be discussed at periodic meetings. Management staff, invited experts should take part in these conferences.

6. Sustainable development in construction

6.1. Introduction

Rapid industrial development in the world as a result of scientific and technological progress became a reason of excessive consumption of natural resources of the Earth and its excessive pollution. Construction based on the use of non-renewable fossil fuels and mineral resources is one of the main areas of human activity that adversely affects the natural environment. It is responsible for consumption of large amounts of energy, water and the change of the air and atmosphere's quality. The negative effects are seen in deterioration of the natural environment – a rapid rate of forest, soil and water degradation. The challenges the construction faces can be defined as follows (Kibert, 2008; Ali and Nsairat, 2009; Akadiri et al., 2012; Izadpanah et al., 2015):

- Rational use of natural resources.
- Reduction of the energy consumption of a building process.
- Improvement of the quality of life in buildings.
- Reduction of life cycle costs of buildings.
- Increase of materials' reuse and their recycling.
- Improvement of the energy efficiency in the building industry.
- Reduction of the amount of technological waste.
- Replacement of building materials harmful to the environment.
- Extension of buildings' durability.
- Efficient use of renewable energy sources.
- Increase of the consumers' awareness of the construction market.

The reduction of natural resources used and the pollution generation by construction industry are of central importance for the environment. To limit its adverse impact there is a necessity of simultaneous use of modern technologies and materials and the introduction of some changes in the behavior and consumption models, both in relation to citizens and public institutions. For the construction industry this means that besides launching of innovative technologies and products, actions helping their conscious use should be undertaken. Another aim should be to raise the awareness of building owners and users about available opportunities to shape the impact of buildings on the environment, both during their operation and decisions undertaken at the investment planning stage.

Sustainable construction pays special attention to the existence of the correlation between sociocultural sides, economic constraints and environmental issues (Yoon and Lee, 2003; Ali and Nsairat, 2009). The requirements sustainable construction face combine rational design issues, economic performance, cost-effective operation of the building, ecology and optimal conditions of use. The fulfillment of these conditions involves applying modern technologies in materials and workmanship, using renewable energy sources (solar collectors, geothermal and wind energy, use of heat pumps), deliberate interference of building architecture in the surrounding environment, etc. (Izadpanah et al., 2015).

6.2. Sustainable construction concept

The construction industry is one of the main elements of the sustainable development, whose main idea is the economic growth towards the necessary changes to ensure the satisfaction of existing social needs without limiting future generations to meet their own needs. With regard to building construction this idea is called sustainable construction (Wierzbicki and Gajowiak, 2009), which aims at the creation and the responsible management of the healthy built-up area, based on the principle of effective and ecological consumption of the natural resources. It takes into account the environmental aspect and the quality of life as well as cultural issues, social justice and economic constraints.

Sustainable construction involves designing, erecting, operating and pulling down a building in a manner consistent with 4R principle (Adamczyk and Dylewski, 2011):

- Reduction – lower use of natural resources and energy, building materials to erect a building project.
- Reuse – reuse of construction materials where it is possible.
- Recycling – recovery and recycling of materials used in a building construction and designing with materials recovery in mind.
- Renewal – execution of building components out of renewable raw materials and use of energy from natural resources, but mainly from natural carriers.

The achievement of sustainable construction goals requires a correct cooperation among designers, investors, construction industry, contractors and other stakeholders, aimed at achieving the environmental, socioeconomic and cultural objectives. The cooperation concerns such aspects as designing and managing of construction resources, choosing materials, the performance of buildings and finally, the impact on the urban and economic development. Each participant has a slightly different role in ensuring sustainability of construction industry (Siwowski, 2013).

The approach to the concept of sustainable construction is different depending on the area of building construction (residential, office and industrial buildings and infrastructure, etc.). In practice, it comes down to the multi-criteria support of the decision process at both the design stage and the evaluation of investments completed. The realization of sustainable construction depends on an individual strategy of each country and is based on the proper application of scientifically developed methods allowing the assessment and the choice of material, technology, design solutions, construction process, variant and/or strategy in order to meet the principles of sustainable development.

6.2.1. Sustainable construction aspects

Measures that are taken to achieve the objectives of sustainable construction can be divided into (Akadiri et al., 2012; Zabihi et al., 2012):

- Environmental.
- Economic.
- Social.

Tools to evaluate and compare materials, technologies and processes for sustainable development use sets of factors which accurately describe an impact and estimate an economic, environmental and social result associated with every single process. Indicators currently play an essential role in the evaluation of materials, technologies and construction processes for sustainable development (Athens and, Ferguson, 1996; Kibert, 2008; Akadiri et al., 2012).

Ecological aspect

Each building has an impact on the natural environment throughout its life cycle. Environmental activities are to minimize negative impacts on the natural environment (Ali and Nsairat, 2009; Akadiri et al., 2012; Zabihi et al., 2012), e.g. by:

- Protection of natural resources and waste mineralization.
- Reduction of energy use and CO_2 emission.
- Economical site management.
- Reduction of surface site change.
- Special recycling (use of degraded land).
- Economic water management.
- Use of renewable energy.
- Recycling of construction materials.
- Application of innovative technologies.
- Reduction of waste and pollution.

Reduction of the negative impact on the environment is a stimulator of innovative, environmentally friendly solutions, which improve the image of a building and the increased demand for ecological buildings.

Economic aspect

Lowering the cost of operating a building should not clash with the profitability of the use of environmental and energy-saving technologies. It cannot also happen at the expense of too high building price and the durability decline of applied solutions (technologies).

When selecting specific solutions in design, materials and technology it is necessary to make calculations taking into account the following costs (Ali and Nsairat, 2009; Akadiri et al., 2012; Zabihi et al., 2012):

- Investment (purchase of building plot, utility infrastructure).
- Design (elaboration of project documentation).
- Construction (costs of materials and technologies).
- Operation (fees: water, heating, energy, sewage, waste).
- Maintenance (costs of cleaning, preservation, repairs and modernization).
- Liquidation (cost of processing and waste disposal).

Lowering costs throughout a life cycle of a building comes down primarily to the reduction of its material and energy consumption by applying innovative material and technology solutions.

Social aspect

It is aimed at providing appropriate solutions in the area of living comfort, safety, aesthetics and impact on users' health. These objectives are realized through (Ali and Nsairat, 2009; Akadiri et al., 2012; Zabihi et al., 2012):

- Implementation of appropriate solutions of public transport, among other things, for the needs of the elderly and disabled.
- Prediction of possible future building extension or conversion.
- Organization of building's utility parts in relation to the directions of the world, simplicity (typical building block) and aesthetics of a building.
- Insurance of proper microclimate inside a building through the right temperature, humidity and air exchange, protection against noise, optimal lighting.

A well-designed building leads to user's satisfaction and it has an impact on his quality of life and contributes to raising building's utility and economic value.

6.3. Sustainable building design

The principles of sustainable construction concerning a construction work refer to four stages of its life cycle (Athens and Ferguson, 1996):

- Preparation (Concept).
- Realization (construction).
- Operation (use).
- Demolition (recycling).

The particular stages are the set of preparatory and executive actions, which aim at the investment realization, taking into account economic, ecological and social issues (Ali and Nsairat, 2009; Akadiri et al., 2012). This requires a rational approach to the management of resources and measures that can be defined as: the ability to identify and organize in order of priority objectives to be realized, knowledge of how to implement them, knowledge of external and internal constraints. These actions are the result of the work of organizations and people involved in the investment process.

6.3.1. Preparation

The most important stage of the investment process is the one of its preparation, during which decisions are made that affect the whole cycle of "building's life". The decisions made at this stage must be the result of multiple criteria analysis, the building's impact on the man and the environment at the stage of its building, use and demolition. The key importance of the preparation stage of the project is to select concepts and methods to achieve the assumed aim. This requires a close cooperation of all the participants within the design process. The initial concept and design assumptions may prejudge any further stages of the construction process, the building operation as well as the possibility of subsequent reuse of building elements and demolition allowing recycling.

Development of design documentation should be the result of multi-criteria optimization of the decision made with regard to the requirements of an investor (mineralization of investment costs), a user (mineralization of utility costs) and the environment (mineralization of harmful effects). Factors that should be considered in the design of sustainable building are the following (Kibert, 2008; Ali and Nsairat, 2009; Akadiri et al., 2012):

- Energy-saving (use of proper building insulation and reduction of heat loss).
- Use of alternative energy sources (e.g. solar collectors, wind farms, geothermal sources).
- Economy and reuse of building materials and management of waste and sewage.
- Taking into account the needs of potential residents (playgrounds, parking lots, green).
- Quality of indoor environment (ventilation, lighting, heating).
- Rationalization of natural resources management (land, water, air).
- Location (taking into account natural terrain and integration with the landscape).

Adopting specific design solutions referring architecture and installation requires fulfilling a number of arrangements. They are associated with the spatial planning, the media delivery method, ensuring the structural and fire safety, providing the health and hygiene conditions, the environment and landscape protection, as well as the protection against vibrations and noise.

6.3.2. Realization

The building stage plays an important role in minimizing the negative impact of construction works on the environment. However, the possibility of impact on the operation, and the efficiency of a building are much smaller than at the building design stage. During the implementation stage of construction works negative impact on the environment involves cleaning and preparation of the building site (plants and fertile soil removal, land levelling or excavations), construction of access roads and temporary buildings, as well as the necessity of on-site storage of materials and products which are often dangerous. Moreover, during construction there are additional nuisances as notice vibrations, landscape distortion, violation of groundwater level, earth movements, etc. Construction works are also inseparably associated with the use of energy carriers. The application of sustainable construction principles at the building stage refers to the following steps (Kibert, 2008; Ali and Nsairat, 2009; Akadiri et al., 2012):

- Organization of production processes (activity coordination of construction industries involved).
- Development and use of the building site (minimization of storage space).
- Protection of building site against degradation (groundwater protection).
- Logistics of materials supply (use of local raw materials and other building items).
- Reduction of noise during construction (selection of building equipment and machinery).

Another important aspect in the realization of a building process is the management skills of senior staff. These skills refer to the preparatory activities of the investment process, including the selection of subcontractors, the determination of workers' necessary qualifications, the selection and order of products and equipment, the development of a plan ensuring quality. Equally important are business and decision-making skills while solving different problems concerning the construction management.

6.3.3. Operation

The exploitation stage is the longest stage of the building's life cycle and its length depends on the building maintenance (renovation and modernization). Due to a long phase of exploitation the amount of energy used is larger than during manufacturing of the building materials or the construction process itself. A large impact on environmental load of this phase results from the whole energy consumption needed to ensure a proper thermal comfort of a building in our climate. Apart from the design, material and technological solutions accepted to reduce energy use and costs during exploitation phase it is important to (Kibert 2008; Ali and Nsairat 2009; Akadiri et al., 2012):

- Ensure the appropriate level of maintenance (performance of repairs and modernization at the right time).
- Segregate waste (change of habits in waste management).
- Save water and electricity (regardless of its acquisition source)).
- Use of energy-saving household (high energy saving).

Lowering operation costs of a building by selecting appropriate design solutions contributes to increased construction costs and consequently to reduce its availability. The availability in economic terms is a very important feature of sustainable houses and the reduction of future maintenance costs compared to a traditional building should not be made at the expense of too high price of such building.

6.3.4. Demolition stage – recycling

Construction activities generate large amounts of waste during the production of materials, the building process, as well as during operation of a building (repair and modernization) but especially during the demolition (dismantling) of a building (Kibert, 2008; Adamczyk and Dylewski, 2012). The management of construction waste generated is of great importance to the environment. The waste from construction, repairs and building dismantling constitutes largely a very valuable secondary raw material. Its main component is concrete, brick and ceramic rubble. These materials after simple processing are complete aggregates which can be applied in the preparation of construction site, the land levelling (filling holes and excavations), the formation of insulating layer on local landfills, hardening of construction sites and temporary roads. The main assumptions in the recycling of construction materials are to process them as little as possible and to achieve the best material recovery. It is obtained by:

- Selection of different materials for the building renovation and demolition.
- Adaptation of the material in the new structure of the building.
- Reuse of recycled materials.
- Recycling of materials intended for other applications.

These actions aim at achieving savings from limitations of the waste disposal and the storage of waste coming from the building dismantling and the import of new aggregates to the construction site. With implementation of the principles of sustainable construction the important thing is the choice of construction materials whose impact on the environment is minimized. These materials, among others, are recycled building materials that should be used on site.

6.4. Building assessments and certificates

The tools used for comprehensive assessment of buildings, taking into account environmental, financial and social criteria of sustainable development are certificates and building evaluation (Alyami and Rezgui, 2012; Ding, 2008;

Kibert, 2008; Reed et al., 2009). The scope of the assessment involves the entire life cycle of a building, or only selected stages. These ratings take into account different points of view of all stakeholders: users (owners and tenants), designers, investors, builders etc., but also 'neighbors' and the rest of society.

6.4.1. Environmental assessment

One of the methods used for environmental life cycle assessment is the one included in the ISO 14040 analysis of LCA (*Life Cycle Assessment*). The method evaluates the effects (impact) the item / building has on the environment during its entire life cycle, i.e. “from the cradle to the grave". In the literature, there are two LCA approaches distinguished, i.e. "modular" (bottom-up), in which the scope of the research includes building materials or individual modules of a building and “from the top to the bottom” (*top down*), where the whole building and its entire life cycle are assessed (Erlandsson and Borg, 2003). LCA is a technique aimed at reducing the negative impact of building on the environment, through the analysis and the evaluation of potential risks as well as the choice of alternative variants of solutions (Li et al., 2010). It considers a drawn bill of decisions made at the stage of materials’ production stage, construction, operation and demolition of a building. Methodology of environmental evaluation of life cycle consists of four main stages (ISO 14040):

- Goal and Scope Definition.
- LCI – Life Cycle Inventory.
- LCIA – Life Cycle Impact Assessment.
- Interpretation.

The LCA analysis applied to assess a building includes the process – erection of a building, its operation, reuse and utilization. It is important to trace the impact on people and the environment-from raw material acquisition through production of materials, transportation to the destination, operation, and utilization of the building. Taking into account the entire life cycle of the building it can be expressed as follows (Environmental Design, 2004).

$$E_C = \sum_{i=1}^{7} E_i \,, \tag{6.1}$$

where: E_i – *i-th* component of building’s impact on the environment, respectively: E_1 – initial impact (production of materials, design and building construction), E_2 – use, E_3 – maintenance, E_4 – repair, E_5 – renovation, E_6 – demolition, E_7 – recycling.

The components of the environmental impact relating to particular stages of a life circle must be associated with the environment destruction corresponding to important environmental criteria. The impact categories are: global warming, natural resources and ozone depletion, acidification, waste disposal, air pollution inside and outside the structure, toxicity (Environmental Design, 2004).

$$E_i = \sum_{j=1}^{7m} w_j Q_j \ , \qquad (6.2)$$

where: w_j – *j-th* a weight vector representing the validity of the individual criteria, *m* – a number of significant environmental criteria, Q_j – *j-th* a vector of criteria values.

The *LCA* analysis helps to select the most efficient economically and the least damaging to the environment and society way of the project realization. It can be done by comparing the overall costs and other loads of alternative construction concepts, building technologies or maintenance strategies appropriate for the implementation and operation of a given project. The *LCA* analysis includes the costs incurred by an investor as well as the costs and loads of users and social costs and loads, e.g. associated with environment generated by investor's activity within a life cycle of a building.

6.4.2. Building ecological certification

Multi-criteria certification systems introduce standards for sustainable buildings and define criteria of sustainable development. These systems refer to such factors as ecology, economy, socio-cultural factors, functionality, technology and process and location. The tools used for the comprehensive assessment of buildings, taking into account environmental, financial and social criteria of sustainable development include certifications, among which the most common are: LEED, BREEAM, CASBEE, DGNB and EU Green Building (Alyami and Rezgui, 2012; Reed et al., 2009; Roderick et al., 2009: Kawazu et al., 2005).

BREAAM Method

BREEAM (Building Research Establishment Environmental Assessment Method) has been developed since 1990 by the U. K. Building Research Establishment (BRE). It is considered as the first green buildings assessment method (Ding, 2008; Kibert, 2008; Alyami and Rezgui, 2012). It is a comprehensive building assessment method relating to the operation of buildings, the design construction and utilization process. The main goal of developing the BREEAM method is to "*Provide authoritative guidance on ways of minimizing the adverse effects of buildings on the global and local environments while promoting a healthy and comfortable indoor environment*" (Baldwin et al., 1998).

In the process of ecological BREEAM certification three stages are distinguished, i.e. pre-assessment, design, post-construction (BRE, 2011). The analysis of pre-assessment stage is designed to provide the necessary information regarding the use of materials and technologies that allow obtaining maximum points in the BREAAM system. At the design stage documentation (design and executive) is prepared confirming building's compliance with all the BREEAM requirements for a given category. At the final post construction stage all the assumptions of the previous stage are given credibility in the form of reports, expert opinions, as-built documentation, which confirms the compliance of the realized project with the BREEAM guidelines.

The building certified in the BREEAM system is evaluated by awarding points. They are given in particular categories of different weights depending on a building's type (residential, office, public utility, etc.).

The classification of the building for assessment requires minimum 6 out of 9 criteria fulfillment. These are: management, health and wellbeing, energy, water, waste and land use and ecology. Sometimes additional criterion of innovation applied in a building is used that raises a final assessment of a building. The scoring in each category gives a partial result. It is the basis for evaluation of the project or the existing building. The points are added, multiplied by appropriate weights and measures giving the final result. The percentage result in the following scale is obtained [%], i.e. Acceptable < 30, Pass 30–44, Good 45–54, Very Good 55–69, Excellent 70–84, Outstanding ≥85 (Roderick et al., 2009).

Tab. 6.1. Criteria and weights in BREEAM system (BRE, 2011)

Criteria	**Weights [%]**
Management	12
Health and Wellbeing	15
Energy	19
Transport	8
Water	6
Materials	12,5
Waste	7,5
Land Use and Ecology	10
Pollution	10
Total	100
Innovation (additional)	10

The BEEAM certificates are adapted to different types of buildings/construction works, which define the energy demand, various technological and location opportunities influencing on the selection of appropriate sources of energy, other energy-saving concepts, specific emissions, the production of rubbish and ways of managing certain types of waste. This is also related to the function, the behavior patterns, the type of investment, different ways of management and administration, and social programs.

LEED Method

LEED (*The Leadership in Energy and Environmental Design*) is an environmental assessment system that was developed in the United States and was designed by the U. S. Green Buildings Council (USGBC). The method is one of the world's most popular systems of assessment and certification of buildings. This method allows to analyze the use of resources, location and to create comfortable environment in a building with a minimum amount of waste and optimization of energy use. The method developed is a comprehensive tool to assess the environmental quality of the building according to a point system specified for selected categories and subcategories. LEED certificates are used to assess different types of buildings (there are 8 categories of buildings and interiors). The latest and most popular version of LEED developed as LEED-NC 2009 has been consistently used for most building types except single-family homes (Kibert, 2008). Regardless of the category chosen, certification includes 6 groups of categories in which a total number of 110 points can be obtained. The rating takes into account a design, use and utilization stage, but omits management processes.

Tab. 6.2. Criteria and points in LEED system (USGBC, 2012)

Criteria	**Point (max)**
Sustainable Sites	26
Water Efficiency	10
Energy & Atmosphere	35
Materials & Resources	14
Indoor Environment Quality	15
Total	100
Innovation and design process	6
Regional Priority	4

To obtain LEED certification a building has to get at least 40 out of 110 possible points, i.e. 100 basis points, additional 6 for innovation and 4 for regional priorities (Reed et al., 2009). There are four stages of qualification:

Certified 40–49 (average certificate), *Silver* 50–59 (silver certificate), *Gold* 60–79 (gold certificate), *Platinum* 80–110 (platinum certificate).

The points awarded in particular criteria refer primarily to environmental sources such as energy, water and natural resources. The LEED system promotes the use of the installations of renewable energy sources (photovoltaic units, wind turbines, biomass stoves, geothermal pumps and devices for obtaining energy from water), the protection of natural environmental resources (land for construction, natural resources), the use of natural light and ventilation inside a building and the optimal location of a building with infrastructure and transport.

CASBEE Method

CASBEE (*Comprehensive Assessment System for Building Environment Efficiency*) has been developed since 2001 by the Japanese Sustainable Building Consortium (JSBC). It is a comprehensive system of environmental efficiency assessment that evaluates and rates the environmental performance of buildings. It can be used for design, evaluation and management of the building (Reed et al., 2009). CASBEE defines two areas of assessment, i.e. Environment Quality *Q* as'' *Evaluates improvement in living amenity for the building users, within the hypothetical enclosed space (the private property)*'' and Environmental Lode *L* defined as '' *Evaluates negative aspects of environmental impact which go beyond the hypothetical enclosed space to the outside (the public property)*'' (IBEC, 2011). In each of these areas 54 assessment criteria with their indicators are defined. In the set of criteria there are no aesthetic and economic assessments.

Tab. 6.3. Criteria and weights in CASBEE system (IBEC, 2011)

Term		Criteria	Weight
Q	1	Indoor Environment	0,50
	2	Quality of Service	0,35
	3	Outdoor Environment on Site	0,15
L	1	Energy	0,50
	2	Resources and Materials	0,30
	3	Off – site Environmental	0,20

The total scores for *Q* and *L* result from the sums of weighted average scores of all the criteria. The value of weight indicators assigned to particular areas and assessment criteria can be determined on the basis of existing knowledge (Reed et al., 2011). The ratio of total assessment results for *Q* and *L* is determined by *BEE* (*Building Environmental Efficiency*) indicator, which is calculated using the following formula (IBEC, 2011).

$$BEE = \frac{Q\,(\text{Environmental Quality})}{L\,(\text{Environmental Load})}\,. \tag{6.3}$$

Determination of the building class takes place on the basis of the BEE indicator. A building can be classified to one of five classes: Poor (C), Slightly Poor (B), Good (B+), Very Good (A), Superior (S). These classifications are awarded through examining a building under different assessment categories that guarantee the application of the concepts of sustainability in the construction. According to accepted rating sustainable buildings are those whose *BEE* factor is larger than value one, namely, the comfort of the building is not achieved at the expense of increasing the impact on the environment (e.g. at the expense of increasing energy use).

The CASBEE certificate is developed with a view to the public sector (the basis for making right administrative and construction decisions) and the private sector (design tool, standard assessment, pattern promotion).

6.4.3. Economic assessment

The traditional approach to design a building does not include the costs incurred in the full life cycle of the building but only the initial cost of construction (the cost of building's realization). It causes negative consequences, both financial and environmental. The cost of construction works that meet the sustainable construction requirements are usually higher than the construction cost of traditional buildings. It results, among others, from the need for application of innovative architectural solutions, technologies and materials (Feist et al., 2012; Mlecnik, 2013). The costs associated with building operation, i.e. energy and water use play a key role. It should be noted, however, that the search for energy savings during the operation stage is only a part of the cost analysis in a full life cycle of a building (LCCA - *Life Cycle Costing Analysis)*. Therefore, the criterion of construction cost as well as savings in the operation stage should not become the only reason while making design decisions.

To analyze the economic profitability of building investments there are many methods, i.e. CBA (*Cost-Benefit Analysis*) and NPV (*Net Present Value*). One of them is the method for estimating life cycle costs LCCA (*Life Cycle Costing Analysis*) which was included in ISO 14040 and 14044 standards. This method, unlike others, allows determining assumed costs generated at all the stages of the building life cycle. It is used, among others, to compare different structural, material and technological variants. The method is based on the comparison of building investment costs, operating costs increasing with the period of use and demolition costs (Abraham and Dickinson, 1998; Glucha and Baumann, 2004).

It comes down to the analysis of five main life cycle stages of a building:

- Concept - costs of market research, concept and design.
- Design – costs of design documentation.
- Construction – costs of organization, processes and transport.
- Operation – costs of operating, repairs and modernization.
- Demolition – costs of dismantling, recycling or waste disposal.

The total costs (LCCA) incurred in the above mentioned stages can be divided into the costs of purchase, possession and demolition (Hong et al., 2007). The LCCA method allows to determine the total economic costs of a building in its considered life cycle using the following formula:

$$LCC = K_N + \sum_{t=1}^{n} \frac{K_E}{(1+s)^t} + K_L \,, \tag{6.4}$$

where: K_N – cost of building purchase (investment) [zł], K_E – annual cost of building operation (maintenance and operation) [zł/year], K_L – demolition (recycling), n – assumed number of building's years of life, t – another year of operating a building, s – interest rate (discount rate).

The LCC analysis determines decisions concerning particular stages of the life cycle of the building. From a designer's point of view it involves the ability to optimize construction projects by assessing different solution variants and finding compromise solutions.

Building energy certification

The energy certification of buildings refers primarily to the economic aspects of sustainable development. The energy efficiency assessment of the building is also the most recognized impact area of the building on the environment (Sartori and Hestnes 2007). This is due to the fact that reducing energy consumption at the building's operation stage gives tangible results in the form of financial savings. Designing buildings with low energy demand like passive buildings is the result of such thinking. The assessment criteria of low energy houses are focused primarily on the building and narrowly on the environment, i.e. to the energy impact of a building on the environment during the operation stage. This is a significant calculation, but only partial and does not consider the overall impact on the environment.

Passive house certificate

The Passive House certificate is an example of the assessment of a building, which refers to the energy savings during the building operation, i.e. without the calculation of energy needed to produce building materials and technologies of erecting a building. This is an example of partial assessment of environmental, economic and social costs. The Passive House certificate determines criteria of a passive house which are based on three basic assumptions (Mlecnik, 2013).

- The annual demand for space heating is of maximum 15 kWh/(m2a) and it is not obtained at the expense of the increase in the energy use for other purposes (e.g. electricity).
- The factor of the primary energy demand for operational purposes (heating, hot water production, electricity in the household) cannot exceed 120 kWh/(m2a).
- The tightness of external building shell (air flow rotation) smaller than 0,6 the building volume for an hour (max. n501 = 0,6 1/h).

Obtaining required values of indicators involves the selection of appropriate design, material and technological solutions (Feist et al., 2012). It is necessary, in particular, to pay attention to the proper geometry of a building, the insulation partitions (opaque to 0,15 W/(m²·K) and 0,8 W/(m²·K) for transparent partitions), ensuring tightness and elimination of thermal bridges of external partitions, the energy recovery from waste air of ventilation system ($\eta_{oc} \geq 70\%$), high efficiency of heating and hot water system using energy from renewable sources.

Net zero energy building certificate

More progressive search is focused on construction characterized by the original energy demand of a building that equals about 0 kWh/(m2a). An example of such building with very high energy efficiency is NZEB (*Net zero-energy building*). The energy balance of such building assumes that the amount of original energy supplied from the external grid is equal to the amount of original energy exported to the grid. This means that a part of the energy produced on site will be delivered to the external power grid. This is due to the characteristics of the NZEB building, where the energy production takes place under the right conditions and if they are not present the energy supplied from the external grid is used (Sartori et al., 2012).

Obtaining the NZEB certificate involves meeting similar requirements for passive buildings posed but with even higher degree of providing excellent insulation of external partitions, heat recovery from ventilation and maximum use of heat gain. The nearly zero or very low amount of energy required should come to a very high extent from renewable sources, including renewable energy produced on-site or nearby. For systems gaining and storing solar, geothermal or wind energy passive solar heating systems, installations of solar collectors with a large surface, wind turbines and photovoltaic installations are applied (Pless and Torcellini, 2010). The idea of zero energy buildings is still very expensive to be executed. However, in connection with EU restrictions concerning energy characteristics of buildings (Directive EPBD 2010/31/UE) this situation will change in the near future.

6.4.4. Social assessment

Social life cycle assessment is a relatively new concept of evaluating sustainable development and it is one of the components of an integrated life-cycle analysis of the building. The social assessment, in its current form, is already included in the environmental LCA and economic LCCA analysis. The increase of social costs awareness causes ideas to consider social assessment separately, without environmental and economical analyses, to obtain a clear picture of the investment impact on society.

The SLCA (Eng. Social Life Cycle Assessment) analysis is an example of new, so-called third part referring to the social assessment resulting from a building's impact. The proposed approach is a relational assessment through reference to both the benefits resulting from the application of the solution (design, material and technology) and the risks associated with their use. The social assessment can be one of the most decisive grounds for the choice of the project among assessed building variants sometimes prevailing over the environmental and economic reasons (Zinke et al., 2012).

The SLCA method is used for identifying a negative impact of a building on people's health and environment and associated with them social consequences appearing in a life cycle of a building. According to the assumptions included in the guide titled "Guidelines for social life cycle assessment of products" (2009), four main stages can be distinguished:

- Purpose and scope of survey (comfort, safety, aesthetics).
- Analysis of resources (identification of social indicators).
- Assessment of impact (characteristics of scoring system and weight indicators).
- Interpretation (determination of cause and effect relationships).

In the method issues that may refer to particular social groups (e.g. employees, direct users, society) are examined. They are defined as a set of indicators such as accident and illness risks, required qualifications of employees, user's comfort, environmental pollution, etc.). The variety of social indicators imposes the necessity to relate the assessment with specific stakeholders (users, employees). The assessment of the social impact is difficult to determine because what for some groups is beneficial, it does not have to be for others. The complexity of social issues also results from the way they have been considered in the methods of the environmental and economic assessments applied so far. For the time being, the social assessment does not have theoretical and methodological grounds developed, including tools and standards. In the literature examples of proposed simple computational tools can be found. They allow fast, convenient and accurate social assessment (Kleiber, 2011).

6.5. Conclusion

The negative construction impact on people and the environment became the reason for which a lot of studies and analyses were carried out. Their aim was to develop effective tools for reducing its negative effects. These tools are used in establishing certification/assessment systems which in an easy way would give a user information on the environmental characteristics of his building. The range of tools proposed to carry out the assessment include the multi-criteria ecological certificates, i.e. LEED, BREAM, CASBEE and others, the energy certificates, among others, Passive House, Net Zero Energy Building and the analyses referring to the full life cycle of a building, i.e. LCA, LCCA, SLCA. A common part of all these systems is the assessment of particular characteristics while their scope and quantity are variable as well as the values and weights assigned to them.

The developed systems allow the assessment of the building, element and material impact on users and the environment, thereby eliminating these design, technological and material solutions that adversely affect environment. The assessment results with the use of different methods are, however, quite divergent. Therefore, there are works on creation of a single, coherent system of assessment whose indications would be useful in planning, designing, erecting, using, and demolishing a building. The development of such assessment system creates the grounds for the preparation of new standards, legal and technical guidelines concerning construction realized in accordance with the idea of sustainable development.

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