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ISBN: 978-83-947920-2-2

M22: OPTIMISATION OF CONSTRUCTION PROCESSES

This book is a result of the project carried out within the framework of ERASMUS+ programme.

Project number: 2015-1-PL01-KA202-016454

OPTIMISATION OF CONSTRUCTION PROCESSES

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OPTIMISATION OF CONSTRUCTION PROCESSES

Thordur V. Fridgeirsson

Jerzy Rosłon

Iceland, Poland, 2017

This project has been funded with support from the European Commission.
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Cover design:
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ISBN 978-83-947920-2-2

Print and cover:

POLCEN Sp. z o.o.
ul. Nowogrodzka 31, lok. 333
00-511 Warszawa
www.polcen.com.pl
(księgarnia internetowa)

This manual is part of the Construction Managers' Library – a set of books related to the wide area of management in construction. The books were created within the Leonardo da Vinci (LdV) projects No: PL/06/B/F/PP/174014; 2009-1-PL1-LEO05-05016, 2011-1-PL1-LEO05-19888, and ERASMUS+ project No: 2015-1-PL01-KA202-016454, entitled: "COMMON LEARNING OUTCOME FOR EUROPEAN MANAGERS IN CONSTRUCTION, phases I, II, III and IV – CLOEMC)". Warsaw University of Technology, Civil Engineering Faculty, Department of Construction Engineering and Management was the Promoter of the Projects.
The following organisations were Partners in the CLOEMC I Project:
- Association of Building Surveyors and Construction Experts (Belgium),
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The objective of this project was to create first, seven manuals conveying all the information necessary to develop civil engineering skills in the field of construction management.
The following manuals have been developed in CLOEMC I (in the brackets you will find an estimate of didactic hours necessary for mastering the contents of a given manual):
M1: PROJECT MANAGEMENT IN CONSTRUCTION (100),
M2: HUMAN RESOURCE MANAGEMENT IN CONSTRUCTION (100),
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M4: BUSINESS MANAGEMENT IN CONSTRUCTION ENTERPRISE(100),
M5: REAL ESTATE MANAGEMENT (100),
M6: ECONOMY AND FINANCIAL MANAGEMENT IN CONSTRUCTION (240),
M7: CONSTRUCTION MANAGEMENT (100).
The manuals created for the purposes of the library are available in three languages: Polish, Spanish and English. The manuals may be used as didactic materials for students of postgraduate courses and regular studies in all three languages. Graduates from the courses will receive a certificate, which is recognized by all organisations – members of the AEEBC, association of construction managers from over a dozen European countries.
Polish representative in the AEEBC is the Polish Association of Building Managers, in Warsaw.
Partners of the CLOEMC II project were:
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Within the second part of the project the following manuals were developed:
M8: RISK MANAGEMENT (130)
M9: PROCESS MANAGEMENT – LEAN CONSTRUCTION (90),
M10: COMPUTER METHODS IN CONSTRUCTION (80),
M11: PPP PROJECTS IN CONSTRUCTION (80),
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The manuals were prepared in four languages: Polish, Portuguese, German and English.

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M14: DUE-DILIGENCE IN CONSTRUCTION (100),
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M18: HEALTH AND SAFETY IN CONSTRUCTION (100),
M19: MANAGING BUILDING PATHOLOGY AND MAINTENANCE (100).

The manuals were prepared in five languages: Polish, Portuguese, German, French and English.

Partners of the CLOEMC IV project were:
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- Polish Association of Building Managers (Poland).

Within the fourth part of the project the following manuals were developed:
M20: REVITALISATION AND REFURBISHMENT IN CONSTRUCTION (100),
M21: BUILDING INFORMATION MODELING – BIM (120),
M22: OPTIMISATION OF CONSTRUCTION PROCESSES (120),
M23: DIVERSITY MANAGEMENT IN CONSTRUCTION (100),
M24: MECHANICS OF MATERIALS AND STRUCTURES FOR CONSTRUCTION MANAGERS (120),
M25: CSR - CORPORATE SOCIAL RESPONSIBILITY IN CONSTRUCTION (100).
The manuals were prepared in three languages: Polish, German and English (and additionally English version with summary in Icelandic language).
The scope of knowledge presented in the manuals is necessary in activities of managers - construction engineers, managing undertakings in the conditions of the modern market economy. The manuals are approved by the European AEEBC association as a basis for recognising manager qualifications. Modern knowledge in the field of management in construction, presented in the manuals, is one of prerequisites to obtain EurBE (European Building Expert) cards, a professional certificate documenting the qualification level of a construction manager in EU. The manuals are designated for managers - construction engineers, students completing postgraduate studies "Management in construction" and students completing construction studies. Postgraduate studies got a recognised program, and graduates receive certificates recognised by 17 national organisations, members of AEEBC.
More information:
- about the project: www.cloemcIV.il.pw.edu.pl
- about the EURBE CARD: www.aeebc.org

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CHAPTER 1

INTRODUCTION - LEARNING OUTCOMES

(J. ROSŁON)

1.1 INTRODUCTION

1.1.1 Optimisation

One can easily say that optimisation is one of the oldest sciences or practices. Since the beginning of the mankind, people strived for perfection when it came to their creations, products, gains, or self-improvement. What is more, many phenomena, preceding human race, aim at achieving optimum status. Examples include evolutionary processes in which nature selects species or individuals dominant in a given environment (local optima). Another example is the minimum total potential energy principle. It dictates that (at low temperatures) a structure or body shall deform or displace to a position that (locally) minimises the total potential energy (the ground state / lowest-energy state) (fig. 1.1) [4]. Or the molecular mechanics phenomenon of systems striving for the energy minimisation [3].

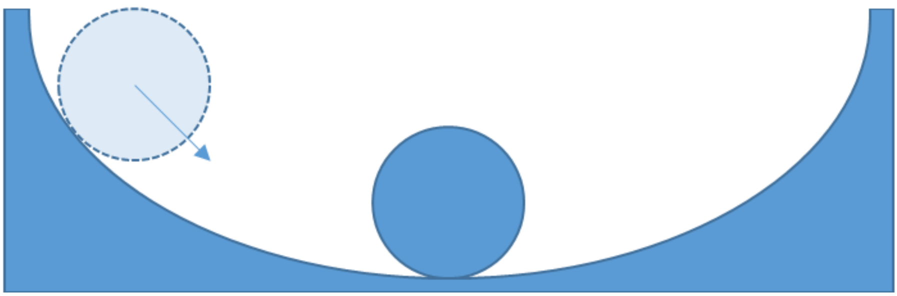

Fig. 1.1. Minimum total potential energy principle [own source]

The operation principles of the aforementioned phenomena are being studied by researchers in order to create modern computational algorithms. Some of them include genetic algorithms (basing on evolution processes) and

simulated annealing (basing on steal annealing process). Both algorithms are described in chapter 3.
The science branch that deals with such phenomena is called optimisation (subset of mathematics). It aims to find the best possible elements from a certain set according to the previously specified criteria. These criteria are expressed by mathematical functions, so-called **objective functions** [6].

1.1.2 Single criteria optimisation

The most common type of optimisation is a single-criteria optimisation. It assumes choosing one criterion and finding the optimal solution according to it. This criterion can be e.g. minimising the duration of a project or maximising its profits. Such optimisation omits other aspects of the problem. It is worth stressing here that not only the global optima (the best possible solution) but also the local optima (the best solution in a certain sub-space of all solutions) may exist for the objective function being investigated. This phenomenon is shown in the figure 1.2. [6].

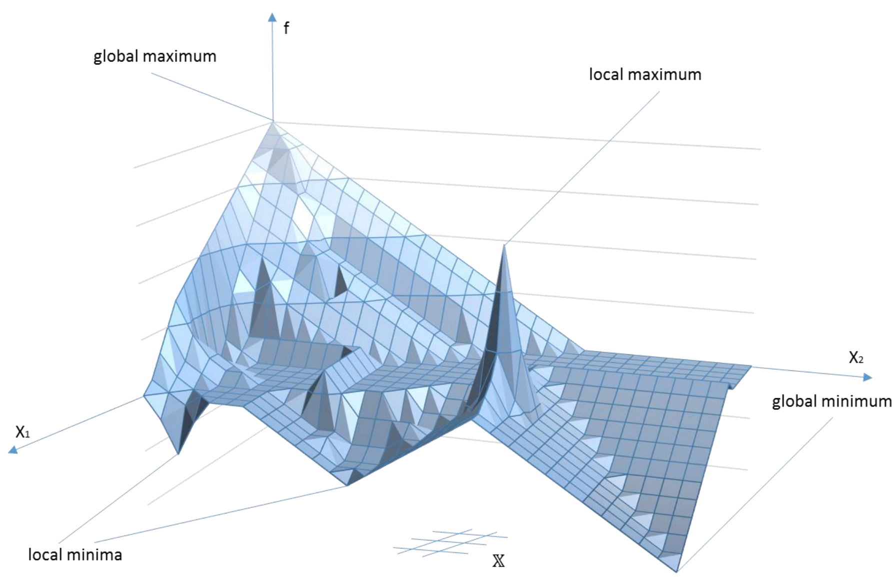

Fig. 1.2. Local and global optima, example [own source].

Local minima and maxima can be also called as **local optimum** or **local extremum**. At the same time Global minima and maxima can be also called as **global optimum** or **global extremum**.
It is worth stressing here that the objective function may have several equivalent global extrema (these optima are the so-called **optimal set**). If the function has exactly one global optimum, we can define it as the **strict global optimum (extremum)**.

1.1.3 Multicriteria optimisation

While making a decision or during optimisation process one can often encounter problem that has to be solved in terms of more than one criterion. **Multi-Criteria Decision Problems** can be divided into two categories [1], [5]:

- **Multiple-Attribute Decision Problem - MADP** – there is a limited (and countably low) number of decision options, each of which has a predetermined and relevant level of achieving attributes (not necessarily quantifiable) set by the decision maker. Based on these characteristics, a decision is made.

  An example would be a choice of a contractor for construction works. There are 3 possible contractors assessed on the base of 3 criteria: reputation, financial stability, and cost. We have limited number of decision options, each can be described by the relevant level of achieving each of the 3 attributes.

- **Multiple-Objective Decision Problem - MODP** – they do not have a predetermined number of options with specific attribute problem values. Instead, these problems have a set of quantifiable goals on the basis of which the decision is made, and a set of well-defined constraints corresponding with the values of the attributes (decision variables) of the possible options.

  An example would be finding the perfect balance between minimising the cost and time of the construction project (2 criteria). This time we do not have a predetermined number of options, we are focusing on the final result.

  Key factors for project optimisation (from a management perspective) are time, capital (cost), and resources. It should be noted here that the shortest duration does not correspond to the lowest execution cost. On the total cost curve (figure below) we can mark the relevant points [2]:

- t_n – normal time, which corresponds with the lowest cost – c_{min};
- t_{lim} – the shortest possible time for completing the project, it corresponds with the limit cost (which value is quite high) – c_{lim}.

The total cost curve is estimated by the analysis of different variants of the project implementation (many different options). If the time of the projects surpasses the normal time, the total cost is rising. Therefore the optimal solution is somewhere between shortest and normal time. However there is no one answer to the problem and the outcome will depend on the preferences of decision makers.

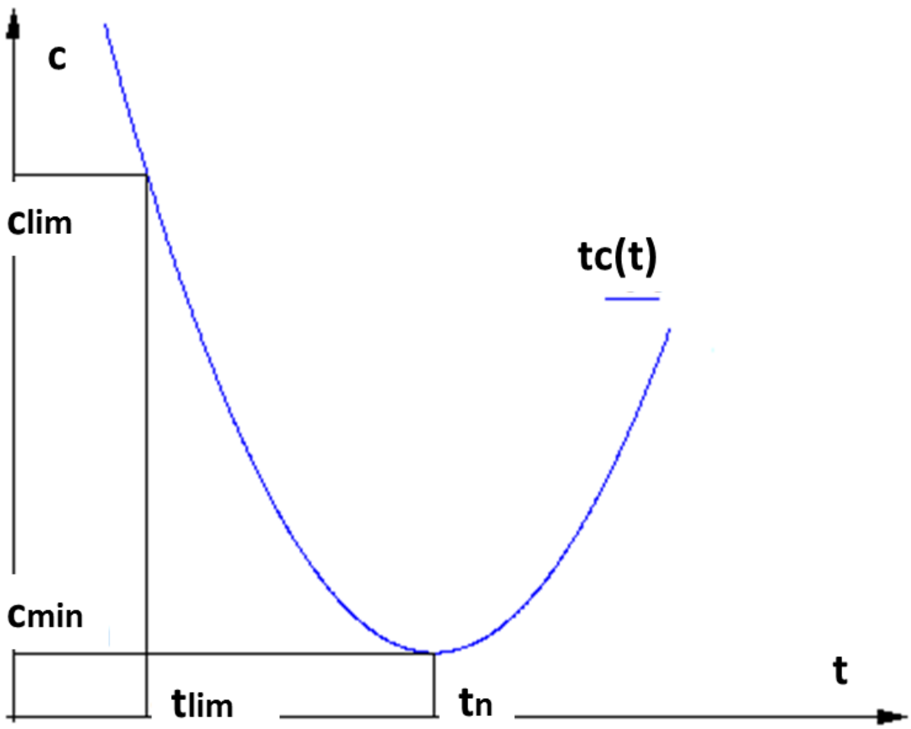

Fig. 1.3. Graph: the total cost curve, relevant points [own source]

1.2 LEARNING OUTCOMES

This manual presents chosen aspects of decision making and optimisation that can be extremely helpful for construction managers.

Decision makers need tools that will enable them to prepare for the unknown by thinking broadly about the full range of plausible scenarios as well as constructing robust strategies regardless of how the future unfolds.

The reader will gain basic knowledge of decision models, including model design. Manual will help to scope the decision problem, accumulate data, design decision-making models and test them.

Furthermore the reader will gain an insight into activities connected with the area of optimisation in construction. Series of different methods are described, including linear optimisation and metaheuristic methods. The manual presents principles of methods and fields of their usage, and suggests how they can be implemented in construction practice.

Different aspects of optimisation in construction are presented. The manual provides an insight into optimisation of structures (design), logistics, and schedules (first case study).

The second case study concerns "Scenario planning" - a powerful instrument that guides and supports the imagination, creativity, and vision necessary for mapping a range of viable strategies for competitive success.

For each proposed method authors provide means, tools and software that can aid construction managers in their everyday work.

Armed with the powerful techniques described in this manual, readers will be able to maximise their results.

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CHAPTER 2

TOOLS USED IN DECISION MAKING IN CONSTRUCTION

(T. V. FRIDGEIRSSON)

2.1 INTRODUCTION

Decision analysis should lead to making the optimal decision in decision in context of mathematical, social and psychological evidences.

Optimal decision does not guarantee the outcome but reduces the probabilities of failure. Recently human factors and cognitive biases have been subject to increasing interest in the industry and the public sector. The works of *Daniel Kahneman* and *Amos Tversky* are in particular interesting and accessible for them interested in how social factors and psychology impact our decisions [1].

Decisions are a diverse creature to deal with. They span form the obvious chose to the state were many scenarios are the possible outcome. To select a contractor and the only decision parameter is the price the uncertainty is nonexistent. The lowest bidder receives the contract. However, few decisions are so simple and straightforward that a single parameter can be considered decisive. What if the contractor is financially weak? What if he is not in possession of the knowledge to finish the work? What if he cannot meet the deadline? The uncertainty regarding the decision assumptions directs us to considering the risk and different possible outcomes. Risk is usually as closely connected to decisions as the moon follows the Earth.

Decisions are fascinating. They, themselves, cost next to nothing. However, the consequences can be costly if the decision is badly conceived or rewarding if the decision maker gets it right. We might argue that managers are primarily payed to make decisions. What to produce? Where to build? What type of design? How many men? How much to invest? There are next to numerous input factors for large construction projects.

In an attempt to reflect the fundamental assumptions for a decision we must assemble a calculative model. In the model the parameters and variables are connected in an attempt to come to the optimal decision.

Let´s assume that the management team of a large construction company is in the strategic process of marketing a new building site. The management team identifies five variables to decide the economic viability of the project:

- Cost of marketing.
- Size of the market.
- Market share.
- Project operation cost.
- Investment cost.

Let´s imagine that the members of the management team are rather optimistic on this project and the results of the marketing effort. There are hopes for 30% return on the investment. So, the management team are in good spirit when they assess the uncertainty for each of the project variables. They project that each of the parameters have 80% chance of success. Pretty good or what? Before you answer bear in mind that these parameters are connected. They all have to add up to ensure the success and expected profit. If these variables are independent the chance of success is only 33%. This basic statistical evidence could dent the optimistic spirit of the management. They now know that they need more information do build the decision on solid platform. Each variable must be studied and understood in details.

2.2 DECISION MODELS

A model is a simplification of reality. The purpose is to entangle the major assumptions for the decision and publish them in an attempt to optimise the decision. The making of the model is also very imperative to understand the problem and the project. Usually we would use spreadsheets and Microsoft Excel is the most used software currently.

Decision models consist of variables and data according to the following definition:

1. Data: Data are known numerical facts i.e. cost, resources, capacity, distances etc..
2. Uncontrolled variables: Uncontrolled variables are numerical data that the decision maker cannot control. Demand, inflation, currencies and future returns on investment are few examples.

3. Decision variables: Decision variables are in the domain of the decision maker and he can decide the quantity. Number of items produced, number of workers, capital investment are few examples.

The purpose of the model is to connect the parameters and forwards the manager to a decision based on the predefined assumptions in the model. Post the model abstraction we formulate the parameters connection mathematically and use our spreadsheet for the computation.

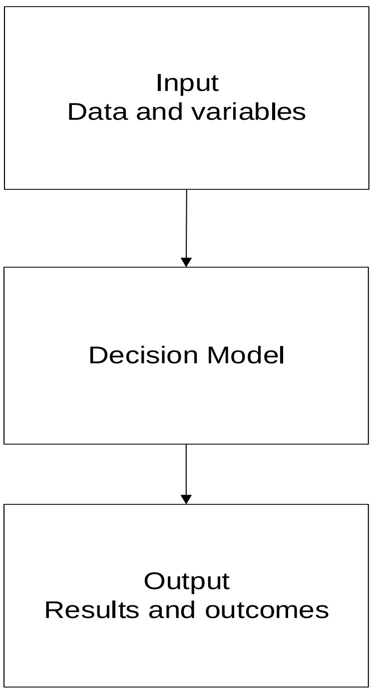

Fig. 2.1 The outline of a decision model.

As we have a spreadsheet model with connections we can calculate. Spreadsheet models are extremely useful and offers numerous possibilities for managers to observe different scenarios, options and versions impacting the decision.

In its most simple form a profit based decision model is as follows:

Profit = revenues – cost

Mathematically we note that profit is a function of revenues and cost:

$Y = f(X_1, X_2)$ were Y is profit and X_1 and X_2 revenues and cost.

The profit (Y) is dependent on the two parameters; or how large are the revenues (X_1) and cost (X_2) respectively. Y is therefore dependent variable and X_1 and X_2 are independent variables.

In context of the before mentioned definition we say that revenues and cost are inputs and the profit the output.

It is not by default that clear functional relationship are between independent and dependent variables. Models come therefore in several types. One categorization of models are:

Descriptive Model: These models demonstrate the current state of nature usually based on recognized mathematical relationship. The simple profit model is a descriptive model to name an example.

Another symptom if this type of models is that the independent variables can be subject to uncertainty. Demand is usually not known beforehand to name an example. In situations where uncertainty is a factor the application of simulation, statistical distribution and other methods to deal with uncertainty enters the picture. Descriptive models are deployed to explain how the system can evolve under different conditions and what might to be expected to happen in the future.

Prescriptive/Optimisation model: Optimisation model differs from descriptive model in the way it forwards a particular best (optimal) solution on basis of the inputs.

An example could be a management team do analyze the price tolerance on the fly-route from Warsaw to London during the summer period. The analysis indicates that if the price is 600€ the demand will be 500 passengers/day but if the price is reduced to 300€ the demand will increase to 1200 passengers/day. Fixed cost (cost type independent from numbers of passengers) is 90.000€ per each flight. The decision is to optimise the profit of the fly-leg.

Firstly the mathematical relationship must be decided between independent and dependent variables. We know that the demand is a function of price. As we only have data on price and demand from two points (600€, 500 passengers) and (300€, 1200 passengers) we are forced to assume that the relationship can be determined by the equation of a straight line:

y = mx + b; y is demand, x is price, m is the slope and b is the intersection with the y-axis.

This leads to m = (500-1200)/(600€-300€) = -7/3 and b = y-mx = 500-(-7/3)(600) = 1.900.

Data	
Airline Capacity (passangers)	300
Fixed cost/flight (€)	90.000
Demand function:	
Slope (-7/3)	-2,33
intercept	1.900

Revenue	Model
Unit price (€)	500
Demand	733
# flights/day	3
Total Revenue	366.667
Cost	
Fixed cost (€)	270.000
Profit (€)	96.667

Tab. 2.1 A simple decision model for pricing an air line ticket.

This is what we need to formulate the model to compute the optimal profit:

Profit = demand x price – fixed cost x no. of flights/day

The model in Excel is on the picture above. The objective is to determine the price resulting in max profit. The price is the decision variable and the decision determinant as the demand is dependent on the price.

2.2.1 Model design

Decision models are arranged to understand the decision problem and connect causes and effect. The model design must be based on logic if the model is to be workable. The design must be carefully prepared. All necessary parameters must be included and the relationship studied. The recommended way of designing the model is to look at the work as stepwise process.

2.2.2 Scoping the decision problem

Usually the problem is obscured by uncertainty. If demand is more sparse than anticipated the profit will probably suffer. If cost is lower than anticipated the profit will probably increase. The first step is therefore the problem scoping. What are we looking for exactly and in which direction will the object point? The decision maker must begin with outlining the causes for the work to being initiated. Even to invest in analyzing what he is not looking for. Sometimes causes and effect diagnose is a sensible approach. If the problem is sales dependent (decreasing sale for example) the decision maker must isolate the causes for the problem and ask: What variables impact the sale? As the objective of sales operation is to maximize profit the direction is towards increased profit. The variables impacting the sales might be price, demand, sales/salesman, the variable cost/item sold, etc.

Common mistake is to miss out on scoping the problem which can easily lead to the wrong perception of the true causes.

2.2.3 Data accumulation

When causes and effect have been diagnosed the picture is made fuller by assembling the appropriate data. Data can be retrieved in the form of market surveys, interviews, historical evidences, public numbers and googling to name few examples. Even pure estimates might be required. The data integrity must be accounted for if needed. Some data must be associated with numerical range or marked up specially to notify that they must be used with precaution.

2.2.4 Model design

When we have scoped the problem with causes and effect diagnosed and our data sources we must determine if the model is of descriptive or optimisation type. Next is to connect the variables and the data sources. A helpful technique is the application of influence diagram to visualize what does impact what and the name of the interconnected data. Influence diagrams are somewhat related to decision trees. We use nodes and arrows to connect the nodes. They are also related to network planning techniques in projects as they are predecessor/successor based and looping is not allowed.

The symbolism is that an ellipse shaped node means uncertainty, rectangle node means decision and a polygon node means value. Observe that other types of influence diagrams also exist.

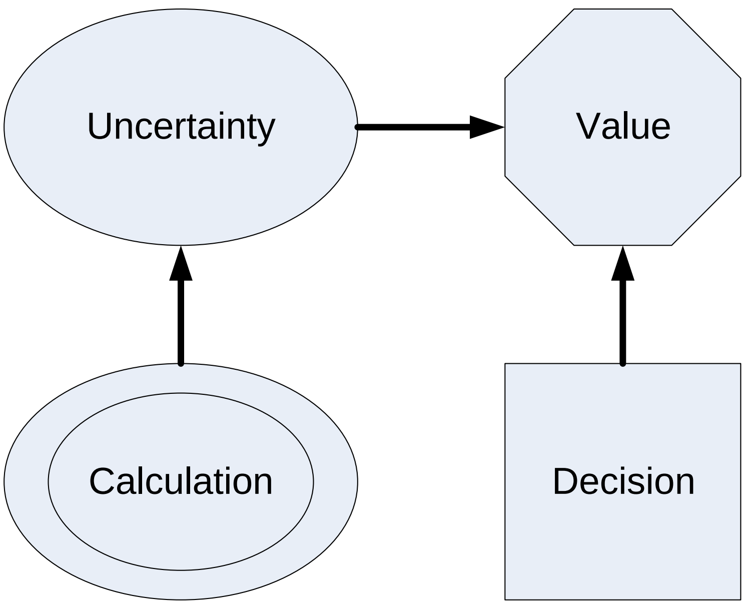

Fig. 2.2 The nodes and major symbols in influence diagrams.

The nodes are connected with the arrows to demonstrate the interconnected impact. When an arrow from node A is connected node B we call A the predecessor of B and B the successor of A. Important details are decided when no connections are to be found as then we know that relationship are insignificant in context of the decision.

Influence diagrams are arranged from right to left. Nodes were the uncertainty must be computed are marked as such i.e. by double marking. If we need to emphasize the strength of the relationship we could use cross impact analysis to determine the weight if the impact.[1]

Pretend that a construction company is contemplating to develop a building site. The decision is based in the Net Present Value (NPV) of a 10 years revenue stream by the following equation.

$$NPV = \sum_{t=1}^{10} \frac{Income - cost}{(1 + rates)^t}$$

The NPV is the decisive decision factor and is influenced by two uncertainty parameters; the income and the cost. Both these parameters are calculative and the node must be denoted as such. The model is developed to the left by segmenting the income and cost in sub-parameters that have influence on the income and cost. Income is a function of how many apartments will be sold (sales) and the number of apartments sold is a function of the market share and the market size. The same approach is used to determine the cost factors and gradually a model abstraction is worked out towards the expected result far to the right.

[1] CPA is outside the scope of this text. See e.g. [3]

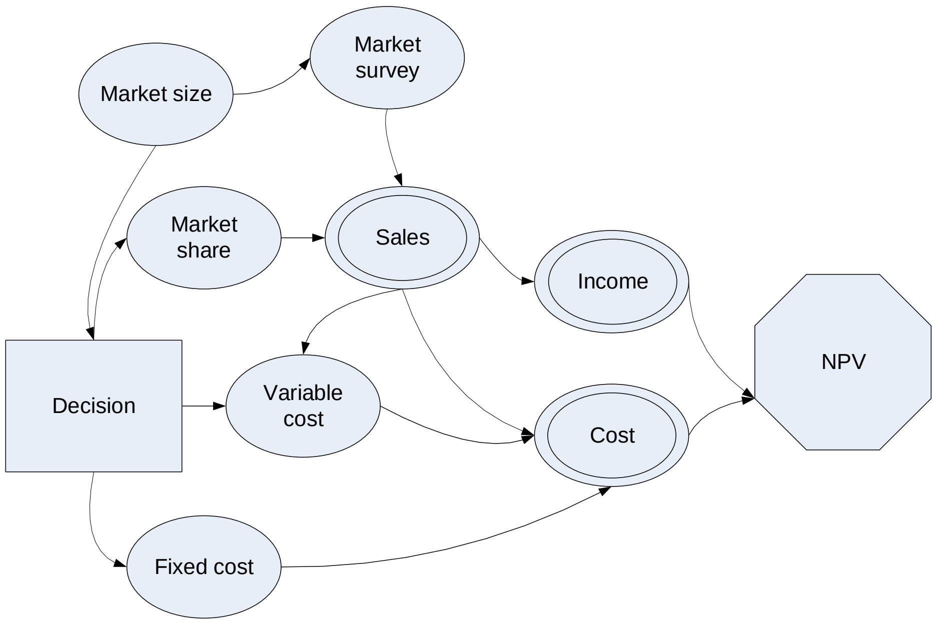

Fig. 2.3 An influence diagram for an investment project.

2.2.5 Testing the model design

The model will gradually be formed. However, the usability should be tested. The primarily concern is that it does not reflect the real state of nature. If the model indicates a huge profit (or loss) the decision maker should be concerned. The question is if the design is flawed or some of the variables are not realistic. If the model is flawed it can be extremely dangerous and lead to overconfidence. Another risk is that models are usually based on "normal" conditions. So called "Black Swan" events, i.e. rare unexpected events with high impact, are usually not accounted for [2]. Moreover, even a sophisticated model will never capture reality.

The model will therefore benefit from rigorous testing by asking the What if? question. This question is intended to evaluate how sensitive the variables in the model are to changes. If the outcome/result is highly impacted by a variance in a particular variable it may be of concern. If a change in a variable does not impact the outcome/result we can relax a bit. The sensitive variables might be considered risky and subject to further screening. The main assumptions of the model are tested by for sensitivity by replacing the original values by new values. The variable causing the biggest swing from the expected result is also the variable with the most uncertainty and most likely to impact the decision. This is also the reason for the What if? label. What if we change this variable? What happens to the expected outcome?

The following is a stepwise process for sensitivity analysis:

Firstly is the formulation earlier described to decide the variables impacting the decision. The formulation in this case is:

Profit = sales in units x (unit price-variable costs) – fixed cost.

As can be seen the sales in units is a calculative size and is decided by:

Sales in units = market size (number of units) x market share (%).

Secondly is to choose range of values to present each variable. We could use high value, most likely value and low value for each variable.

Thirdly we place the values one by one in the model and document the impact on the result when the high and low values are used. The figure below displays a spreadsheet model were the results (profit) are tested with high and low values respectively.

(1) Outcome (Profit)			
13.500			
(2) Most likely value	**(3) Name of variable**	**(4) Low value**	**(5) High value**
150	Sales in units	40	640
200	Unit price (000€)	150	250
1.500	Market size (units)	1.000	4.000
10%	Market share (%)	4%	16%
100	Variable cost/unit (000€)	35	45
1.500	Fixed cost (€)	5.000	1.000

	Low value (000)	High value (000)	Difference (000)
Unit price (000€)	6.000	21.000	15.000
Market size (units)	8.500	38.500	30.000
Market share (%)	4.500	22.500	18.000
Variable cost/unit (000€)	23.250	21.750	- 1.500
Fixed cost (€)	10.000	14.000	4.000

Fig. 2.4. Spreadsheet decision model with scenarios.

On the basis of the spreadsheet model a Tornado diagram is presented for better visualization of the problem. All variable are significant as there is a noteworthy swing in profit in all cases. However, the market size is the most vulnerable variable followed closely by the variable cost. Observe that "sales in units" is a calculated parameter.

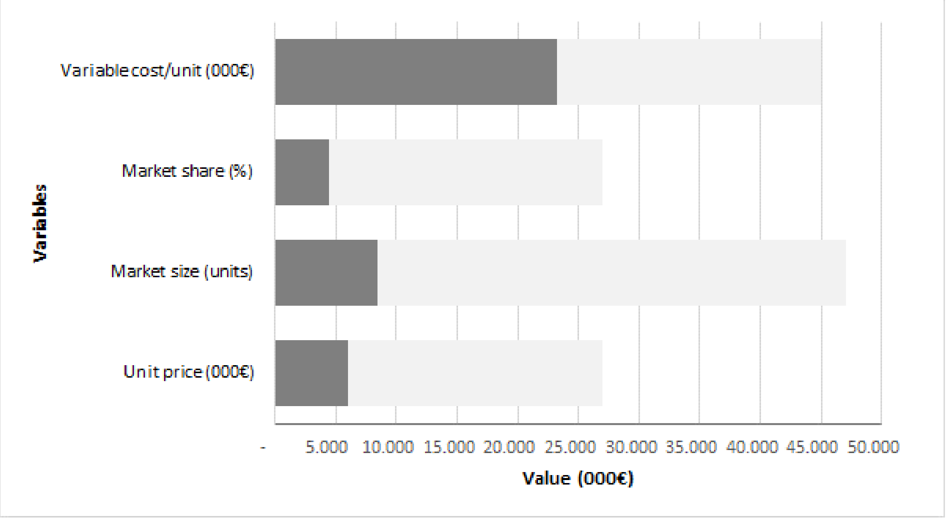

Fig. 2.5 Sensitivity analysis for the decision model.

The most common functions in Excel for sensitivity analysis are Data tables, Scenarios, and Goal seek.

2.3 LINEAR OPTIMISATION

The decision maker might wish to emulate as many outcomes as possible within defined constraints and select the optimal outcome. What impact our chose are the constraints framing the decision. The decision maker spots opportunities to increase profit by hiring more people with special skills but recognizes that these people are not available. A construction company spots business opportunity but knows that it can only harvest the opportunity by large capital investment which is out of reach as things stay. In short several constraints can limit the options of the decision maker. The decision maker must find the optimal solution within the constraints he is facing.

The stepwise procedure is: Firstly to decide the decision variables; secondly to define the constraints and thirdly to solve for the optimal solution.

2.3.1 Swan Concrete ltd. case

Swan Concrete ltd. produces cement and other substances for the construction industry. One particular product is a special mixture to blend the cement to enrich the concrete with special qualities needed under extreme circumstances. The mixture is called Super X and is available in 50 litres high pressure containers. The overall market for Super X is segmented into two market segments:

- Hydro market
- Fertilizer market

Super X is made of two very rare ingredients, A and B, in different quantities with respect to which market to offload the product. The table below shows the ratios in context of the market segments.

Super X	Hydro (H)	Fertilizer (F)
Ingredient A	40 l	20 l
Ingredient B	10 l	30 l

Tab. 2.2 Ratios in context of the market segments.

The Just in Time inventory control of Swan Concrete is configured in such a way that the following supply is available for the production:

Ingredient A = 200.000 l.

Ingredient B = 150.000 l.

On addition only limited numbers of containers are purchased each week. The containers are only available in the quantity 4000 pieces for market H and 4500 pieces for market F.

The decision maker calculates the profit for each product. He estimates that each contained for market H donates 30€/container and market F gives 25€/container.

At first glance this seems a simple task as market H is more profitable. However, what complicates matters are the resources needed. In container for market H we need double amount of ingredient A than in container for market F. We must therefore include the production constraints in the decision to optimise the ratio of products that contributes most profit for Swan Concrete.

The following are the known constraints:

- 200.000 l ingredient A
- 150.000 l ingredient B.
- 4000 container for market H.
- 4500 containers for market F.

Next is to describe the constraints mathematically. First constraint is 200.000 l surplus of ingredient A. These resources are used to produce on the two markets, H and F. Each produced unit demands 40 l for market H and 20 l on market F.

The quantity of ingredient A for all possible composition are:

$$40H + 20F$$

To produce 10.000H and 5.000F the volume of ingredient A is:

$$40.000 + 10.000 = 50.000 \text{ l}$$

With this formulation all possible compositions are known towards the constraints that apply for ingredient A.

$$40H + 20E \leq 200.000$$

Same applies for ingredient B.

$$10H + 30F \leq 150.000.$$

But there are also other constraint, the limits to the number of containers.

$$1H \leq 4000 \text{ (containers H)}$$

$$1F \leq 4500 \text{ (containers F)}$$

The sign $\leq$ means that the constraint is up to maximum. Other possible constraint are minimum ($\geq$) or equal to (=).

The profit is decided by the profit margin each produced container contributes. The function is therefore.

$$\text{Profit (€)} = 30H + 25F.$$

The decision is to maximize the profit with respect of the constraints:

$$4H + 2E \leq 200.000$$

$$1H + 3F \leq 150.000$$

$$1H \leq 4000$$

$1F \leq 4500$

$H, F \geq 0$

To solve this graphically we nullify each variable. This means that we assume that all products are offloaded to each marker separately; all 200.000 l of ingredient A are used to produce for market E if production for market H is nullified. The maximum production for market F is

200.000/2 = 100.000

This is the first coordinate we are looking for:

H = 0, F = 100.000

The other coordinate is identified by defining F as null.

(1) H = 50.000, F = 0.

Now we have the values for the first constraint. We do the same for the remaining three:

(2) H = 0, F = 50.000; H =150.000, F = 0.

(3) H = 4000 for all values of F.

(4) F = 4500 for all values of H.

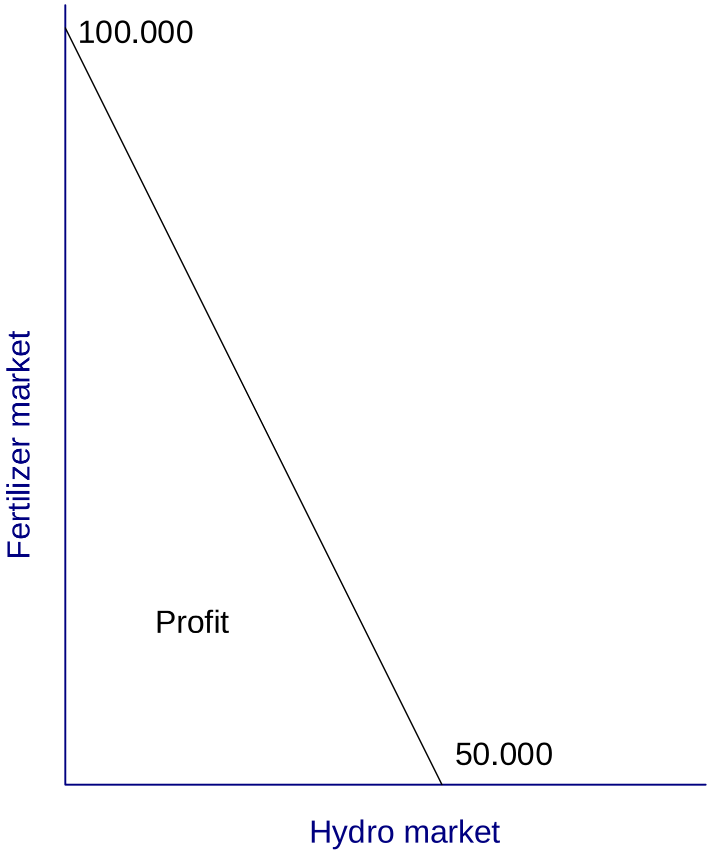

Fig. 2.6 The results for the first condition (of four).

The figure shows the result for the first constrain. The line between the intersection points indicates all possible compositions if 200.000 litters of ingredient A are used (=). The area under the line is all possible compositions (markets H and F) were less than 200.000 litres of ingredient A are used (<). The line is therefore defining the profit in context of the first constraint.

Next picture visualizes the results when we use all four constraints. The area favourable for all constraints is the one under the intersection of the four lines. This area must contain the optimal decision values as it demonstrates all profitable options. To find the optimal solution we must arrange an objective function.

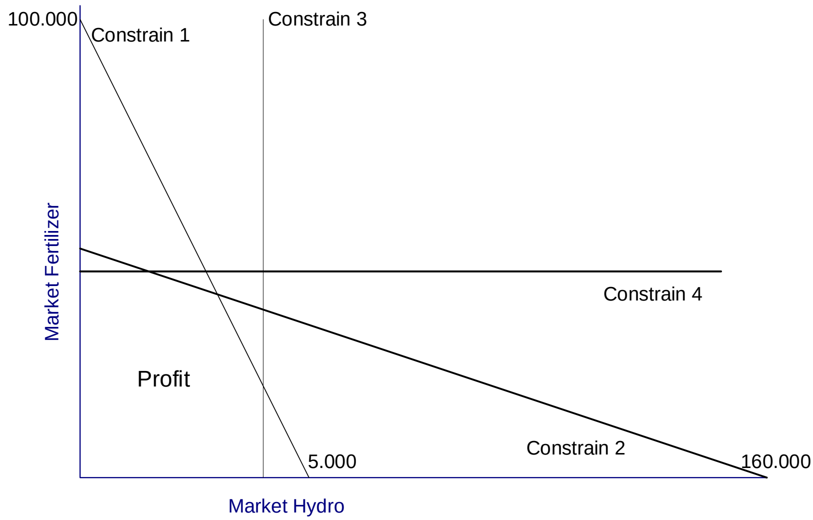

Fig. 2.7 The results after all conditions are considered. The area "profit" defines the coordinates the condition include.

However, we do not know this function yet. We know it is linear as is a straight line and we know that the values of the function must be inside the "optimal" (profit) area as other have been excluded. So we do not know the function bur we now the profit coefficients in the function (30€ and 25€):

Profit = 30H + 25F

We can work from this point by inserting in the profit function and repeat previous commands to find the intersection points for axis's H and F.

H = 0, F = 3000

H = 2500, F = 0

As the decision maker is aiming at maximizing his profit the further from origio the coordinates are the better. The point furthest from origo is the best option. The functions are intersective lines so this point must be a corner point on the lines framing the profit area. After testing this

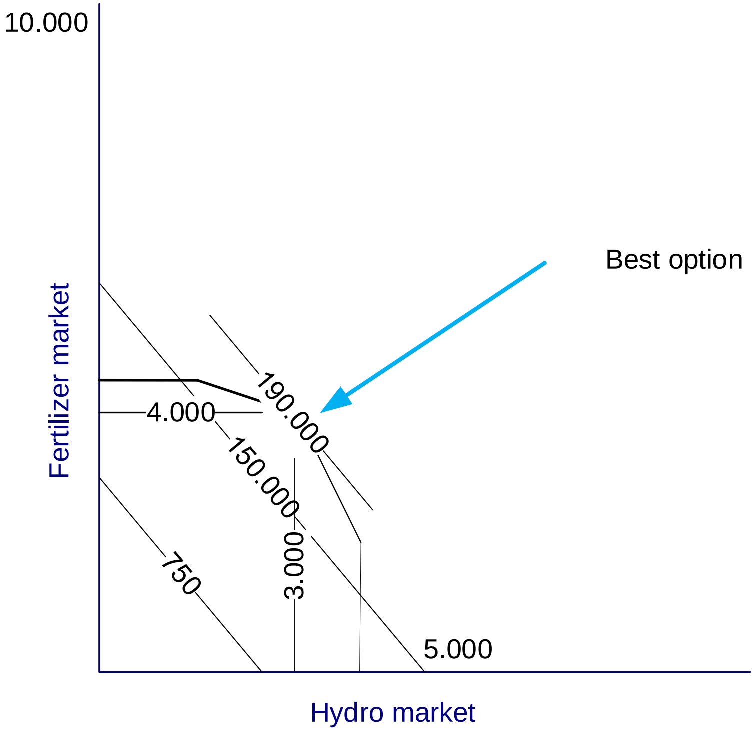

Fig. 2.8 The best option for maximizing is the point furthest from the origo.

The solution is:

H = 3000

F = 4000

Profit =190.000 € = 30(3000) + 25(4000).

The decision maker knows now the volume contributing the best profit: it is acquired by producing 3000 containers for Hydro and 4000 containers for Fertilizer. The production is therefore:

$4H + 2E \leq 20.000 = 12.000 + 8000 = 20.000$ l of ingredient A (all available).

$1H + 3F \leq 15.000 = 3000 + 12.000 = 15.000$ l of ingredient B (all available).

$1H \leq 4000; 3000 < 4000$.

So there are 1000 unused containers for the product on market H.

$1F \leq 4500; 4000 < 4500$

So there are 500 unused containers for market F.

Conditions (1) and (2) are called bounded. The objective function cannot use higher values for the production on markets H or F.

Conditions (3) and (4) are not bounded as it is possible to produce more on the markets with respect to them.

2.4 REFERENCES

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CHAPTER 3

OPTIMISATION ALGORITHMS

(J. ROSŁON)

3.1 OPTIMISATION METHODS

Optimisation methods (including scheduling optimisation methods) can be classified into three methods: mathematical (also called exact), heuristic and metaheuristic [35], [37].

Among the exact methods are e.g. linear programming (LP), dynamic programming (DP) (these methods can be useful for finding the global optimum, however, suffer from some drawbacks – discrete decision variables and the exponential increase in the number of solutions as the number of decision variables increases), Branch and Bound method (effective method, however, requiring high skill of expertise and proper restrictions setup) [31].

The heuristic methods include priority rule-based heuristics. These methods are fairly complicated to use, and their use might be slightly problematic when it comes to more complicated schedules. The use of heuristic methods does not guarantee finding the optimal solution of the given problem.

The tasks sequencing problem in construction is far more complicated than in other disciplines (i.e. production processes). It is caused by the uniqueness of each construction project (in terms of technology, location, size, availability of resources, etc.) [16], [18], [29]. Various authors are trying to implement different models which will resemble (to some extent) realistic constraints and complicated characteristics of the problems (different objective functions, criteria, financing models, hybrid algorithms, nondeterministic data, etc.) [2], [15], [20], [21], [22]. Practical problems in construction can be easily qualified as NP-hard (non-deterministic polynomial-time hard) problems. The time needed for solving these problems grows exponentially with the increase the problem's size [13], [28]. That is why mathematical and heuristic methods do not allow for finding solutions of complicated construction problems in acceptable time [16]. For the same reasons metaheuristic algorithms seem to be the most appropriate measures for scheduling and task sequencing [24].

Widely analysed metaheuristic methods include: Particle Swarm Optimisation (PSO), Ant Colony Optimisation (ACO), Genetic Algorithms (GA), Simulated Annealing (SA), Tabu Search (TS). These algorithms do not guarantee finding the optimal solution of the given problem and their results are subject to input parameters. However they are very useful when it comes to solving NP-hard problems, because they allow for finding suboptimal solutions in acceptable time [32].

Below some examples of optimisation algorithms are briefly described for construction managers to understand their principles.

3.2 EXACT METHODS

The exact methods are sometimes also called mathematical methods. Those methods are enumerative and may be viewed as tree search algorithms. Their search covers the whole search space, and the main problem is solved by dividing it into simpler problems [33].

3.2.1 Linear Programming

Linear programming (LP) (also known as linear optimisation) is a method to achieve the best outcome by a mathematical model whose requirements are represented by linear relationships.

Although first works on LP by Fourier can be dated back to XIX century, the first practical formulation of a problem was done by Leonid Kantorovich in 1939. The method was developed during World War II and was used to reduce costs incurred by soviet army.

Linear programming can be applied to various fields of study. It is used in business, economics, and also some engineering problems (planning, routing, scheduling, assignment, design, etc.). Industries in which LP was used include: manufacturing, transportation, telecommunications, energy, and many more.

However when facing complex problems, the LP cannot compute the results in acceptable time. In such instances, it can be used only as an algorithm for solving sub-problems.

More information on LP can be found in chapter 2.3.

3.2.2 Dynamic Programming

Dynamic programming (DP) (also known as dynamic optimisation) is a method for solving more complex problems by breaking them down into a set of simpler sub-problems. It solves each of these sub-problems just once, and then stores their solutions, so the next time the same sub-problem occurs, instead of recomputing its solution, DP simply looks up the previously computed solution. Such practice saves a lot of computation time.

This procedure is based on the principle developed by its founder - Richard Bellman - that says: "the subpolicy of an optimal policy is itself optimal" [33].

Dynamic programming applications and limitations are similar to those of LP.

3.2.3 Branch and Bound Algorithm

Branch and bound (B&B, BB, or BnB) is based on an implicit enumeration of candidate solutions of the considered optimisation problem [33]. The algorithm was proposed by A. H. Land and A. G. Doig in 1960. The name *Branch and Bound* was introduced in the work on the traveling salesman problem by J. D. Little et al.[25].

The algorithm explores search space by dynamically building a tree (associated search space) which root node represents the given problem. The leaf nodes represent potential solutions and the internal nodes are sub-problems of the total solution space. The pruning of the search tree is based on a bounding function that prunes subtrees which do not contain any optimal solutions [33].

B&B is one of the few exact algorithms capable of solving NP-hard optimisation problems. However, its use require high skill of expertise and proper restrictions setup.

The applications of B&B include: knapsack problem, travelling salesman problem, machine learning, scheduling, cutting stock problem, economics, and more.

There are several software applications of B&B (and similar methods, like branch and cut), including programs such as BARON or ABACUS. Also, on the internet, one can find variety of public pre-written codes and software packages.

If your company employs programmers, they can easily implement this optimisation algorithm into your projects.

For more information, please refer to: [3], [33].

3.2.4 Constraint Programming

Constraint programming (CP) is a language built around concepts of tree search and logical implications [33]. As the name implies, optimisation problems in CP are being modelled by means of a set of variables (which take their values on a finite domain of integers) linked by a set of constraints (in mathematical or symbolic form).

The use of CP is complicated, and requires programming knowledge or IT specialists. However some researchers accomplished very good results with the use of CP. In 2015 they managed to successfully optimise schedules for the large projects (even 2000 activities) [27].

There are several software applications of CP, including programs such as IBM CP Optimiser (used in successful case mentioned above), Gurobi or Minion. Also, on the internet, one can find variety of public pre-written codes and software packages. If your company employs programmers, they can implement this optimisation algorithm into your projects.

For more information, please refer to: [1], [27].

3.3 HEURISTICS

The word *Heuristic* derives from the Greek verb *Heuriskein (ενρισκειν)* which means "to find" / "to discover". A heuristic technique is an approach to problem solving that employs a practical method not guaranteed to be perfect (or optimal), but sufficient for the current goals. Such algorithms are being used when finding optimal solution is impractical (i.e. due to the time needed for calculations) or impossible.

Heuristics consist of a rule or set of rules which seeks good solutions at a reasonable computational time. They are approximate algorithms in the sense that they provide hopefully good solutions for relatively little effort. However they do not guarantee finding optimal solutions. They are especially important for solving complex, real-life problems which are often encountered by engineers, analysts, and managers.

There is a great variety of heuristic methods that are very different in nature. That is why, it is difficult to supply their full classification. Furthermore, many of them have been designed to solve a specific problem without the possibility of generalization or application to other similar problems. However, below several categories of different heuristics are listed [4]:

Decomposition Methods

The original problem is broken down into sub-problems that are simpler to solve. It is important that in a general, that sub-problems belong to the same problem class.

Inductive Methods

As the name implies, in these methods the idea is to generalise the smaller or simpler versions to the whole case. Techniques that have been identified in these cases which are easier to analyse, can be applied to the whole problem.

Reduction Methods

These methods involve identifying specific properties which are generally fulfilled by the good solutions. These properties are set as boundaries for the main problem. In this order the space of the solutions is restricted by simplifying the problem. One has to be careful because there is risk is that the optimum solution of the original problem may be left out outside of the previously set boundaries.

Constructive Methods

These methods base on building a solution of the problem step by step. Usually they are deterministic methods and base on the best choice in each iteration. These methods are being widely used in classic combinatorial optimisation.

Local Search Methods

In local improvement or local search methods, algorithm starts with a feasible solution of the problem and then tries to progressively improve it. In each iteration a movement is performed from current solution to another with a better value. The algorithm ends when, for another solution, there is no other accessible solution that improves the value.

In general, heuristic algorithms are very specific and problem-dependent. That is why they were developed further. The constructive and local search methods formed the foundations of the so-called meta-heuristic procedures [4], which are described in the next subchapter.

A metaheuristics are problem-independent algorithms that provide a set of strategies or guidelines to develop heuristic optimisation algorithms. However a strict definition has been elusive and many researchers and practitioners interchange heuristic and metaheuristic terms. Sometimes, the metaheuristic term is even used to refer to a problem specific implementation of a heuristic optimisation algorithm which works according to set guidelines.

3.4 METAHEURISTICS

Metaheuristics can be briefly described as next level heuristics. The word added at the beginning of the term (suffix) - *Meta* - derives from the Greek and means "beyond" / "upper level".

According to Talbi [33]: "Heuristics find "good" solutions on large-size problem instances. They allow to obtain acceptable performance at acceptable costs in a wide range of problems. In general, heuristics do not have an approximation guarantee on the obtained solutions. They may be classified into two families: specific heuristics and metaheuristics. Specific heuristics are tailored and designed to solve a specific problem and/or instance.

Metaheuristics are general-purpose algorithms that can be applied to solve almost any optimisation problem. They may be viewed as upper level general methodologies that can be used as a guiding strategy in designing underlying heuristics to solve specific optimisation problems".

Many researchers agree that heuristics are problem-dependent techniques. As such, they are usually adapted to the problem so they can take advantage of its particularities. However, sometimes they are too greedy and tend to get trapped in local optima, as a result failing to discover the global optimum solution.

Metaheuristics, on the other hand, are problem independent techniques. Therefore they do not take advantage of any specifics of the problem (they can be treated as black boxes). Usually, they are not greedy and can accept a temporary deterioration of the solution (e.g. the simulated-annealing algorithm – see below). That fact allows them to explore the solution space more thoroughly and, as a result, find a better solution (which can even sometimes be the global optimum itself). However, it has to be noted that although metaheuristics are problem independent techniques, it is necessary to do some fine-tuning of their input parameters in order to adapt the algorithms to the considered problem.

3.4.1 Particle Swarm Optimisation

The Particle Swarm Optimisation (PSO) was invented by Russell Eberhart and James Kennedy in 1995 [36]. As its name implies, it was inspired by the flocking and schooling patterns of birds and fish. Both men were developing computer simulations of birds flocking around food sources. At some point they realised that their algorithm works good in terms of optimisation problems.

When a swarm is looking for food, its individuals (particles) spread in the environment (solution space) and move around independently. At first they move around randomly. However, as the time goes by, they movement is influenced by their local best known position. At the same time, they are guided toward best known positions in the search space, which are updated as better positions by other individuals. That is how the swarm moves to the best solutions.

If we consider a flock of birds circling over an area in which they can smell a hidden source of food, the following pattern occurs. The bird which is closest to the food chirps the loudest, thus attracting other birds. If any other bird comes closer to the food, it starts to chirp even louder. The pattern continuous until the one of the birds finds the food.

The algorithm keeps track of a series of global variables: target condition, global best (called: *gBest*) – value indicating which particle is currently closest to the target, and stopping value (which indicates when the algorithm should stop).

The individuals (particles) store following: position (data representing a possible solution), a personal best (called: *pBest*), and velocity (value indicating how much the data/ current position can be changed).

To explain the velocity value, a simple example can be given. Two fishermen are searching the lake for the deepest point in order to find the biggest fish. At the beginning of each step, they tell each other how deep the lake is at their current position. At first both of them start from different ends of the lake (figure 3.1). The depths are pretty similar, so they both go their own ways.

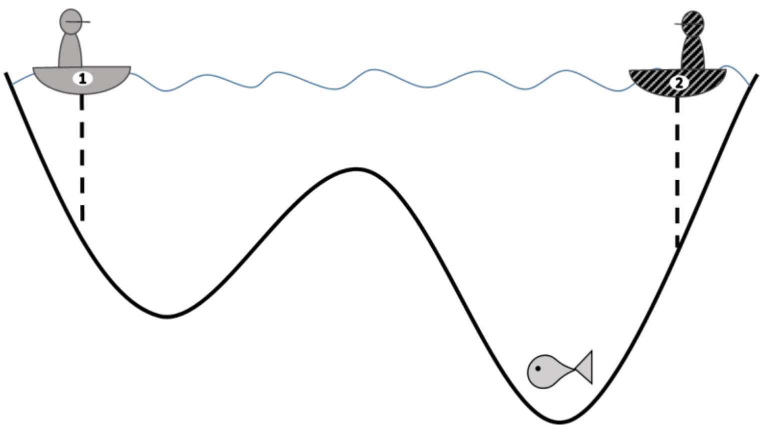

Fig. 3.1. PSO principles – stage 1 [own source]

At some point the second fisherman announces that his position is better (figure 3.2). Fisherman 1 starts to move towards him rapidly and the lake beneath him gets deeper and deeper.

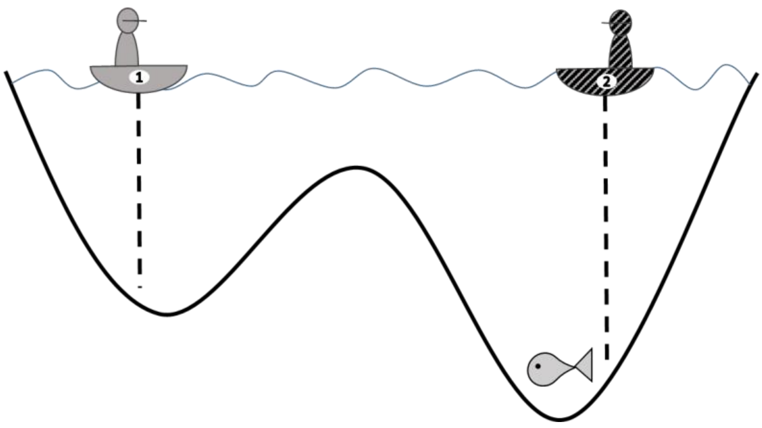

Fig. 3.2. PSO principles – stage 2 [own source]

However a few moments later, the situation becomes more complicated (figure 3.3) –fisherman 2 still has a better positon, and by moving towards him, the position of the first fisherman is getting worse. That is when fisherman 1 decides to move slower than before in order to check the bottom of the lake more carefully.

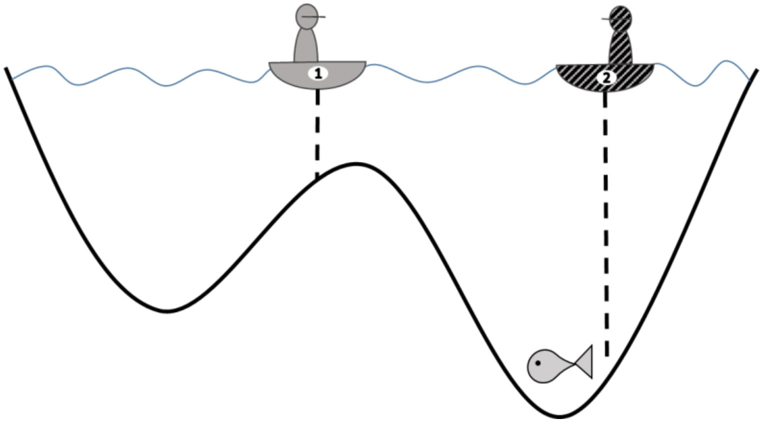

Fig. 3.3. PSO principles – stage 3 [own source]

Finally, the first fisherman's position is getting better again (figure 3.4). Thanks to the help of the second fisherman, he managed to escape the local optimum.

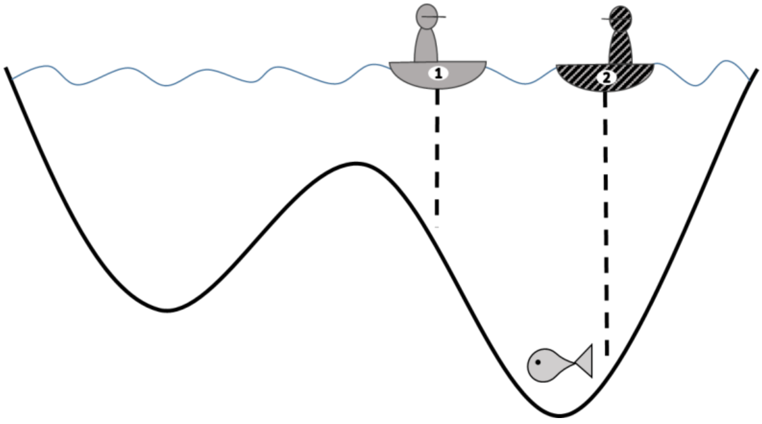

Fig. 3.4. PSO principles – stage 4 [own source]

In order to avoid getting stuck at local optimums, several population topologies (neighbourhoods) can be used. These neighbourhoods can involve a group of particles which act together (communicate between each other) or subsets of the search space that particles happen into during testing [17]. Some of the popular topologies include (figure 3.5):

a) Single-sighted – individuals only compare themselves to the next best

b) Ring topology – each particle compares only to those to the right and left

c) Fully connected topology – every individual compares to each other

d) Isolated – particles only compare to those within previously established groups

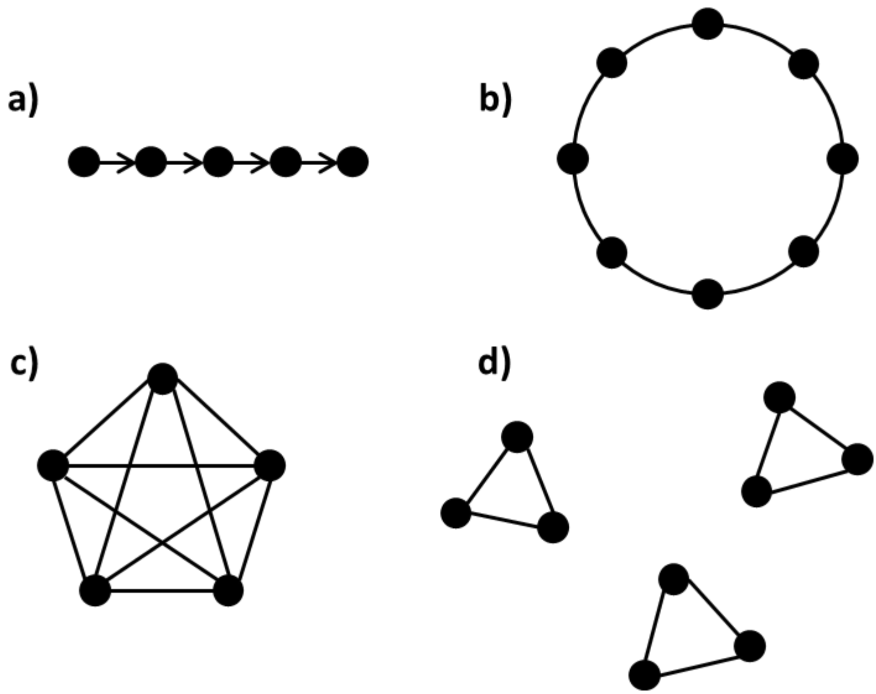

Fig. 3.5. PSO topologies [own source]

Particle swarm optimisation applications include i.e. function optimisation, machine learning, chemical engineering, economics, finance, geometry, physics, circuit design, scheduling.

Currently there is no commercial software for construction scheduling applications of PSO. However, the internet is full of public pre-written codes and software packages (like: MATLAB, or WIOMAX). If your company hires programmers, they can easily implement this optimisation algorithm into your projects.

For more information, please refer to: [9], [36].

3.4.2 Ant Colony Optimisation

This algorithm was proposed by Marco Dorigo in 1992 in his PhD thesis. [26]. The ant colony optimisation algorithm (ACO) was developed to search for an optimal path in a graph.

ACO is a metaheuristic method. Its use does not guarantee finding the optimal solution of the given problem. However it is a very useful tool when it comes to solving very complicated problems, because (as most metaheuristics) it allows for finding suboptimal solutions in acceptable time.

The algorithm is based on the ants behaviour. When an ant tries to find a route between its nest (anthill) and a food source, it leaves a chemical trail called a pheromone on the ground when they travel between food source and nest. The purpose of the pheromone is to guide the other ants towards the target point. However, pheromones trails evaporate over time, so that unless they are reinforced by more ants, the pheromones will disappear.

At first an ant will leave the anthill and begin to wander in a random direction. As it paces around, it lays a trail of pheromone. Because of that, when the ant finally finds some food, it can track its way back to the nest. By doing so, the insect leaves another layer of pheromone on the path (figure 3.6).

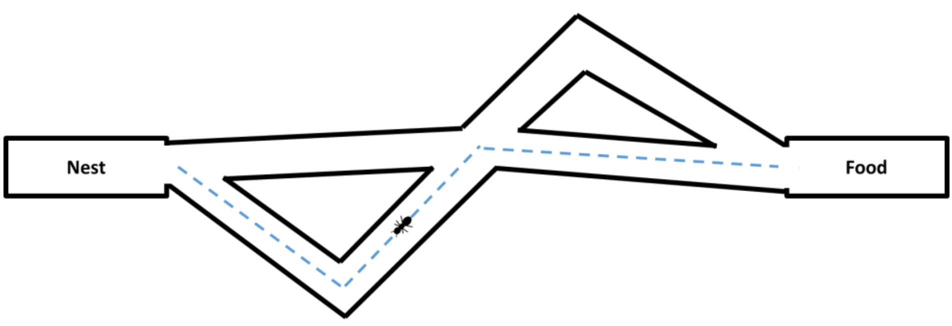

Fig. 3.6. ACO principles – stage 1 [own source]

Other ants trail randomly one of the alternative ways and they also lay pheromone trails. Each ant that finds the food will leave some pheromones on their paths. Any other ant that senses the pheromone will follow its trail with a certain probability. As time goes by, the pheromone density on the path will increase and more and more ants will follow it to the food and back to the anthill (figure 3.7).

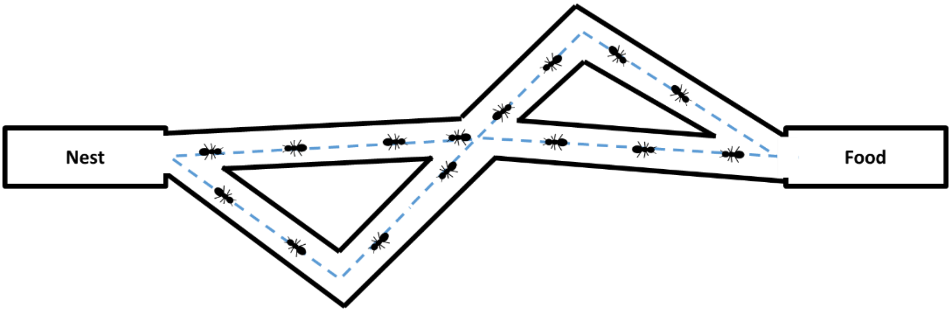

Fig. 3.7. ACO principles – stage 2 [own source]

The shortest path is reinforced with more pheromones because the ants on this trial lay pheromone trails faster. The higher the pheromone density, the more probable is that an ant will stay on a path. So, the most reinforced trail is more attractive to next ants. While the pheromone trails on longer paths evaporate over time (figure 3.8).

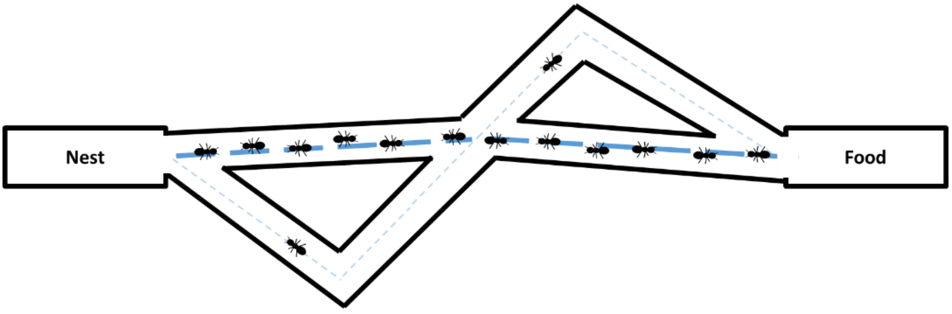

Fig. 3.8. ACO principles – stage 3 [own source]

If all the food is collected, the trial will be renewed no longer and the path will disappear after a while. The ants will look for new, random locations (figure 3.9).

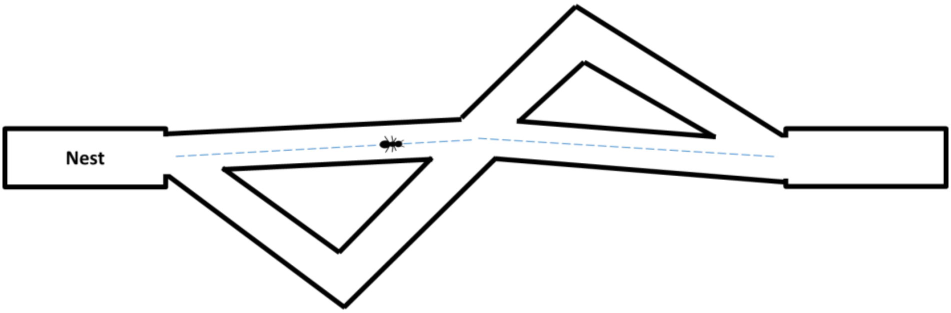

Fig. 3.9. ACO principles – stage 4 [own source]

In its basic form, the algorithm allows for finding shortest routes. However, after some adjustments, they can be used for various problems like: vehicle routing, scheduling problems, assignment problems, data mining, cash flow optimisation, power electronic circuit design, and many more.

Currently there is no commercial software for construction applications of ACO. However, the internet is full of public pre-written codes and software packages (like: ACOTSP.V1.03, AntSolver, or AntMiner+ v1.0.). If your company employs programmers, they can easily implement this optimisation algorithm into your projects.

For more information, please refer to: [7], [8].

3.4.3 Genetic Algorithms

A Genetic Algorithm (GA) is a type of evolutionary algorithm. This metaheuristic algorithm imitates the natural selection process in biological evolution with selection, mating reproduction and mutation. It is one of the most popular and widely used optimisation techniques.

The idea of creating such algorithms is said to be based on ideas of Alan Turing, Nils Aaall Barricelli, and Alex S. Fraser (1950s) [36], however the algorithms as they are used today were popularised by John Holland in the early 1970s (particularly by his book Adaptation in Natural and Artificial Systems - 1975) [14].

To explain how GA works, some basic biological concepts must be given with the reference to construction management optimisation problems [19]:

Individuals (candidate solutions) – these are the basic specimen subject to evolution. In biology, these individuals are living in the environment. The goal of evolution is to create a specimen that is adapted the best to the given environment (the fittest individual). In GA, the individual is represented by a candidate solution of an optimisation problem (i.e. construction schedule).

Population – a set of individuals subject to evolution.

Fitness – a function that allows to rate given individual (according to the optimisation problem)

Phenotype – features of specimen determining its fitness (adaptation to the given environment). In GA, the parameters of the solution subject to assessment (i.e. makespan of the project, NPV).

Genotype – a structural representation of the phenotype. It is a complete description of an individual. A genotype may be represented by a single chromosome. In terms of optimisation problem, it may be description of the construction schedule (i.e. vector of tasks' starting times).

Chromosome – a sequence of genes, it stores genotype of an individual.

The evolution process (both natural and the computational algorithm) is performed in accordance with basic rules [19]:

- the genotype of an individual is subject to modifications during reproduction process. The two basic modifications are effects of crossover (swapping parts of the two genotypes – figure 3.10) or mutations (random changes in chosen values of genes – figure 3.11)
- the changes introduced to genotypes result in changes of a new child phenotypes. The fact is influencing their fitness level (which is analysed with the objective function)
- the changes introduced to genotypes are random, so there is the same probability of both improving and decreasing in fitness level of new generations
- the new generation individuals are compared (in accordance with their fitness level). The better the individual, the more probable it is for it to reproduce (they become a parental generation)

- the individuals that did not adapt to the given environment (weakest in terms of objective function) are going extinct
- the individual genotype is subject to changes (mutation, crossover). The individual phenotype is subject to natural selection process.

Genetic algorithms introduce modifications with a certain probability. Introduction of mutation is crucial, because crossover operations may sometimes eliminate outcomes which contain elements of the optimal solution.

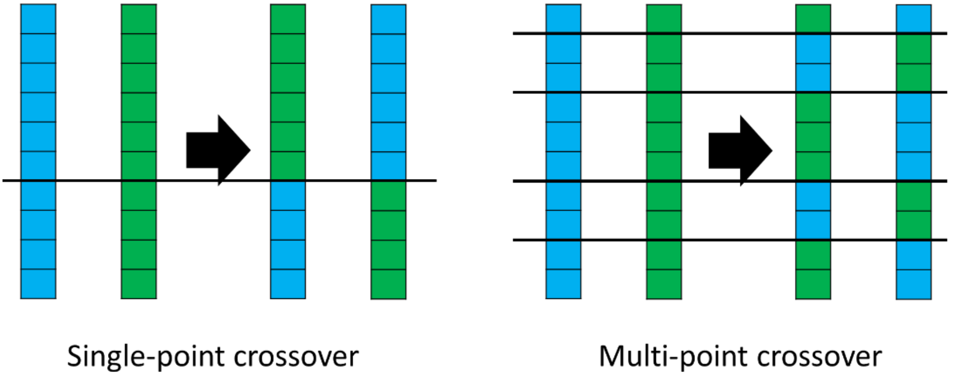

Fig. 3.10. GA – crossover examples [own source]

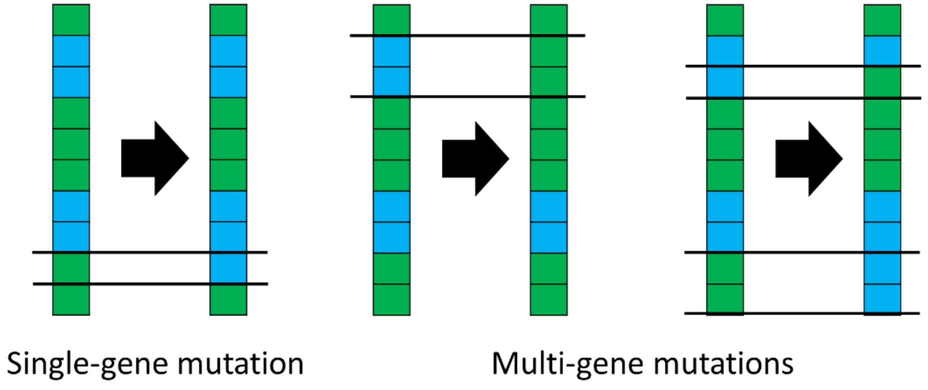

Fig. 3.11. GA – mutation examples [own source]

The algorithm consists of the following steps (also depicted in figure 3.12):

- Creation of initial population - the individuals are randomly generated
- Evaluation - computing the objective values of the solution candidates
- Fitness Assignment- using the objective function to determine fitness values. The better the function value, the better the adaptation of a chromosome
- Selection - the fittest chromosomes are chosen for the reproduction process
- Reproduction - new generation is created with the use of modification procedures described above.

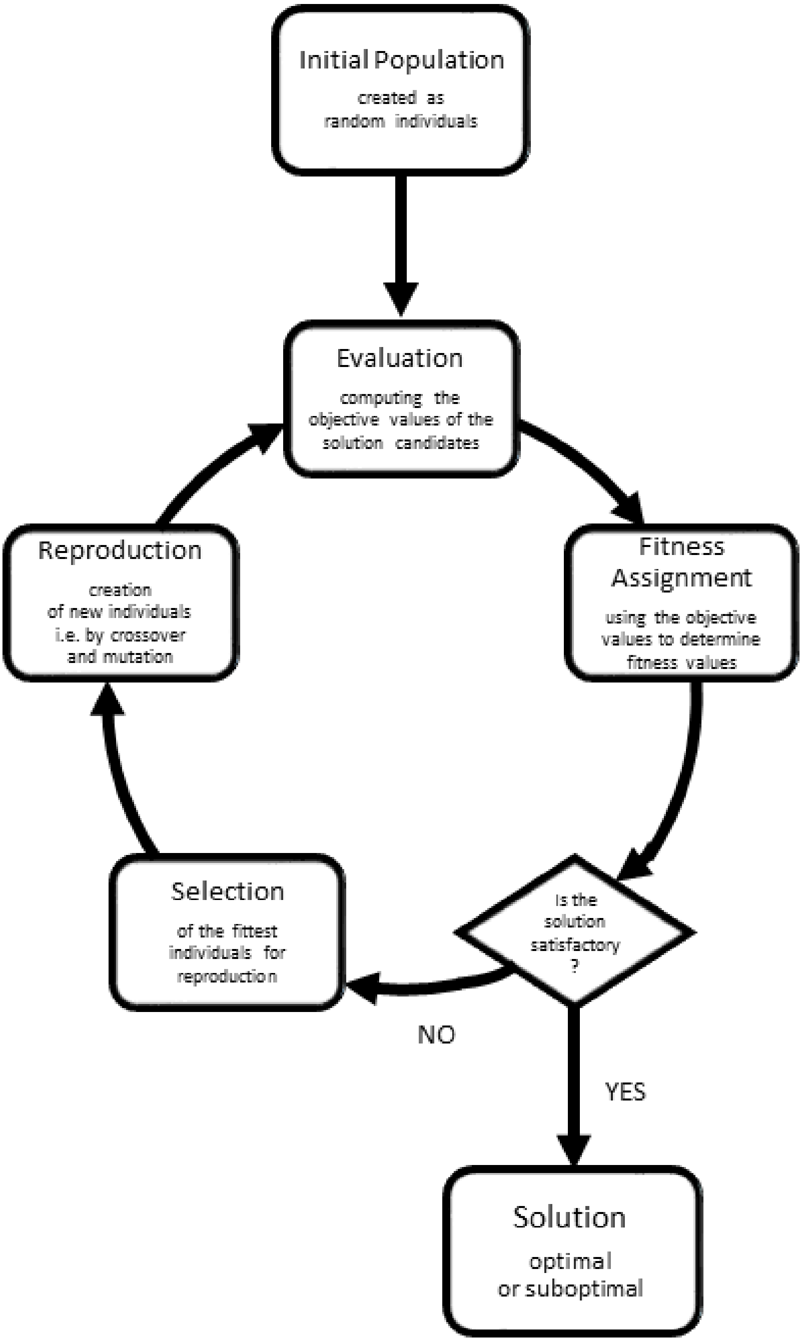

Fig. 3.12. Genetic algorithm principles [own source]

Genetic algorithms are widely used. Some of its applications include: finances management, computer-automated design, bioinformatics, biology and computational chemistry, climatology (modelling global temperature changes), decryption, construction of facial composites of suspects by eyewitnesses in forensic science, control engineering, design of water resource systems, design of anti-terrorism systems, economics, scheduling (including job-shop scheduling), image processing, linguistic analysis, mechanical engineering, medicine, plant floor layout, music production, quality control, traveling salesman problem, vehicle routing, and many more.

There are several software applications of GA, including programs such as Evolver or PIKAIA [5]. Most of them are compatible with popular MS Excel spreadsheets [31]. They are quite easy to use even by relatively unexperienced users.

Also, on the internet, one can find variety of public pre-written codes and software packages. If your company employs programmers, they can easily implement this optimisation algorithm into your projects.

For more information, please refer to: [6], [12].

3.4.4 Simulated Annealing

This algorithm was inspired by the annealing process in metallurgy (hence the name). Such technique involves heating a material to the temperature above its recrystallization temperature, maintaining a suitable temperature, and then cooling it in order to improve its properties (until it freezes). The temperature parameters have to be carefully selected to avoid the system getting stuck in a meta-stable state (local optima).

The simulated annealing algorithm (SA) was developed by Kirkpatrick on the base of Metropolis works [36]. The physical annealing was replaced with the simulation (table 3.1).

Metallurgy	**Optimisation algorithm**
System states	Solutions
Energy	Optimisation goal (i.e. time or cost)
Change of state	Neighbouring solutions

Metallurgy	Optimisation algorithm
Temperature	Artificial temperature parameter
Frozen state	Obtained solution

Tab. 3.1. Relation between annealing in metallurgy and simulated annealing optimisation algorithm [own source]

This algorithm can be used especially for problems in which finding an approximate global optimum is more important than finding a precise local optimum in a fixed amount of time.

In order to explain the principles of SA a simple example can be given. Let us assume the following situation. A person is climbing the mountains. The goal is to reach the highest peak. However, there is a fog, so the visibility is limited to only few meters, and one never knows if the peak he is standing on is the highest one. The climber is starting in the morning, and has to reach the highest point by the dusk and set up a camp there (figure 3.13).

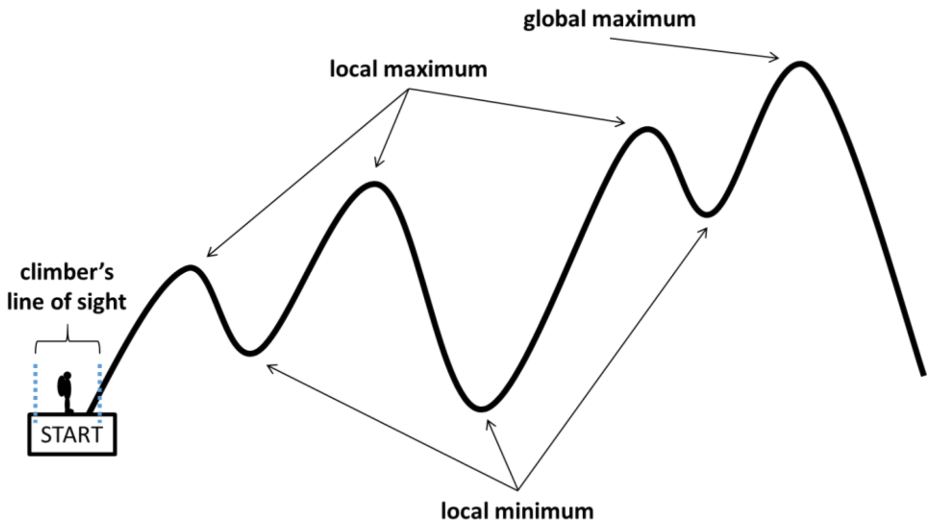

Fig. 3.13. SA – explanation – problem [own source]

The climber starts his ascend, he reaches the first peak - local maximum (figure 3.14). Since his line of sight is restricted by fog, he does not know if that is the highest peak. It reflects complicated optimisation problem in which we do not know all the possible solutions.

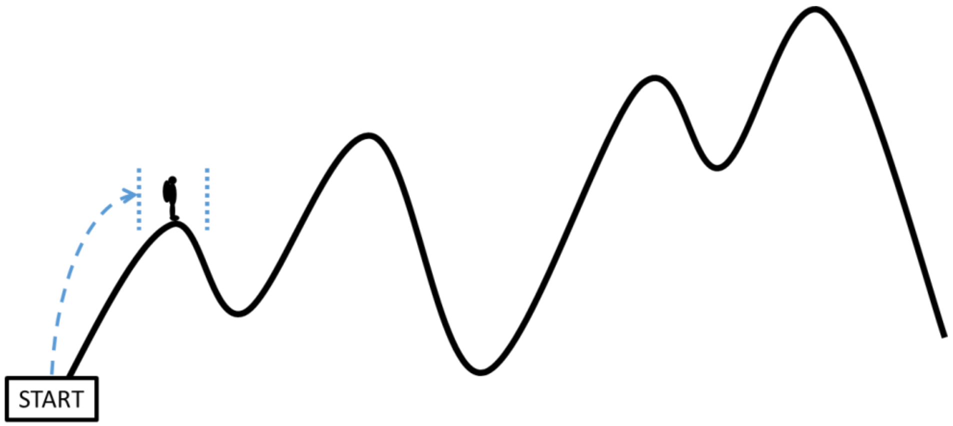

Fig. 3.14. SA – explanation – high temperature [own source]

Now he has to decide whether he wants to stay here for a night, or take a risk and go down, hoping to find another peak, hopefully higher than the one he is standing on right now.

If he was to act according to the simple, greedy algorithm, he would have stayed at the top of that mountain. The found solution would have been the first local maximum.

However, according to the SA algorithm he is willing to go down with a certain probability. The more time he has till dusk (the higher the temperature parameter), the more probable it is that he will decide to go further.

The situation is repeated (figure 3.15) when the climber reaches the second peak (another local optimum). Although this time it is later (the temperature parameter is lower), so there is a less chance that he will decide go further if it means going down.

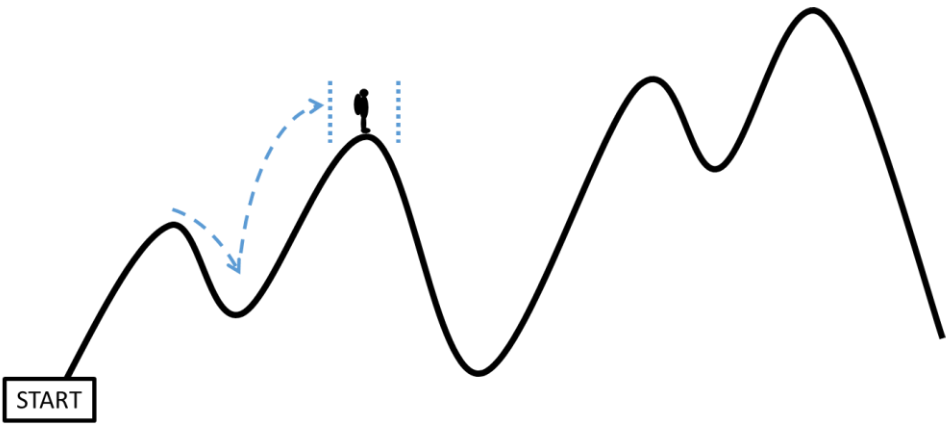

Fig. 3.15. SA – explanation – medium temperature [own source]

When the climber reaches the third peak, it is late (low temperature parameter – low probability of him looking for a better solution if the neighbouring ones are worse). He decides to set up a camp and stay there for a night (figure 3.16).

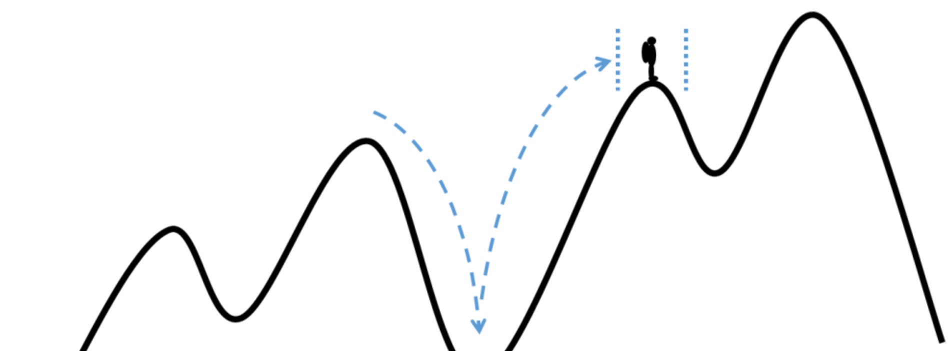

Fig. 3.16. SA – explanation – low temperature [own source]

As you can see he did not find the global optimum, however the height he reached was quite impressive. The same applies to the SA algorithm. It does not guarantee finding the best solution (just like other metaheuristic algorithms), however it is a very useful tool when it comes to solving a complex problem. SA allows for finding suboptimal solutions in acceptable time. Of course the more time we can spend on the solution search (the longer the cooling process), the more chance we have to get the better outcome.

Simulated annealing applications include i.e. function optimisation, image processing, chemical engineering, economics, finance, machine learning, circuit design, scheduling, routing problems.

Currently there is no commercial software for construction scheduling applications of SA. However, the internet is full of public pre-written codes and software packages (like: MATLAB). If your company hires programmers, they can easily implement this optimisation algorithm into your projects.

For more information, please refer to: [34], [36].

3.4.5 Tabu Search

The Tabu search algorithm (TS) was developed by Fred Glover in 1980s. The word "tabu" comes from Tonga (Polynesia) and is used for the things that cannot be touched since they are sacred [36].

The basic idea behind this algorithm is to search the solution space by a sequence of moves [30]. In this sequence, some moves are considered *tabu moves* – they are forbidden. The TS algorithm avoids getting stuck in local optima by storing the information about previously checked solutions in form of *tabu lists*. The list is growing as the algorithm proceeds. However, when it reaches its maximum capacity, the oldest entries of tabu list are being overwritten be the new ones.

The principles of the TS algorithm are depicted in figure 3.17.

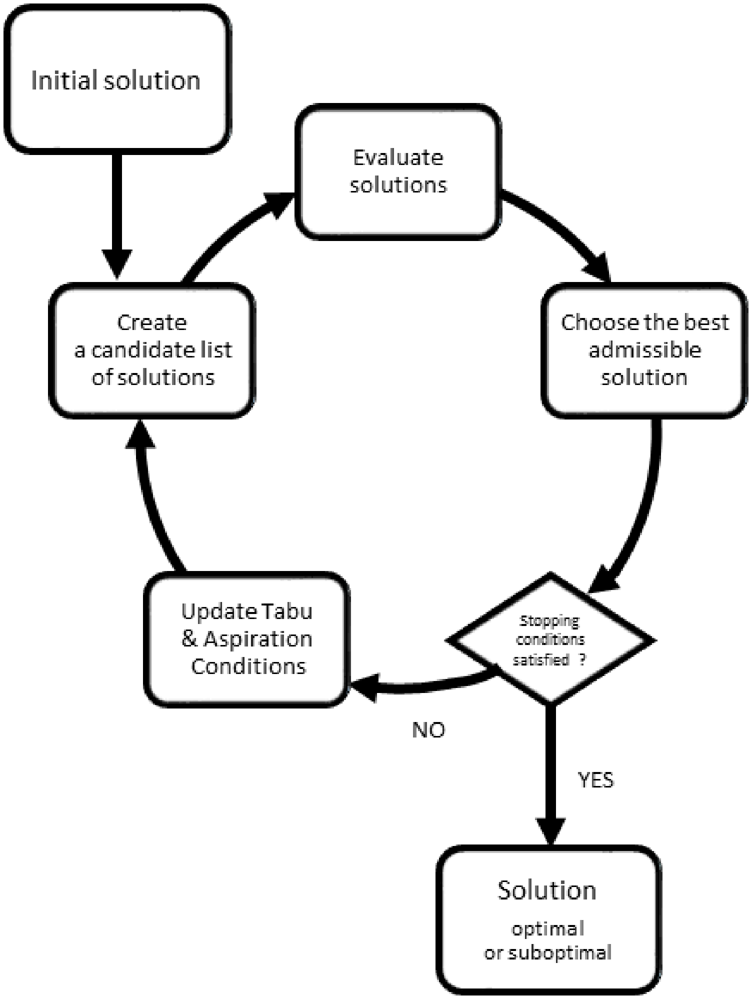

Fig. 3.17. Tabu search algorithm principles [own source]

More complex approaches store specific properties of the individual solutions instead of the phenotypes themselves in the list. Such situation leads to more complicated algorithms, but may also result in rejecting new solutions which actually are good. Therefore, *aspiration criteria* are being defined which override the tabu list and allow certain individual solutions [36].

In order to explain the principles of TS a simple example can be given - minimum spanning tree problem with constraints [23]. The objective is to connect (link) all nodes at minimum cost (figure 3.18).

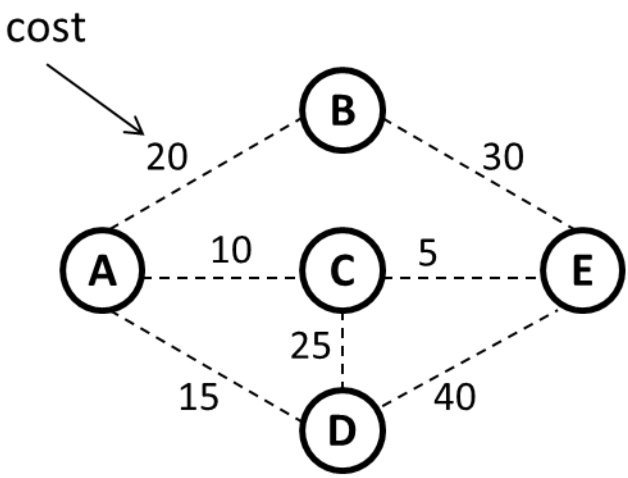

Fig. 3.18. TS example - problem [own source]

Additionally two constraints are given:

Constraint 1: Link AD can be included only if link DE also is included. (otherwise, penalty:100)

Constraint 2: At most one of the three links – AD, CD, and AB – can be included. (Penalty of 100 if two of the three are selected, 200 if all three are selected.)

In figure 3.19 an optimal solution without considering constraints is given. It will be considered as an initial solution. The cost of this solution equals AB + AC + CE + AD:

20 + 10 + 5 + 15 = 50

If the constraints are taken into account, we have to add a penalty of 200: 100 for link AD (constraint 1: link DE is not included), and 100 for simultaneous existence of links AD and AB (constraint 2). The total cost of this solution is 50 + 200 = 250.

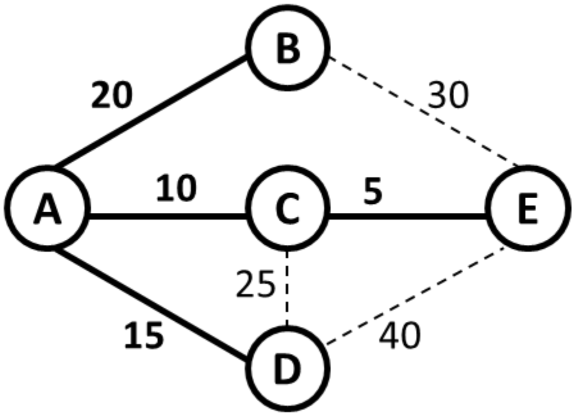

Fig. 3.19. TS example – initial solution [own source]

In the next step (iteration / movement of the TS algorithm) we will try to remove one link and replace it with the other, such that all the nodes will still be connected (main objective). The costs of possible solutions are presented in table 3.2.

Added link	**Deleted link**	**Cost of the new solution**
BE	CE	75 + 200 = 275
BE	AC	70 + 200 = 270
BE	AB	60 + 100 = 160
CD	AD	60 + 100 = 160
CD	AC	65 + 300 = 365
DE	CE	85 + 100 = 185
DE	AC	80 + 100 = 180
DE	**AD**	**75 + 0 = 75**

Tab. 3.2. TS example – costs of new solutions 1 [own source]

The local optimum is 75. Link DE is deleted and link AD created. Obtained solution is presented in figure 3.20. Newly created link DE is added to the tabu list, so in the next step we will not consider deleting that connection. The only exception would be considered if such move would result in a better solution than the best solution found previously (aspiration condition).

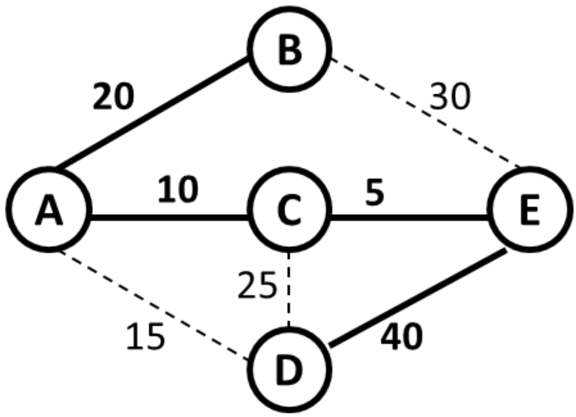

Fig. 3.20. TS example – 2nd solution [own source]

The next iteration of the algorithm starts by creating another list of candidate (new) solutions (table 3.3).

Added link	Deleted link	Cost of the new solution
AD AD AD	DE (tabu) CE AC	Tabu move 85 + 100 = 185 80 + 100 = 180
BE BE **BE**	CE AC **AB**	100 + 0 = 100 95 + 0 = 95 **85 + 0 = 85**
CD CD	DE (tabu) CE	60 + 100 = 160 95 + 100 = 195

Tab. 3.3. TS example – costs of new solutions 2 [own source]

After this move (deleting AB and creating BE link) we are escaping local optimum, the new outcome is 85 (figure 3.21).

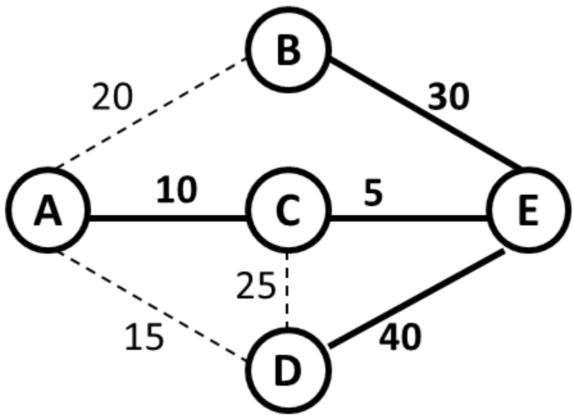

Fig. 3.21. TS example – 3rd solution [own source]

Our tabu list is expanded by new link: BE. We can start the new iteration (table 3.4).

Added link	**Deleted link**	**Cost of the new solution**
AB AB AB	BE (tabu) CE AC	Tabu move 100 + 0 = 100 95 + 0 = 95
AD AD AD	DE (tabu) CE AC	60 + 100 = 160 95 + 0 = 95 90 + 0 = 90
CD CD	**DE (tabu)** CE	**70 + 0 = 70** 105 + 0 = 105

Tab. 3.4. TS example – costs of new solutions 3 [own source]

In this step tabu is overridden, due to the aspiration condition (the new solution move is on the tabu list, however it is better than any other solution checked so far). The resulting connections between nodes are depicted in figure 3.22.

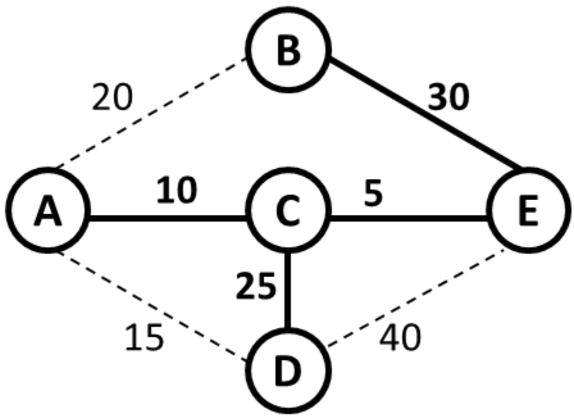

Fig. 3.22. TS example – 4th solution [own source]

The following iterations are calculated until stopping condition occurs. Usually it means, that the maximum number of iterations or maximum computation time is exceeded (both values are being set before the algorithm is started).

Common applications of TS span the areas of i.e. scheduling, image processing, resource planning, telecommunications, molecular engineering, logistics, waste management, mineral exploration, financial analysis, energy distribution, biomedical analysis.

In recent years, many articles were published in a wide variety of fields documenting successes of TS, giving exemplary solutions whose quality often significantly surpassed those obtained by other methods.

There are several software applications of TS, including programs such as METSlib or Opt Quest [10]. Most of them are compatible with popular MS Excel spreadsheets [31]. They are quite easy to use even by relatively unexperienced users.

Also, on the internet, one can find variety of public pre-written codes and software packages. If your company employs programmers, they can easily implement this optimisation algorithm into your projects.

For more information, please refer to: [10], [11], [36].

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CHAPTER 4

OPTIMISATION OF STRUCTURES (DESIGN)

(J. ROSŁON)

4.1 INTRODUCTION

4.1.1 Construction structures design

Prior to considering methods for optimisation of structures, the basics of the structural design process should be mentioned. Such process usually follows the same progression as any other design task. However, design process of building structures may be complicated due to its interdisciplinary character. The input from various stakeholders, like: clients, architects, and structural and building services engineers may lead to large number of revisions or even to revisiting earlier design phases [1].

In its classical form, the design process consists of following stages:

1. The conceptual design stage – creation of initial concepts meeting broad design requirements (like functionality) set by clients or architects.

2. The preliminary design stage – further development of conceptual design (one or more). Preparation of detailed proposals.

3. The detailed design stage – development of all information required for construction (sufficient for coordination of its components and elements).

As the design process proceeds and more detailed information are available, the space of possible solutions is getting smaller and thus easier to search by optimisation algorithms. However, the sooner the optimisation process is started, the greater range of possible solutions - the greater the possibility of substantial cost reduction (or improvement of other parameters).

4.1.2 Optimisation of structures

Design optimisation was loosely defined by Papalambros and Wilde as the selection of the best design within the available means. The process involves [6]:

1. The selection of a set of variables to describe the design alternatives.

2. The selection of an objective (criterion), expressed in terms of the design variables, which we seek to minimise or maximise.

3. The determination of a set of constraints, expressed in terms of the design variables, which must be satisfied by any acceptable design.

4. The determination of a set of values for the design variables, which minimise (or maximise) the objective, while satisfying all the constraints.

In increasing order of complexity, structural design optimisation tasks are generally considered to be (also depicted in figure 4.1) [1]:

- ***Optimisation of size*** *(and shape) of cross-section for discrete structural members, such as beams and columns, or thickness of continuous material, such as panels or floor slabs. This is often referred to as size optimisation.*

- ***Shape Optimisation****, varying positioning of nodes or connections and definition of lines, curves and surfaces that describe structural form.*

- ***Topology Optimisation****, varying the configuration and connectivity of members or material.*

4.1.3 Drivers and barriers

Construction companies may greatly benefit from performing optimisation of structures. However it is worth to note that several barriers have to be overcome first. According to Shea and Luebkeman [7], and Baldock [1], main drivers for structural optimisation in the building industry include:

- rapid generation and evaluation of a large number of design alternatives (especially desirable in the early stages of a project)

- discovering previously unknown feasible solutions (in particular when it comes to highly complex structures)

- cost benefits (e.g. reduced material or construction cost and increased potential revenue, maximisation of floor space or quality)

- time savings (thanks to computer-assisted search)

- marketability of optimisation capabilities (e.g. by offering clients maximisation of net lettable floor space or minimisation of steel tonnage)

- decision support in the design process.

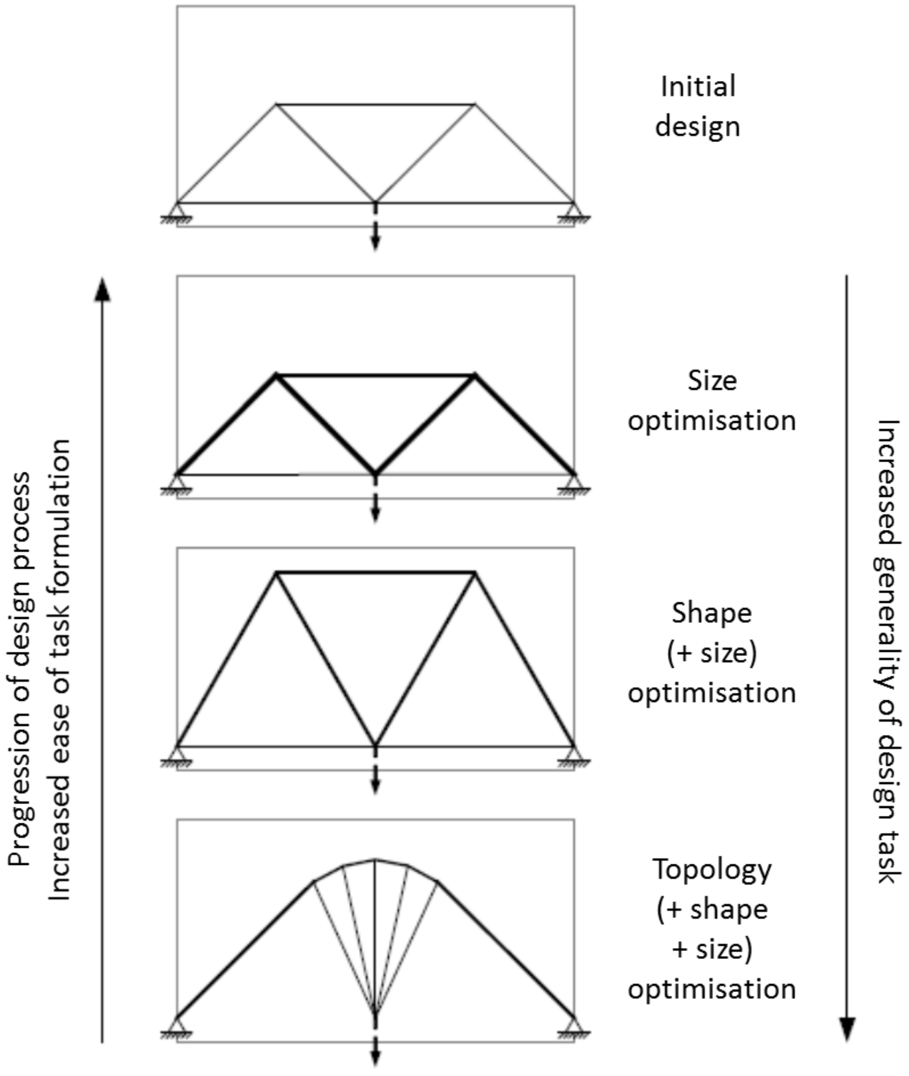

Fig. 4.1. Structural optimisation tasks illustrated through the example of the design of a simply-supported, centrally point-loaded structure [1]

At the same time they list some of most common barriers:

- ill-structured problems
- architectural constraints

- time required for the design process (the process of introducing the structures optimisation or new type of problem in a construction company might be time-consuming. Especially taking into consideration tight schedules. That is why some initial investments may need to be made, before cost-benefits are achieved)

- choosing the right method and model of optimisation (e.g. issues of scale in extending small research case studies to practical design scenarios)

- risk of specifications changes (optimisation tools must robust so they can adapt to specification changes)

- lack of tools, experience and knowledge required to implement optimisation methods

- user scepticism (same applies to any other relatively new techniques)

- optimisation results can be hard to verify (just like with any other professional software, it has to be used by someone with the substantial knowledge in the given field. Also, when it comes to complex problems, some methods may not be able to find best solutions).

4.1.4 Comparison to other industries

Compared to other industries (especially automotive and aeronautical industries) structural design optimisation in construction is relatively underdeveloped. However, a lot of optimisation methods used in those other industries are constantly being transferred to construction.

There are few reasons behind it, all of them quite simple. For example, usually elements being subject of optimisation in automotive industry are very small (especially compared to large construction parts) and mass-produced (in contrary to most elements optimised in construction). Such combination results in a very good ratio of effort to profit.

The example showcasing the phenomenon is presented in table 4.1.

Characteristic	Automotive/aerospace component	Steel building structure
Topological complexity	Generally low, higher for whole body	High, but often ordered, hence parameterisation may be possible
Production volume	Large (up to 100,000s)	Low (generally one-off)
Principal cost considerations	Design, material, knock-on costs of weight	Design, construction, lifecycle costs
Knock on effects of excess mass beyond material cost	Reduces efficiency and vehicle speed	Extra dead-weight increases loads elsewhere in structure
Typical constraints	Stiffness, strength, natural frequency, fatigue	Stiffness (global), strength (local, often buckling-related)
Manufacture	Purpose designed process (e.g. casting) allows flexibility and irregularity of component form	Discrete catalogued structural members from steel supplier
Aesthetic considerations	Minimal	Often critical for topology design

Tab. 4.1. Design and production of a typical automotive component versus a steel building structure [1]

4.2 EXAMPLES, SOFTWARE

Despite all the barriers and drawbacks, optimisation of structures is being successfully used in construction industry. Below some examples are presented:

One of the programmes for optimisation of shape is RESHAPE. The following diagram shows the optimisation of the plates shape (thickness), so that the first natural vibration frequency was equal 2500 Hz [2].

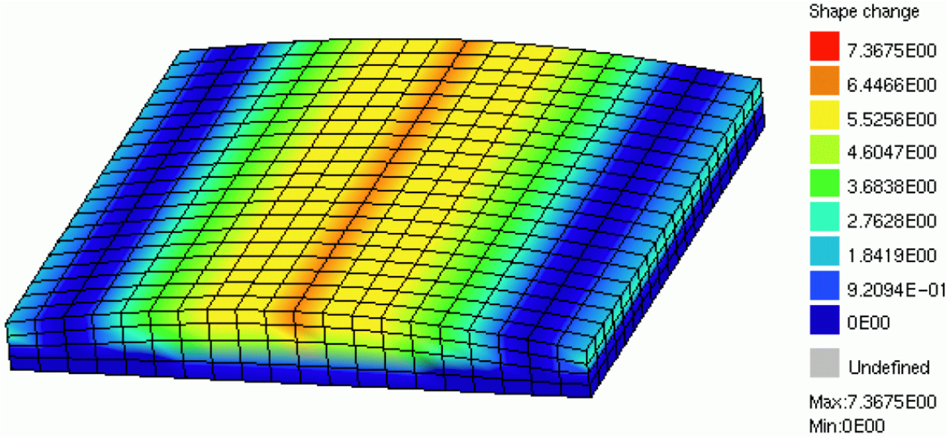

Fig. 4.2. Optimisation of the plate shape [2]

Altair OptiStruct can be used to achieve feasibility of complex structure while creating lightweight results reducing design cost and time. It can be used e.g. to minimise displacement at the top of the building under lateral wind pressure using the least amount of material [5].

Fig. 4.3. Structure optimisation with the use of OptiStruct [5]

Other structure optimisation software include TOSCA, GENESIS, Nastran, Optimus, SODA, or LS-OPT.

Another optimisation task, which can be modelled using the algorithms described in chapter 3, is the problem of mixtures, for example, determining the correct mixture composition to obtain a product containing the proper ingredients, while the raw materials purchase costs are minimised.

Examples of such software are COST (Concrete Optimisation Software Tool), and MixSim. These are systems to assist concrete producers, engineers and researchers in determining optimal mixture proportions for concrete.

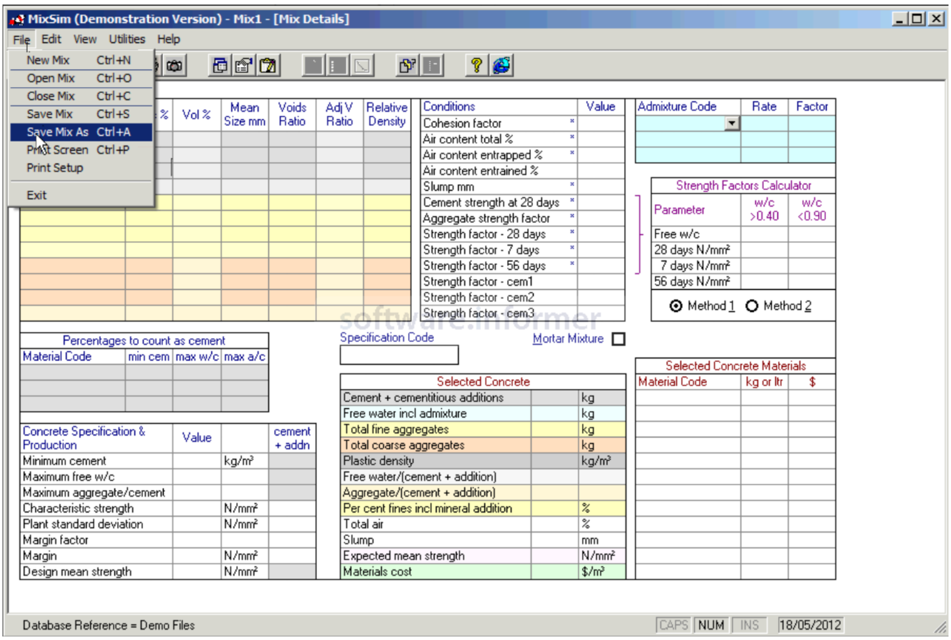

Fig. 4.4. MixSim software [4]

The optimisation of structures is limited not only to the commercial software programmes listed above. The internet is full of public pre-written codes and software packages. If your company hires programmers, they can implement optimisation algorithms mentioned in chapter 3 into your projects.

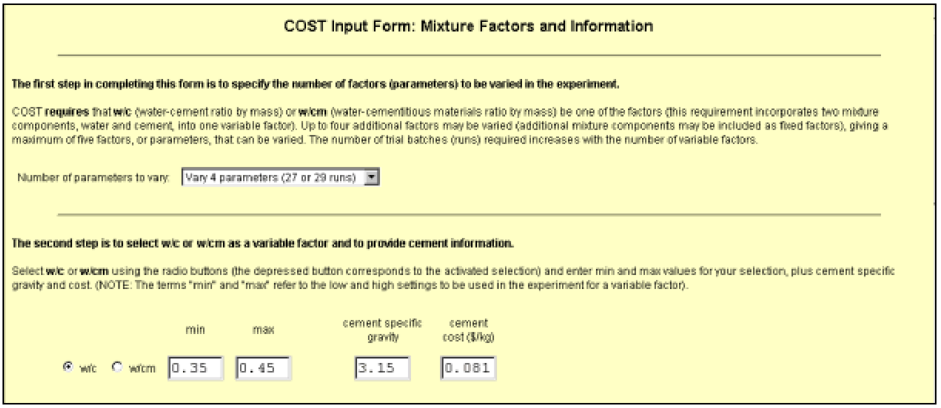

Fig. 4.5. COST software [3]

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CHAPTER 5
LOGISTICS OPTIMISATION
(J. ROSŁON)

5.1 INTRODUCTION

5.1.1 Logistics in construction

The term logistics is usually associated with the detailed organisation and implementation of a complex operation.

In a general business sense, logistics is the management of the flow of things between the point of origin and the point of consumption in order to meet requirements of customers or corporations in a cost-effective way.

The resources managed in logistics can include physical items such as materials, equipment, and liquids; as well as abstract items, such as time and information. The logistics of physical items usually involves the integration of information flow, material handling, production, packaging, inventory, transportation, or warehousing.

Logistics is a key aspect of construction but not everyone is aware of this fact. For example, before a brick is used to construct a wall, it has to go through a long process featuring series of activities (figure 5.1).

It is easy to assume that at the construction site, logistics include crucial activities supporting actual construction process. Materials supply, horizontal and vertical transport, staff welfare, walkways, traffic and gates management, all of these are essential for the success of a construction project.

However, only few construction companies have adopted logistics management, even though various studies estimate that 10% to 30% cost savings can be realised if efficient logistics management practices are implemented [9].

A construction logistic manager is regarded as one of the most challenging jobs in the construction industry nowadays. Roles and responsibilities of the construction logistic manager that were listed by many prominent industry stakeholders (e.g. CIOB, Mace, Laing O'Rourke, Skanska) [8]: all aspects of the logistics supply chain, stores management, development and optimisation of site logistics solutions to meet the needs of the project. The logistics manager is also required to manage the movement of people, goods and equipment at the construction site and control site facilities management.

The areas of his work include [8]:

- **planning/programming** – e.g. site set-up, internal and external logistics routes, usage of key assets
- **mobilisation** – e.g. security, traffic management, installation and management of accommodation, creation of operational procedures and methods, inductions, meetings
- **supply chain management** – e.g. storage, access, plans, procurement, materials, sub-contractors, control, KPIs
- **programme support** – e.g. meeting deadlines
- **safety** – e.g. preparation, inspections, risk assessments
- **fire** – e.g. Site Emergency Plan, lifesaving equipment
- **site communications** – e.g. noticeboards, email lists, displays, updates
- **signage** – e.g. placement, standards
- **delivery management** – e.g. process, system, instructions, management, standards
- **vehicles, plant, equipment and vertical transport** – e.g. management, register, control
- **security** – e.g. compliance with rules, management
- **workforce** – e.g. management, recruitment
- **environmental** – e.g. risk assessment, Site Waste Management Plan, reporting, control
- **Corporate Social Responsibility (CSR)** – e.g. newsletter

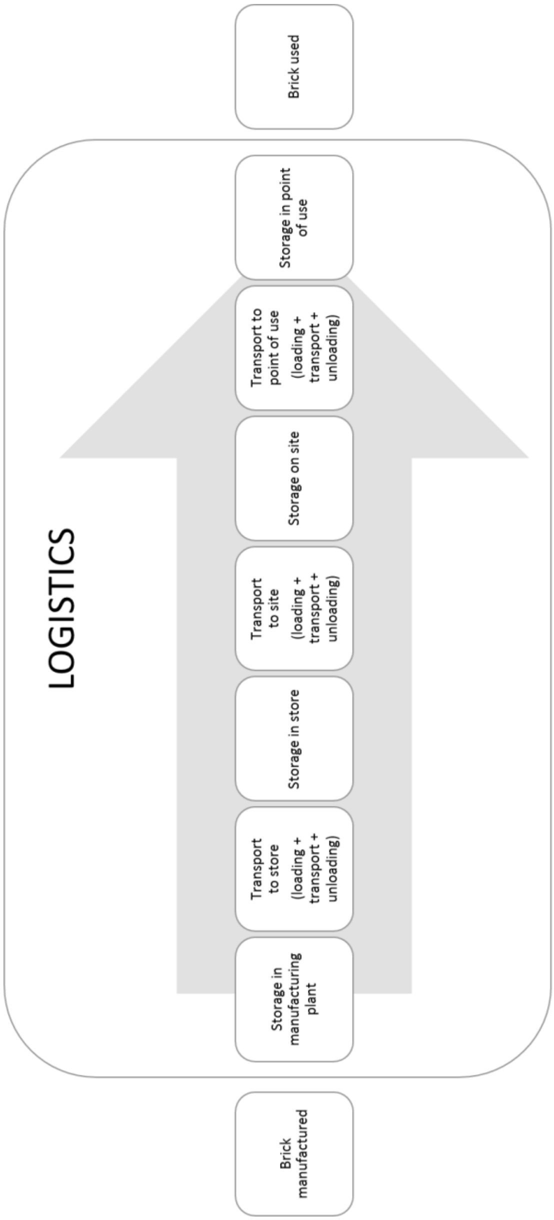

Fig. 5.1. Logistics of a brick [own source]

5.1.2 Optimisation of logistics

Logistics optimisation can be applied to small scale problems (like better organisation of a single work station or storage area) or to the whole project management. In the last case it is strongly connected with Lean Logistics and lean thinking.

The lean philosophy aims to make a company fit, reducing costs while optimising and improving performance. Value stream mapping (VSM) is one of the most common approaches organisations take on their first steps towards becoming leaner. Lean actions can be focused on the specific logistics processes, or cover the entire supply chain.

The minimisation of the resources is one of the most common logistics motivations. The complexity of logistics can be modelled, analysed, visualized, and optimised by dedicated simulation software. Such software often uses one of the algorithms described in chapter 3 of this manual. It can optimise supply schedule, vehicle routes, complex shift patterns, layout of the site or storage area, and many more.

5.1.3 Drivers and barriers

One possible barrier for the implementation of logistics management in construction is the fragmented nature of the industry and the need to integrate and compile large amount of logistics data. Examples of these logistics data include timings and capacities of supplier deliveries, transportation modes of material deliveries, construction activities demand, and site space availability [9].

However, when implemented, proper logistics management can benefit in the following ways [7]:

Clients:

- faster project implementation
- improved project certainty
- lower overall cost
- reduced impact on the environment
- waste minimisation

Contractors:

- improved project certainty
- reduced over-ordering of materials (reduced cost and waste)
- improved site efficiency, faster project implementation
- reduced risk of accidents (improvement of H&S level)
- lower overall cost
- waste minimisation

Logistic optimisation allows for significant savings and reduction of waste. Reduction of site traffic even by 50-70% ensures reduced impact on the environment.

All materials can be delivered on site every day as needed so that the construction team can work to maximum productivity and no excessive space is needed for storage. The stored materials are easy to locate which speeds up the project, and improves efficiency.

Good logistical planning encourages overall efficiency and flexibility, avoids any clutter and is better organised, with substantial benefits for health and safety.

5.2 EXAMPLES, SOFTWARE

Most of the programmes for logistics optimisation deal with route and schedule optimisation. These include: ArcLogistics [2], ODL Studio application - Open Door Logistics [4], MJC²'s distribution planning & logistics optimisation software DISC (DIstribution SCheduling) [5], TrimFleet by Trimble [3], or Synchro [6].

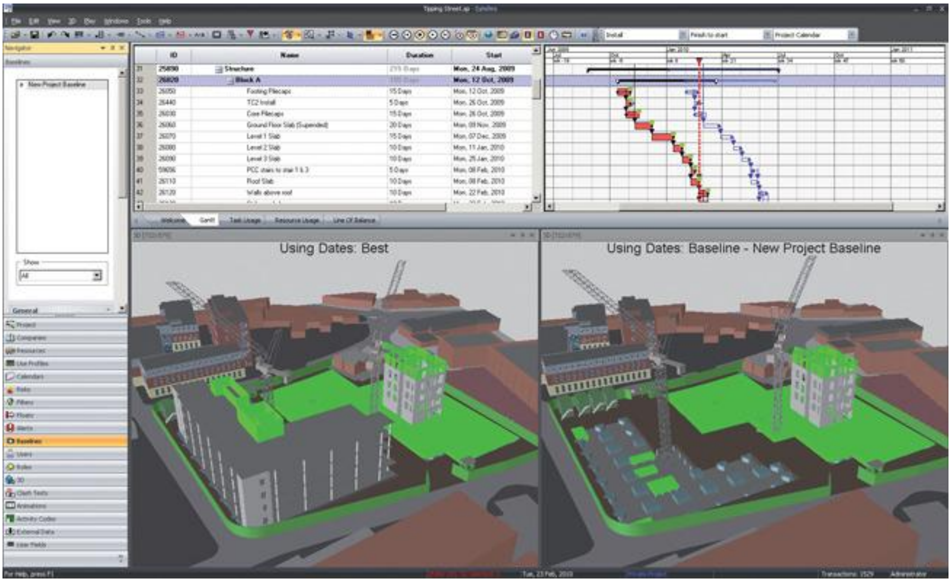

Fig. 5.2. Synchro software [1]

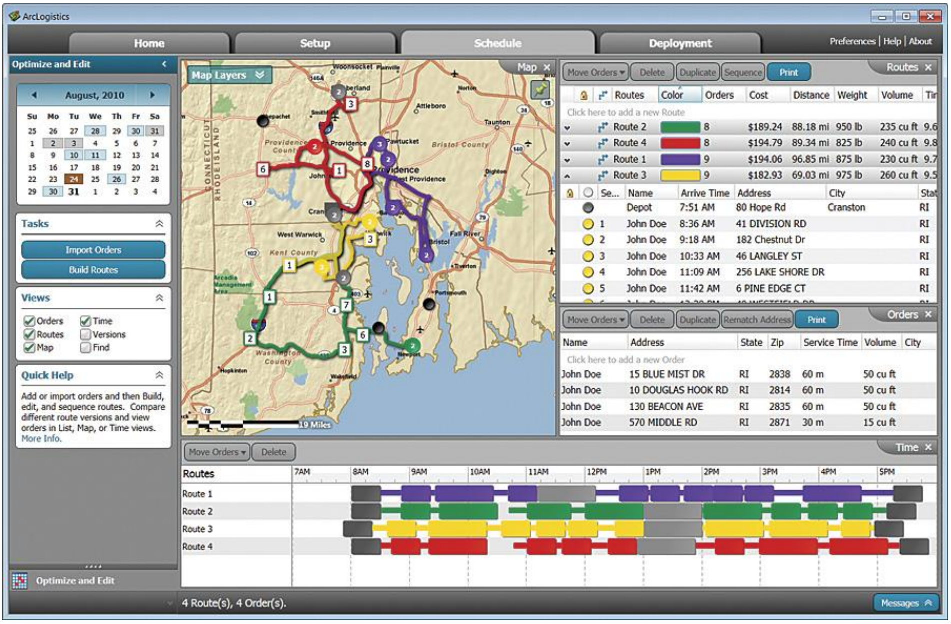

Fig. 5.3. ArcLogistics software [2]

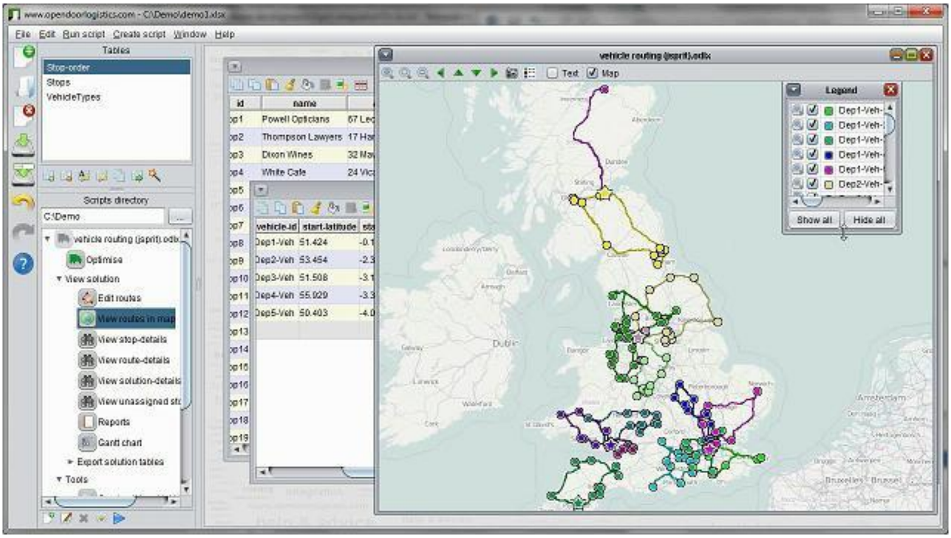

Fig. 5.4. Open Door Logistics software [4]

The optimisation of logistics is limited not only to the commercial software programmes listed above. The internet is full of public pre-written codes and software packages. If your company hires programmers, they can implement optimisation algorithms mentioned in chapter 3 into your projects.

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CHAPTER 6

CASE STUDIES

6.1 SCHEDULE OPTIMISATION (J. ROSŁON)

6.1.1 Case study

This case study presents the possibility of using GA and TS algorithms by a contractor for the purpose of schedule optimisation. To achieve that goal, a model of construction project was created in xls spread sheet. The example was taken from [1].

In the presented example, contractor builds a sport facility, consisting of three varying buildings (A, B, C) of similar technology. Each building has a defined list of summary tasks (work packages) such as preparation works, ground works, foundation works, concrete works, technological breaks, finishing works etc. The contractor estimated cost, duration, and workforce demand for each task (table 6.1).

ID	Tasks	Predece-ssors [ID]	Succe-ssors [ID]	Estimated cost [EUR]	Expected duration [days]	Required workforce [groups of workers]
1	Start	-	2, 3, 4	0	0	0
2	Earthworks A	1	5	8 500	5	1
3	Earthworks B	1	6	8 750	13	1
4	Earthworks C	1	7	8 000	11	1
5	Foundation works A	2	8	24 000	4	3
6	Foundation works B	3	9	24 000	7	3
7	Foundation works C	4	10	24 000	7	3

ID	Tasks	Predece-ssors [ID]	Succe-ssors [ID]	Estimated cost [EUR]	Expected duration [days]	Required workforce [groups of workers]
8	Technological break A	5	11	0	5	0
9	Technological break B	6	12	0	5	0
10	Technological break C	7	13	0	5	0
11	Building construction A	8	14	268 000	19	4
12	Building construction B	9	15	268 000	35	4
13	Building construction C	10	16	252 500	21	4
14	Finishing A	11	17	157 000	20	5
15	Finishing B	12	17	154 000	38	5
16	Finishing C	13	17	147 500	35	5
17	End	14, 15, 16	-	0	0	0

Tab. 6.1 Exemplary construction project [own source]

Financing assumption: invoices are issued every month, discount rate is 10%, indirect costs 75 000 EUR/day; penalty of each day of overrun 2 500 EUR. Due-to-time – 7 months = 147 workdays.

Initial version of the schedule predicted simultaneous realization of all three buildings (figure 6.1).

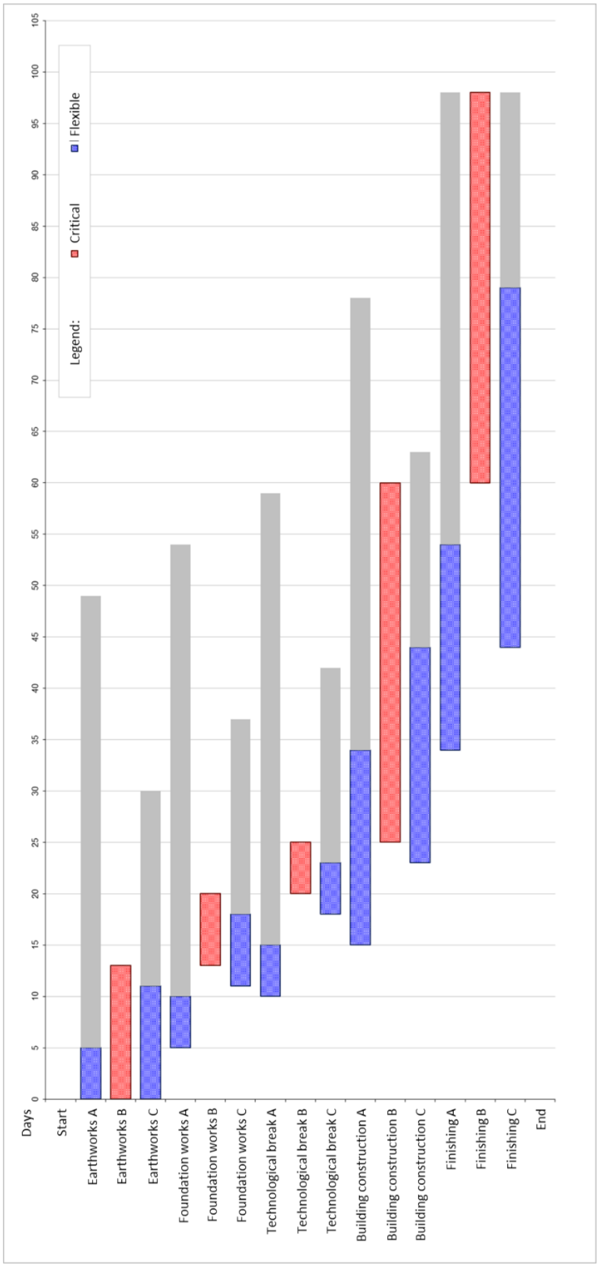

Fig. 6.1 Schedule – parallel execution of works [own source]

The main optimisation criterion was selected: reducing (minimising) maximum monthly cash flow (CFmax). Such criterion is rather rarely used in the literature due to the fact it is hard to predict, nevertheless it is a very important factor for a construction contractor [1]. Constraints used in this example are: WB (work breaks)– groups of workers should not be stopped for less than 1 working week (this constraint is important due to an option of moving workers between construction sites operated by the contractor. Shorter periods of work on one site could influence efficiency due to adaptation time of workers to a new workplace).

System of contractual penalties related to delays of works (constraints taken under consideration):

- requirement of schedule continuum SC,
- penalties related to due-to-time overrun of the investment – TO.

Calculations were performed using Microsoft Excel software (as it is a common tool used in construction companies). Two algorithms were compared: genetic algorithm (GA) – calculated by Pikaia.f (ver. 1.2) (open source version) and tabu search algorithm (TS) – calculated by Crystal Ball OptQuest software, commercial programme [1].

A stochastic attempt was also suggested as a third result group, in order to compare results of deterministic methods with Monte Carlo simulation. Third algorithm was based on tabu search principles but took under consideration assumption that costs of summary tasks (work packages) can be described as probability distribution. For the purpose of this example, triangular distributions were selected for every work package cost, with mean value equal to base values from GA and TS calculations, and minimum and maximum values defined as minus and plus 10% of mean value. Triangular distribution is an approximation of real time probability of events, but its advantage is that it is very easy to define using experience from previously finished projects and data acquired from experts [1].

In the case, tasks were arranged by introducing delays (which gave approx. $8x10^{22}$ possible results). All six possibilities of prioritising building realisation were checked. Results are shown in table 6.2. Symbol "+" means that a constraint is fulfilled and symbol "-" that it is not.

Apart from mentioned above parameters, additional parameters were presented to help assess solutions: Net Present Value (NPV) and duration (t).

The best obtained schedule, and its cash flow and workforce usage graph are presented in figures 6.2 to 6.4.

Parameters \ Method		Parallel execution of works	Object by object (6 variants)		GA (20 runs)		TS - deterministic (20 runs)		TS - stochastic (20 runs)	
Parameters associated with the objective function	CFmax [EUR]	639 998	Max:	198 526	Max:	317 317	Max:	275 843	Max:	287 796
			Mean:	194 350	Mean:	293 589	Mean:	260 467	Mean:	275 833
			Min:	192 086	Min:	277 028	Min:	229 716	Min:	263 377
	WB	-	+		+		+		+	
	SC	+	+		+		+		+	
	TO	+	-		+		+		+	
Additional parameters	NPV [EUR]	346 968	Max:	339 998	Max:	401 192	Max:	386 027	Max:	389 110
			Mean:	339 807	Mean:	390 932	Mean:	384 258	Mean:	388 095
			Min:	339 612	Min:	373 514	Min:	383 373	Min:	379 444
	t [days]	98	Max:	216	Max:	140	Max:	129	Max:	132
			Mean:	216	Mean:	132	Mean:	128	Mean:	129
			Min:	216	Min:	119	Min:	127	Min:	123

Tab. 6.2 Optimisation results [own source]

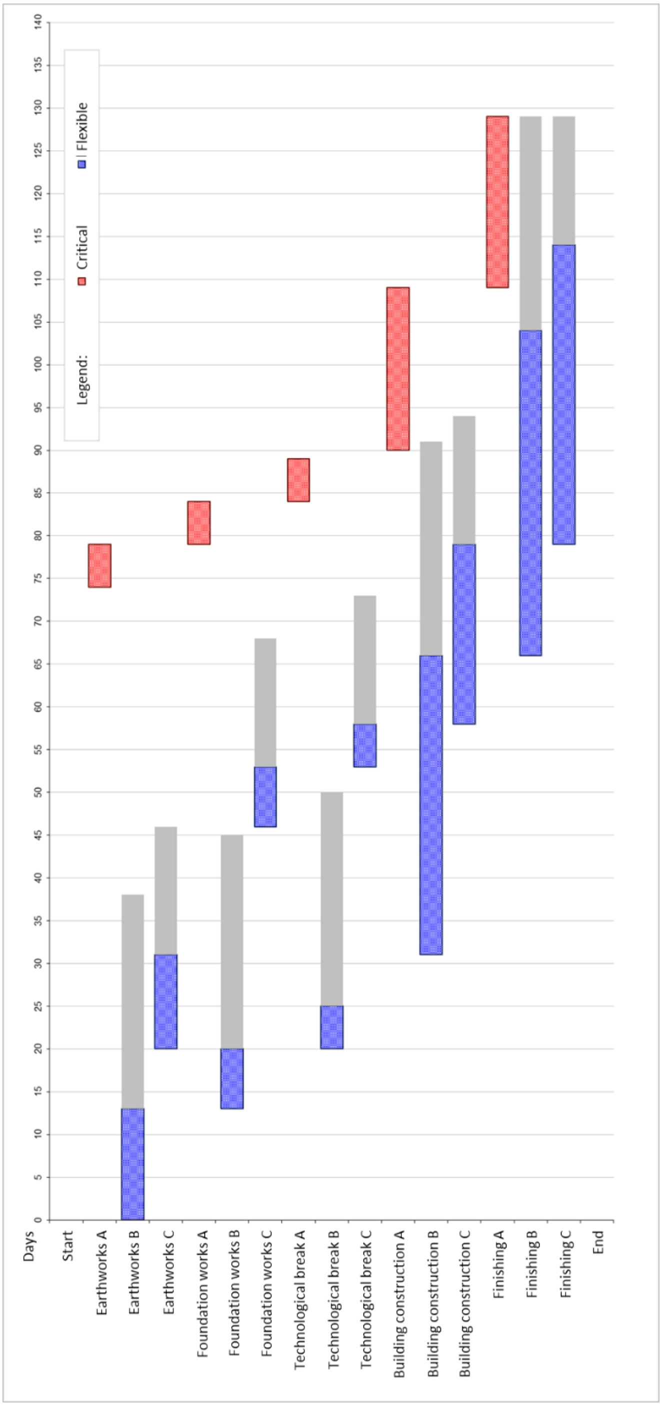

Fig. 6.2 Schedule – best found solution [own source]

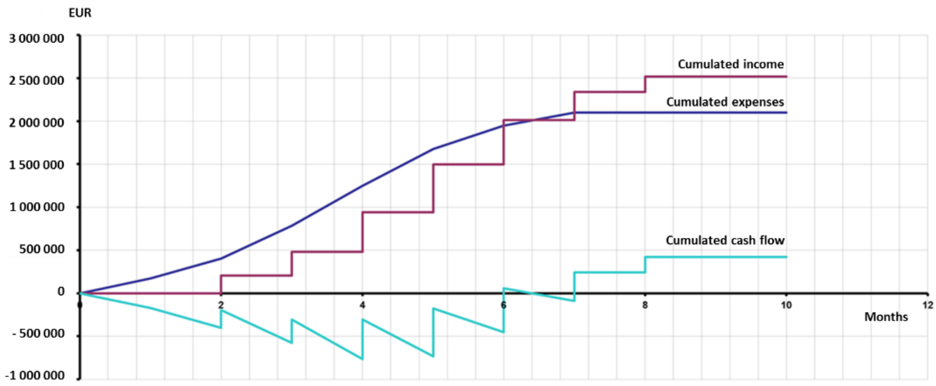

Fig. 6.3 Cumulated cash flow – best found solution [own source]

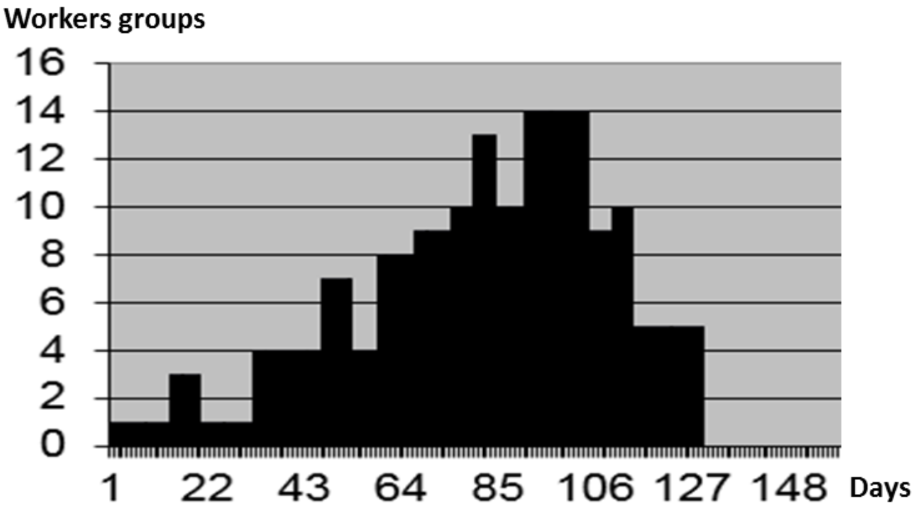

Fig. 6.4 Workforce graph – best found solution [own source]

In the case, the lowest maximum monthly cash flow CFmax was obtained (while satisfying the constraints) with the use of OptQuest application (TS – deterministic). The results calculated by this software were also characterized by greater consistency (smaller difference between the maximum and minimum value of CFmax).

Tabu search algorithm – stochastic variant, in this example gives very similar key results to tabu search – deterministic variant. As expected, difference can be identified mainly in wider range of results and higher value of standard deviation of probability distributions. Running a tabu search algorithm with Monte Carlo simulation is a time-consuming method, since a single simulation pass includes several hundred or thousands additional simulations of defined assumptions [1]. However such approach can help contractor to foresee some unexpected events, and prepare for their outcomes.

The stochastic approach to TS algorithm can give slightly better results than deterministic TS (more robust results), but time needed to complete such simulation properly increase exponentially with complexity of the project's assumptions and therefore can be difficult to use by contractors. However, if they can afford such prolonged period of time for calculations, results should satisfy their needs.

6.1.2 References

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6.2 SCENARIO PLANNING (T. V. FRIDGEIRSSON)

Thinking about the future is hard, mainly because we are glued to the present. We are under the influence of a cognitive bias called "narrative fallacy" defined by Daniel Kahneman who received the Nobel Prize in economics in 2002. We perceive the future as a small variation of our present times. But nothing can be further from reality. *"The times they are a changing"* sang another Nobel Prize winner Bob Dylan back in 1964. The reality is that we live in times of volatile economic conditions, financial uncertainty, political tensions, environmental changes and social risks. It is difficult to arrange a robust plan in times of uncertainty[2].

We must therefore foremost plan for the unexpected.

[2] Main reference [1]

What we know is that the future will be full of surprises even more now than before. Many of the events, technical developments, social circumstances, etc., we now take for granted would have been considered impossible only few years back. The jobs that are were in top demand today did not exist in few years ago. We are in fact preparing students for jobs that do not exist today and educating decision makers and problem solvers to solve problems we do not know yet. Uncertainties are a fact of life and it is a mistake to allow them to postpone business decisions.

According to some estimates, about 90 percent of what we historically "knew" to be correct has subsequently been disproved. Obviously it is difficult to accurately predict the future, let alone control it. But uncertainty—not certainty—is the norm for strategic planning. In hindsight, most surprises should have been predictable and sometimes even preventable. Here are some statements that in light of history should have been challenged:

- "This 'telephone' has too many shortcomings to be seriously considered as a means of communication. The device is inherently of no value to us." (Western Union internal memo, 1876)
- "Heavier-than-air flying machines are impossible." (Lord Kelvin, president, Royal Society, 1895)
- "Everything that can be invented has been invented." (Charles H. Duell, Commissioner, U.S. Office of Patents, 1899)
- "Airplanes are interesting toys but of no military value." (Marshall Ferdinand Foch, Professor of Strategy, Ecole Supérieure de Guerre, 1911)
- "Stocks have reached what looks like a permanently high plateau." (Irving Fisher, Professor of Economics, Yale University, 1929)
- "I think there is a world market for maybe five computers." (Thomas Watson, chairman of IBM, 1943)
- "Computers in the future may weigh no more than 1.5 tons." (Popular Mechanics, forecasting the relentless march of science, 1949)
- "I have traveled the length and breadth of this country and talked with the best people, and I can assure you that data processing is a fad that won't last out the year." (The editor in charge of business books for Prentice Hall, 1957)

- "We don't like their sound, and guitar music is on the way out." (Decca Recording Co. rejecting the Beatles, 1962)
- "But what ... is it good for?" (Engineer at the Advanced Computing Systems Division of IBM, 1968, commenting on the microchip)
- "There is no reason anyone would want a computer in their home." (Ken Olson, president, chairman, and founder of Digital Equipment Corp., 1977)
- "640K ought to be enough for anybody." (Bill Gates, 1981)
- "$100 million dollars is way too much to pay for Microsoft." (IBM, 1982)

Decision makers need a tool that will enable them to prepare for the unknown by thinking broadly about the full range of plausible scenarios as well as constructing robust strategies regardless of how the future unfolds. "Scenario planning" is a powerful instrument that guides and supports the imagination, creativity, and vision necessary for mapping a range of viable strategies for competitive success. Scenario planning is not a vehicle for predicting the future; it is a method of preparing for the future regardless of what happens. This is done by having groups systematically share data and beliefs about their environmental assumptions, analyze their key business challenges, and create "scenes" that describe combinations of critical events and trends. By sharpening thinking and improving the quality of decisionmaking, managers are better able to prepare for the unexpected by developing contingency "what if?" plans.

This team assignment is about developing scenarios and strategies on business problems and decisions relevant to many stakeholders. The intent of this exercise is to efficiently experience a different way of thinking about future possibilities and to better understand your strategic options.

This is a stepwise process and the team is supposed to follow each step precisely.

6.2.1 Step 1 – The BIG QUESTION

We refer to this step as the "BIG QUESTION (BQ)." As a group, decide on a single overarching strategic issue or question relevant to the decision problem. Throughout each step of this exercise, continually associate how conditions might impact the BQ—you might even find surprises that, in hindsight, should have been predictable!

The following BQs are generic examples for developing scenarios:

- How will the music industry fare in times of downloads and file sharing the next 15 years?
- How will the construction industry be in 2035?
- Which technological changes will impact constructrion the most the next 20 years?
- What will be the main housing needs of people in 2035?
- What will be the most important market segments in construction in 2035?
- How will the fight on terrorism fare the next 20 years?
- Etc.

6.2.2 Step 2 – Brainstorm critical events

We know that the unthinkable can be thinkable. A decision maker engages the external environment (competitive or general) through formulating a strategy. A critical event is a possible driving force or future development that potentially creates a material change in the financial structure, management and organization, corporate culture, and quality of stakeholder relationships. These are all controllable decisions within the organization in response to its environment. The competitive environment involves stakeholders who directly or indirectly affect the process and profitability of making and selling goods and/or services. Stakeholders can be customers, competitors, other product that can/will replace current products, the government, the suppliers, the labour, international organizations, people with moral issues, trade associations, new products, etc.

We must also consider driving forces like changes in demographics, sociocultural development, legal matters, politics, macro-economy, technology, etc.

This step involves creative thinking. Everyone is encouraged to imagine what significant and potentially surprising incidents might occur. Think openly and without restraint about any and all possibilities. At this stage, do not worry about the trajectory the event might take, prejudge any suggested event, or worry how it might affect the stakeholder you are working for (organization, government, company, etc.). To anticipate the unexpected, consider both usual and unusual change triggers. Once you have completed this brainstorming session, list as many critical events as there are team members (in no specific order). Keep in mind that the purpose is to prepare, not to predict. Each of the critical events should be described briefly using only a few descriptive words.

Team then evaluates the critical events on the scale (-) 5 to 5 in context of negative or positive impact on the BQ.

Name the key critical events (driving forces) that impact the future.	Value (-5 to +5)
1	
2	
3	
4	
5	
6	
7	
8	
9	
10 etc.	

Tab. 6.3 Step 2 – case study

6.2.3 Step 3 – Develop the scenario

A scenario is a script-like characterization of a possible future operating environment. In many ways it is similar to describing a scene for a screenplay—a brief but complete explanation of conditions to be confronted. As a group, examine the first set of the critical events from the prior step and think about how the unique combination of operating conditions (one from each card or post it note or whatever used in the session) creates an operating environment in which the company must compete. Remember, each card will have a critical event and a trajectory; thus one card might represent a beneficial condition while another might represent one that is detrimental. (Ignore events that have low or no impact). Synthesize these interactions into a narrative description of the future operating environment; do not simply add sentences or list bullet items for the events. Although you should try to be concise it is important to explain the scenario clearly and completely. Give this Scenario #1 a descriptive name and write it as a scenario.

Repeat this process for the second set of cards to create Scenario #2, etc. When the scenario descriptions have been completed, write the scenario names and descriptions in a form similar to the one below.

Scenarios (must be completely different)	
#1	#2
#3	#4

Tab. 6.4 Step 3 – case study

6.2.4 Step 4 – Develop strategies

Regardless of what we think the future might hold, we must still act today even if our knowledge is limited to the past and present. To complete this exercise, your group must discuss the implications of your scenarios. Examine what could happen if these scenes become reality, and what that can mean to your company. Consider both the immediate and longer term consequences to your organization for each of your scenarios. Next, list contingencies you should put in place now to deal with these scenarios. Finally, develop a robust strategy that is resilient and viable regardless of which scenario actually does occur. Consider the following:

- Given these possible futures, what is your overall assessment of the current strategy? What environmental forces challenge your future? Are there common opportunities and threats, regardless of scenario?
- Where is it vulnerable? What major modifications do you recommend to the strategy? Will you be flexible to change this strategy in response to shifting scenarios?
- How will you know which scenario is actually unfolding? What are the "flash points" or "signposts" (either metrics or events)? Which key indicators must occur for that scene to become reality?

When should your mission and vision change in response to environmental shifts?

6.2.5 Step 5 – Presentation

"If anything can go wrong, it will." (Murphy's Law)[3]

Each group will present its scenarios, strategy recommendations, and opinions about the usefulness of scenario planning to the world as it was a part of a strategic decision team for long horizon planning.

6.2.6 Appendix 1 – Guidelines on brain storming

For decades, people have used brainstorming to generate ideas, and to come up with creative solutions to problems. However, you need to use brainstorming correctly for it to be fully effective. Arguably the original approach is presented as early as 1953[4] but the method is under constant improvement. Brainstorming combines a relaxed, informal approach to problem solving with lateral thinking. It encourages people to come up with thoughts and ideas that can, at first, seem a bit crazy. Some of these ideas can be crafted into original, creative solutions to a problem, while others can spark even more ideas. This helps to get people unstuck by "jolting" them out of their normal ways of thinking.

Therefore, during brainstorming sessions, people should avoid criticizing or rewarding ideas. You're trying to open up possibilities and break down incorrect assumptions about the problem's limits. Judgment and analysis at this stage stunts idea generation and limit creativity.

Evaluate ideas at the end of the session – this is the time to explore solutions further, using conventional approaches.

You might consider using Icebreakers if the session is considered difficult to facilitate. As the name suggests, these sessions are designed to "break the ice" at an event or meeting. The technique is often used when people who do not usually work together, or may not know each other at all, meet for a specific, common purpose. There are many types of ice breakers, each suited to different types of objectives. Here we look at a few of the more popular types and how they can be used. These are used to introduce participants to each other and to facilitate conversation amongst them.

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[3] Edward Murphy died ironically in a car accident when he was struck from behind by a British tourist visiting USA and driving on the wrong side of the road.

[4] A book by Alex Osborn named Applied Imagination.

The Little Known Fact: ask participants to share their name, department or role in the organization, length of service, and one little known fact about themselves.

This "little known fact" becomes a humanizing element that can help break down differences such as grade/status in future interaction.

True or False: ask your participants to introduce themselves and make three or four statements about themselves, one of which is false. Now get the rest of the group to vote on which fact is false.

As well as getting to know each other as individuals, this exercise helps to start interaction within the group.

Interviews: ask participants to get into twos. Each person then interviews his or her partner for a set time while paired up. When the group reconvenes, each person introduces their interviewee to the rest of the group.

Problem Solvers: ask participants to work in small groups. Create a simple problem scenario for them to work on in a short time. Once the group have analysed the problem and prepared their feedback, ask each group in turn to present their analysis and solutions to the wider group.

Provided the working atmosphere is favourable these are the steps to take for a successful Brainstorm session:

Step 1: Prepare the Group

First, set up a comfortable meeting environment. Make sure that the room is well-lit and that you have the tools, resources, and refreshments that you need.

How much information or preparation does your team need in order to brainstorm solutions to your problem? Remember that prep is important, but too much can limit – or even destroy – the freewheeling nature of a brainstorming session.

Consider who will attend the meeting. A room full of like-minded people won't generate as many creative ideas as a diverse group, so try to include people from a wide range of disciplines, and include people who have a variety of different thinking styles.

When everyone is gathered, appoint one person to record the ideas that come from the session. This person shouldn't necessarily be the team manager – it's hard to record and contribute at the same time. Post notes where everyone can see them, such as on flip charts or whiteboards; or use a computer with a data projector.

Step 2: Present the Problem

Clearly define the problem that you want to solve, and lay out any criteria that you must meet. Make it clear that that the meeting's objective is to generate as many ideas as possible.

Give people plenty of quiet time at the start of the session to write down as many of their own ideas as they can. Then, ask them to share their ideas, while giving everyone a fair opportunity to contribute.

Step 3: Guide the Discussion

Once everyone has shared their ideas, start a group discussion to develop other people's ideas, and use them to create new ideas. Building on others' ideas is one of the most valuable aspects of group brainstorming.

Encourage everyone to contribute and to develop ideas, including the quietest people, and discourage anyone from criticizing ideas.

As the group facilitator, you should share ideas if you have them, but spend your time and energy supporting your team and guiding the discussion. Stick to one conversation at a time, and refocus the group if people become sidetracked.

Although you're guiding the discussion, remember to let everyone have fun while brainstorming. Welcome creativity, and encourage your team to come up with as many ideas as possible, regardless of whether they're practical or impractical.

Don't follow one train of thought for too long. Make sure that you generate a good number of different ideas, and explore individual ideas in detail. If a team member needs to "tune out" to explore an idea alone, allow them the freedom to do this.

Also, if the brainstorming session is lengthy, take plenty of breaks so that people can continue to concentrate.

Step 4: Taking action

After your individual or group brainstorming session, you'll have a lot of ideas. Although it might seem hard to sort through these ideas to find the best ones, analyzing these ideas is an important next step, and you can use several tools to do this. Previously we have discussed user stories and task descriptions. In order to make them sufficiently detailed and to be certain of the correct priorities an array of methods are applicable.

Examples are:

Need or nice analysis – items sorted by those defined as necessary and those only "nice to have".

Forced ranking – team members sort the topics individually by importance. Then votes are then summed up and the topic with the lowest score is the most important, the topic with the second lowest score comes next, etc.

Affinity diagrams – sorting/grouping into categories so ideas are organized.

Decision analysis matrix – you to list your options as rows on a table, and the factors you need consider as columns. You then score each option/factor combination, weight this score by the relative importance of the factor, and add these scores up to give an overall score for each option.

Paired comparison analysis - The tool is particularly useful when you don't have objective data to use to make your decision. It's also an ideal tool to use to compare different, subjective options, for example, where you need to decide the relative importance of qualifications, skills, experience, and team-working ability when hiring people for a new role.

Net present value calculation (NPV) – financial analysis should consider the time value of money. NPV is decided by finding the initial investment value which is sub tracked from the discounted cash flow over the lifecycle of the project (r = discount factor).

$$Net\ Cash\ Initial\ Investment = \sum_{t=1}^{n} \frac{Flow}{(1+r)^t}$$

Another important financial analysis is **Cost Benefit Analysis** (CBA) also based on financial value of time series but may also consider other utilities than monetary values.

6.2.7 Appendix 2 – Examples of scenario planning

The following are examples of four scenarios based on "Using Scenario Planning as a Weapon Against Uncertainty" (2001). Notice that each of these scenarios contains a succinct label, a one paragraph statement, and expected result:

Paralysis Survival: Companies (and/or economies) deal with unknown, unexpected, and unpredictable external events by pulling into a protective shell. Possible economic shocks include nationalizing major global industries (such as oil) and significant disruptions to global material flows. On the political front, terrorist attacks escalate in different parts of the world, reviving isolationism and protectionism as the U.S.-led antiterrorism coalition falls apart.

Companies react by trying to protect existing assets with layoffs, reduced R&D investment and product development, and lower foreign direct investment. Consumers compound the problem by cutting spending dramatically. In short, a long global recession. **Result**: *Acceptance of inevitable surprises*.

Slow Growth: An economic malaise results from known and expected external events that while disruptive have only moderate impact. There will be debt and currency problems in key world economies, although a full-blown global recession is avoided. Unemployment will be modestly higher but manageable, but consumer confidence will be low. Politically, the war against terrorism heads toward a stalemate as companies get used to its risks and learn to cope with their losses by making modest investments. **Result**: *Passive responses to low expectations*.

Thriving With Chaos: Companies are proactive in exploiting disruptive external events. Corporate and national resolve to succeed in the face of adversity drives modest prosperity as uncertainty is considered a cost of doing business. Companies try to seize business opportunities and make increasing investments in areas that seem to be potentially profitable. In the political arena, the global realignment of the U.S. with Russia and China opens up new market opportunities, but the Islamic and developing nations are shut out of these new alliances. The war against terrorism continues without a clear victory. **Result**: *Opportunistic responses to surprises*.

Global Growth: Foreseeable external events enable countries and peoples of the world to recognize their common goals, thereby focusing on economic development and peace as the route to permanent stability. The recession proves short-lived and the business cycle returns to normal.

The threat of terrorism fades and the global coalition against terrorism evolves into a coalition for peace and commerce. Investments in new energy technologies reduce the role of oil in Middle Eastern politics. Consumers increase their spending as they feel confident about the future, laying the foundations of a sustained economic recovery. Trade barriers are lowered and the developing economies grow in tandem with the developed ones. **Result**: *Aggressive responses to high expectations*.

6.1.8 References

[1] Miesing (2007). Organization Management Journal, Vol 4. No. 2, 148-167.