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MASTER ARBEIT

CRITICAL SYSTEM COMPARISON OF SLIPFORMING TECHNOLOGY AND CLIMBING FORMWORK TECHNOLOGY

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Danksagung

An dieser Stelle möchte ich allen Personen danken, die mir während meiner Masterarbeit mit Rat und Tat zur Seite gestanden sind.

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Graz, am 05.01.2014

(Thomas Stelzl)

Kurzfassung

Gleitschalungstechnik und Kletterschalungstechnik sind stark konkurrierende Technologien im High-rise Sektor. Speziell in den Zielmärkten Dubai und United Kingdom ist die Gleitschalungstechnik marktführend.

Die vorliegende Master Arbeit beschäftigt sich mit der Fertigung von turmartigen Bauwerken in Ortbetonbauweise wobei der Schwerpunkt in der Analyse der Technologien Gleitschalungstechnik und Kletterschalungstechnik liegt. Neben der Beurteilung von technischen Aspekten wurde ein Fragebogen entwickelt, um herauszufinden wie Baufirmen, die diese Technologien in der Praxis anwenden, beurteilen. Ziel der Arbeit war es, die Vorgehensweise von Baufirmen im Systemauswahlverfahren von Schalungssystemen für turmartige Bauwerke, zu erfahren. Die Befragten wurden gebeten beide Schalungssysteme kritisch und objektiv zu beurteilen. Der Fragebogen beginnt mit der Analyse von persönlichen Erfahrungen der Teilnehmer, gefolgt von deren Erwartungen und Anforderungen beider Schalungstechnologien. Hauptteil des Fragebogens ist die Analyse der Auswahlkriterien im Entscheidungsprozess für eine Schalungstechnologie. Des Weiteren wurden die Teilnehmer gefragt wie sie die zukünftige Nachfrage für den Hochhausbau sowie für die Gleitbautechnik einschätzen. Abschließend gaben die Befragen Verbesserungsvorschläge für beide Schalungstechnologien.

Abstract

Slipforming technology and climbing formwork technology are strongly competing technologies in the high-rise sector. Especially in the target markets Dubai and United Kingdom, slipforming technology is market-leading.

This Master Thesis deals with the construction of tower-like in-situ concrete high-rise structures, with special focus on the analysis of both slipforming and climbing formwork technology. Besides the evaluation of technical features, a questionnaire was developed to figure out the point of view of construction companies who apply these formwork systems in practice. The target of the questionnaire was to find out how construction companies as the end-users of these technologies, approach in the selection process for high-rise construction suitable formwork systems. The participants were asked to evaluate both formwork systems in a critical and objective way. The questionnaire starts with the analysis of the personal experience of the interviewed experts, followed by their expectations and requirements of both technologies. Main part of the questionnaire is the analysis of the selection factors for deciding in favour of one formwork technology over the other. Furthermore, the experts gave their estimation about future demands for high-rise buildings as well as for slipforming technology. Lastly, improvement suggestions for both technologies were given.

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1 Introduction

1.1 Objectives

This Master Thesis is based on a research work which is about the construction of high-rise buildings with cast in situ reinforced concrete with special focus on slipform technology and jumpform technology. The objective of research was to find out the advantages and disadvantages of these two technologies with particular consideration of the selection process between these construction methods. The thesis is a commissioned work from the formwork company Doka, an international formwork supplier acting in the construction industry in markets all over the world. On the basis of the knowledge of this research work, Doka believes that they will be better positioned in the future to improve their products and services, providing the construction industry with more efficient, value driven formwork solutions developed to meet the specific needs of the high-rise construction sector.

However, there are two target markets where slipforming technology has a much higher market share than the jumpform technology. Those markets are Dubai and United Kingdom. Thus, the Technical University of Graz was committed to figure out the reason of the strong position of slipforming technology in these markets.

1.2 Methodology

To achieve the goals, a market research was done by the Technical University of Graz. It was decided to develop a questionnaire. The structure of the questionnaire is split up into three parts. It starts with the personal experience in high-rise construction and the use of slipforming and other climbing technologies as well as the expectations and requirements of an end user of these competing technologies, followed by the selection factors for deciding in favour of one formwork technology over another. Lastly, it suggests an opinion on future demands for these technologies. The questions are structured in a way to obtain a statistically evaluable result. Subsequently, following the questionnaire, a face to face interview or telephone interview was planned in order to get additional information on the results of the questionnaire.

The Technical University proceeded as follows:

1. Extensive study of Slipform Technology and Jumpform Technology.
2. Extensive study of market research methods.

3. Decision to develop a questionnaire combined with a follow-up face-to-face interview or telephone interview.
4. Contacting construction companies with high-rise construction experiences.
5. Sending out the questionnaire in advance.
6. Visiting the companies for the interview or getting in contact by phone.
7. Making a statistical evaluation of the survey supported by a professional sociological institution.

The thesis starts with a general part about high-rise buildings followed by structural basics regarding the designing of high-rise buildings. Then, the two construction methods, Slipform Technology and Jumpform Technology are described in particular. Afterwards, a comparison between these two technologies is done.

In the next step, the author goes on with the main part of this research work, i.e. system selection. Here, methods and approaches for system selection are described and explained.

The practical part of this survey is the questionnaire, which you can find in Chapter 9. To get a better understanding about how a questionnaire is developed, basics of marketing and market research are given as well as some information about the statistical evaluation of questionnaires.

In the forefront, the Master Project *"Grundlagen der Marktforschung für die Fragebogenentwicklung"* [1] was written by the author. It can be considered as the basis for the Master Thesis and, in particular, for the development of the questionnaire.

[1] STELZL, Th.: Master Projekt. Grundlagen der Marktforschung für die Fragebogenentwicklung. TU Graz. 2013

2 High-rise Buildings in General

What is it that drives people to erect buildings rising up to the sky? Impressive structures like the **Great Pyramids of Giza** which were built about 4500 years ago show that the desire to create buildings of enormous dimensions has existed for ages. According to the Old Testament, Book of Genesis 11:4, people wanted to build a city called Babel and *"a tower whose top will reach into heaven"*[2]*.*The reason why they wanted to build a tower in this dimension is not clear, but a theory says that this was an attempt of mankind to organize themselves apart from god because of the foregoing flood. Nowadays, reasons for constructing high-rise buildings are different. In previous times buildings of such dimensions were constructed on the basis of religious reasons or to demonstrate power. Today, high-rise buildings are mainly used for financial centres, offices, hotel suites or for residential purposes, and of course for prestige purposes.

2.1 Definition High-rise Building / Skyscraper

A precise definition of a high-rise building does not exist. Many countries have their own definition and building codes. **Emporis**, the biggest homepage about building data, defines a high-rise building as follows:

> *A high-rise building is a structure whose architectural height is between 35 and 100 meters. A structure is automatically listed as a high-rise when it has a minimum of 12 floors, whether or not the height is known. If it has fewer than 40 floors and the height is unknown, it is also classified automatically as a high-rise.*[3]

Another approach for the definition comes from the **International Conference on Fire Safety in High-Rise Buildings.** Here, a high-rise building is defined as *"any structure where the height can have a serious impact on evacuation".*[4] The reason for that is that fire fighting equipment is limited to a certain length. So a building which exceeds the size of the ladder of the fire fighter is defined as a high-rise building. Normally, these ladders have a length of approximately 23 to 30 metres. Depending on the slab-to-slab distance, this is 7 to 10 floors.[5]

Also for skyscrapers there are different definitions. Emporis, for example, defines a building higher than 100 metres as a skyscraper.

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[2] Book of Genesis 11:4

[3] http://www.emporis.com/building/standards/high-rise-building (07.07.2013)

[4] https://en.wikipedia.org/wiki/Tower_block (07.07.2013)

[5] CRAIGHEAD, G.: High-rise security and fire life safety, 3rd Ed., Oxford: Elsevier 2009, p.2

2.2 History of High-rise Buildings

Until the middle of the 18^{th} century, the height of buildings was limited to approximately six floors. People were not willing to walk so many steps, and the elevator technology was not yet integrated into residential buildings. Even though elevators already existed in the mining industry, people were afraid to enter elevators because of the high potential risk of crashing. In 1852, Elisha Otis invented the so-called safety elevator, which prevented the fall of the cab when a cable broke by using an automatic spring operated brake system.[6]

High-rise buildings have their origin in **New York** and **Chicago**. After the great Chicago fire in 1871, one third of the buildings in Chicago were ruins. A short time later, between 1880 and 1890, the population of Chicago increased from 503.185 to 1.099.850 inhabitants.[7] That means it doubled just in 10 years. In addition, the real estate prices increased sevenfold from approximately 130 to 900 \$/m². Due to economic reasons, it was obvious to start designing buildings higher. There were crucial innovations for high-rise buildings at that time. With the decreasing prices of steel, people started to use steel frame constructions for buildings. Another invention was the development of fireproof constructions by Peter B. Wight.[8]

The 42 m high **Home Insurance Building** in Chicago, designed by William le Baron Jenney and built in 1885, counts as the first skyscraper. It was constructed using a steel frame and had 10 storeys. [9]

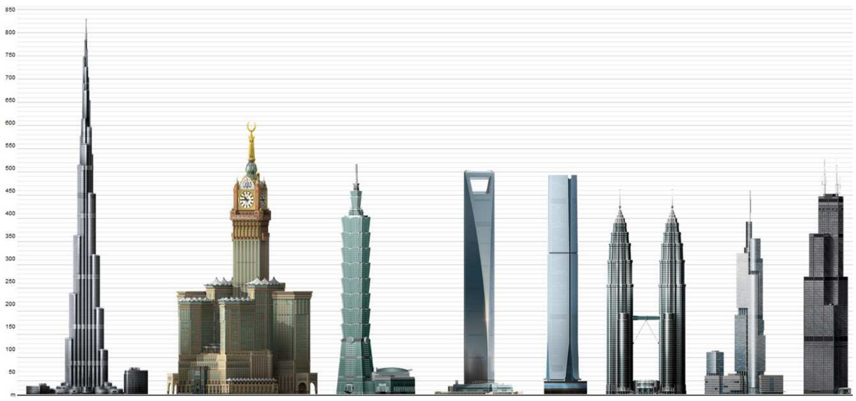

Fig. 2.1 World's tallest buildings 2013 [10]

[6] http://www.thepeoplehistory.com/1850to1859.html (26.06.2013)

[7] http://physics.bu.edu/~redner/projects/population/cities/chicago.html (26.06.2013)

[8] Cf. WERMIEL, Sara: Construction History Vol.9 1993, The Development of Fireproof Construction in Great Britain and the United States in the Nineteenth Century, p.1

[9] CRAIGHEAD, G.: High-rise security and fire life safety, 3rd Ed., Oxford: Elsevier 2009, p.9

[10] http://skyscraperpage.com/diagrams/?searchID=200 (03.12.2013)

3 Structural Basics for Designing High-rise Buildings

This chapter gives the reader the basic information about what needs to be considered in the designing process of a high-rise building. First, the most important types of loads which are acting on high-rise buildings are described, then structural systems are introduced and, at the end, the parts of a high-rise building, which influence structural design most, are outlined.

3.1 Acting Loads

High-rise buildings are usually rather slender and tall structures. However, for the designing process several loads which are listed below need to be considered. All the described loads increase dramatically with the height of the building. Especially **wind loads** and **earthquake loads** determine the structural design of a high-rise building. The loads are only described generally to get a basic understanding of these loads and their influence on high-rise buildings. Detailed structural features and calculations are neglected in this chapter.

3.1.1 Dead Loads

Dead loads are loads which occur due to the constant weight of the structure itself. They are also known as permanent loads. Following elements of a high-rise building are generating the most significant dead loads for the design:

- Walls and columns
- Floor slabs and beams
- Roofs
- Finishes, plaster and screeds
- Cladding

The loads of a high building mainly depend on the size of the structure. The higher the building, the higher are the dead loads acting on the foundation and onto the lower parts of the structure. Thus, the thickness of the walls on the ground floor can reach dimensions which are far beyond the mark of 1 metre.

3.1.2 Live Loads

Live loads are moving variable vertical loads which are added to the dead loads. This can be occupants and furniture, stored materials, moveable partitions, moveable machinery and other stuff that gives additional weight to the permanent loads.

3.1.3 Wind Loads

When designing high-rise buildings, special consideration has to be given to wind loads. Especially in the construction phase strong winds need to be taken into account. On the one hand, to provide safety to the construction workers; on the other hand, to avoid damage to machines which are placed on the top of the buildings. For the decision of the formwork system wind pressure plays a decisive role, too. For example, at high altitudes or in regions where strong winds are expected, crane guided formwork systems are not reasonable because they reach their limits in the lifting process when wind situations are too strong. This can either lead to big delays in the construction process or to dangerous situations for workforces and also for machinery. In such cases, crane independent jumpform or slipform systems should be used.

However, wind causes pressure, which can be shown as follows:

$$q = \frac{\rho \cdot v^2}{2}$$

$$q = \frac{\rho \cdot v^2}{2} = \frac{v^2}{\frac{2}{\rho}} = \frac{v^2}{\frac{1}{1.25} \cdot 2 \cdot 1000} = \frac{v^2}{1600}$$

$$\boldsymbol{q = \frac{v^2}{1600}\ kN/m^2}$$

q … stagnation pressure in Pa

ρ … density of air (1.25 kg/m³)

Wind pressure is affected by the location of the building, by environment (roughness of terrain), by altitude above ground, and by the duration of usage. There are maps and tables in standards for the basic wind pressure for a certain region. Basic wind pressure is a statistical value. It is the **10 minutes mean value** of a **50 year event** measured **10 m above ground**. For designing, the peak pressure of the wind needs to be determined.

As mentioned before, environment and altitude above ground are factors that influence wind pressure. Figure 3.1 shows how the relation between the altitude above ground and the shape of the environment influences the wind velocity.

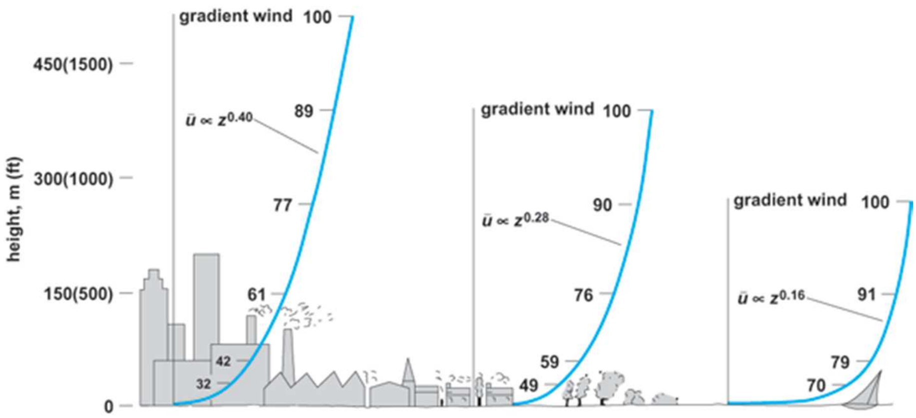

Fig. 3.1 Wind velocity depending on altitude and environment [11]

In rougher environmental areas, the wind speed at the ground is lower and the gradient is less inclined. For this reason, EUROCODE 1 defines five terrain category classes:[12]

- **Terrain category 0:** Sea, costal area exposed to the sea
- **Terrain category I:** Lakes or area with negligible vegetation
- **Terrain category II:** Area with low vegetation such as grass and isolated obstacles (trees, buildings) with separations of at least 20 obstacle heights
- **Terrain category III:** Area with regular cover of vegetation or buildings or with isolated obstacles with separations of maximum 20 obstacle heights (such as villages, suburban terrain, permanent forest)
- **Terrain category IV:** Area in which at least 15% of the surface is covered by buildings with their average height exceeding 15 m

Wind loads can occur as **pressure** and as **suction.** Suction equals to negative pressure and has a major influence on the structural design.

[11] DOKA 2013

[12] Eurocode 1: Actions on structures — General actions — Part 1-4: Wind actions. 2004. p. 94

Therefore, it must not be neglected in the designing process. Horizontal loads are increasing dramatically with building height. Thus, they are responsible for the swaying effect of a building. The stiffer a high-rise building is designed the less it sways.

3.1.4 Earthquake Loads

Besides the wind loads, the earthquake loads have a wide influence on the design of high-rise buildings. Also here the swaying effect increases with the height of the building.

> *An earthquake is caused by a sudden slip on a fault. The tectonic plates are always slowly moving, but they get stuck at their edges due to friction. When the stress on the edge overcomes the friction, there is an earthquake that releases energy in waves that travel through the earth's crust and cause the shaking that we feel.*[13]

The above-mentioned waves are responsible for the swaying of the building. To reduce swaying, a so-called **mass damper** can be introduced in high-rise buildings.

Tuned mass dampers are also called **harmonic absorbers.** These are devices which are installed in structures or buildings in order to reduce the amplitude of mechanical vibrations. Tuned mass dampers stabilize against violent motion caused by harmonic vibration. They reduce the vibration of a system with a comparatively lightweight component. Thus, a reduction of the worst case vibrations can be achieved. Normally, mass dampers in buildings are huge concrete blocks or steel bodies. They are moved in opposition to the resonance frequency oscillations of the structure by means of springs, fluid or pendulums.[14]

The world's largest and heaviest tuned mass dumper is mounted in the **Taipei 101** skyscraper in Taiwan. The damper has a diameter of 18 feet and weighs 728 tons. The building is situated only 660 feet far away from the major fault line. Thus, earthquake loads can be expected with a high probability. The tuned mass damper in Taipei 101 is capable of moving 5 feet in each direction. Thereby it reduces sway up to 40 percent.[15]

[13] http://www.openhazards.com/faq/earthquakes-faults-plate-tectonics-earth-structure/what-earthquake-and-what-causes-them-happen (16.10.2013)

[14] http://en.wikipedia.org/wiki/Tuned_mass_damper (16.10.2013)

[15] http://www.atlasobscura.com/places/tuned-mass-damper-of-taipei-101 (16.10.2013)

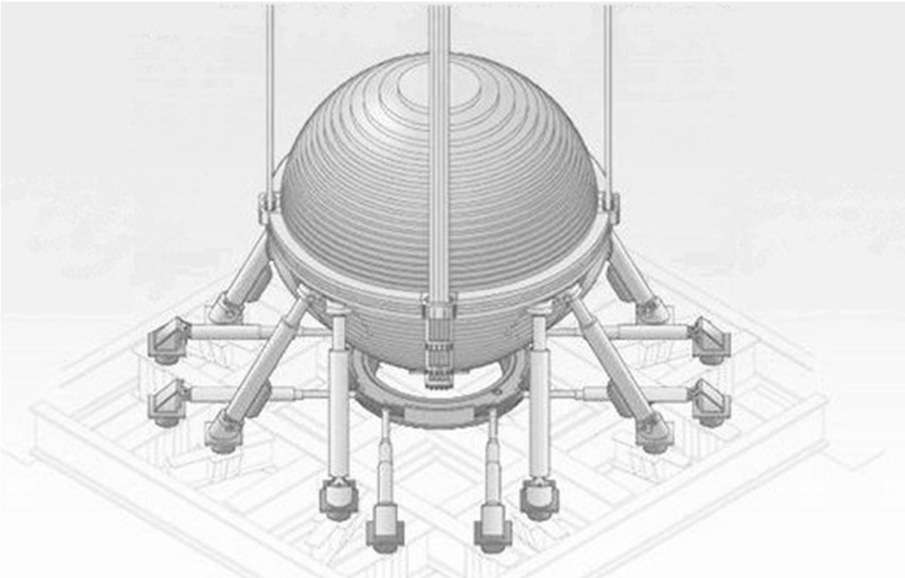

Fig. 3.2 Tuned mass damper in Taipei 101 skyscraper [16]

3.2 Structural Systems for High-rise Buildings

The structural system of a high-rise building must be designed as a three dimensional structure. Such three dimensional structures consist of vertical and horizontal planes. Planes are thin-walled load bearing structures which are responsible for transmitting the acting load. They can be designed as walls, frames, cores and tubes. Additionally to the vertical loads they must be able to carry shear forces, what makes the design of the structural system even trickier. Responsible for the shear forces are mainly wind loads and earthquake loads. The interaction between the vertical planes among each other can be achieved by arranging the horizontal planes accordingly. They have a high degree of stiffness and, therefore, they can be considered as rigid. Vertical planes serve to transfer loads, which consist of vertical loads and horizontal loads from the horizontal planes, down to the foundation. [17]

[16] http://www.taipei-101.com.tw/en/Tower/buildind_13-1.html (08.11.2013)

[17] GREINER, R.: Baustatik 2. Bauwerkssicherheit. Skriptum 2007. p. 61

DROSDOV and LISHAK made a classification of structural systems of multi-storey buildings, which is shown in Figure 3.3

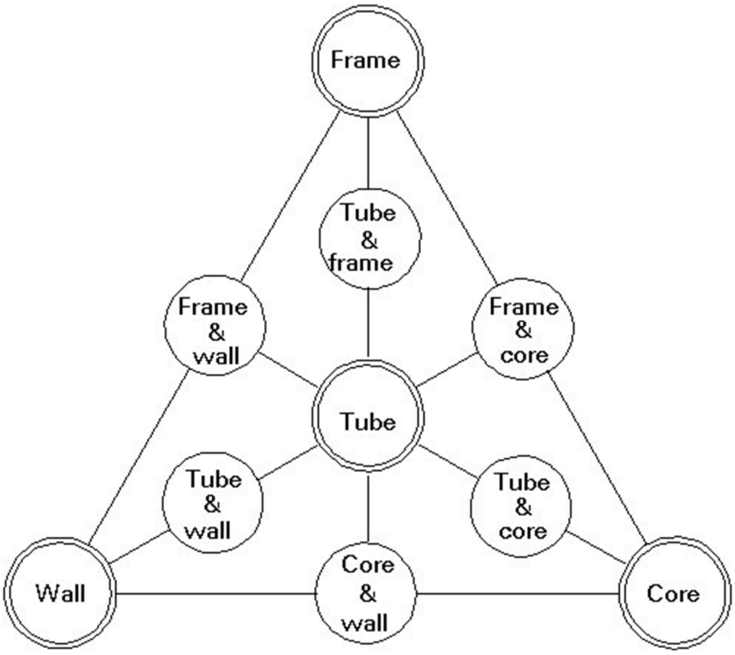

Fig. 3.3 Classification of structural systems of multi-storey buildings [18]

According to DROSDOV and LISHAK the main structural systems are:

- Bearing wall system
- Concrete core system
- Frame system
- Tube system

All systems resist both vertical and horizontal loads. When combining the above-mentioned main structural systems, a range of dual-systems arises. Vertical and horizontal subsystems can be combined in many ways to provide overall structural integrity. Theoretically, a combination of all systems is possible.

[18] DROSDOV, P.; LISHAK, v. I.: Spatial rigidity and stability of tall buildings of different structural schemes. Prefabricated multi-Storey buildings. (Proceedings of Conference held in Moscow, October 1976). Central Research and Design Institute for Dwellings, Moscow. 1978 pp. 27-35

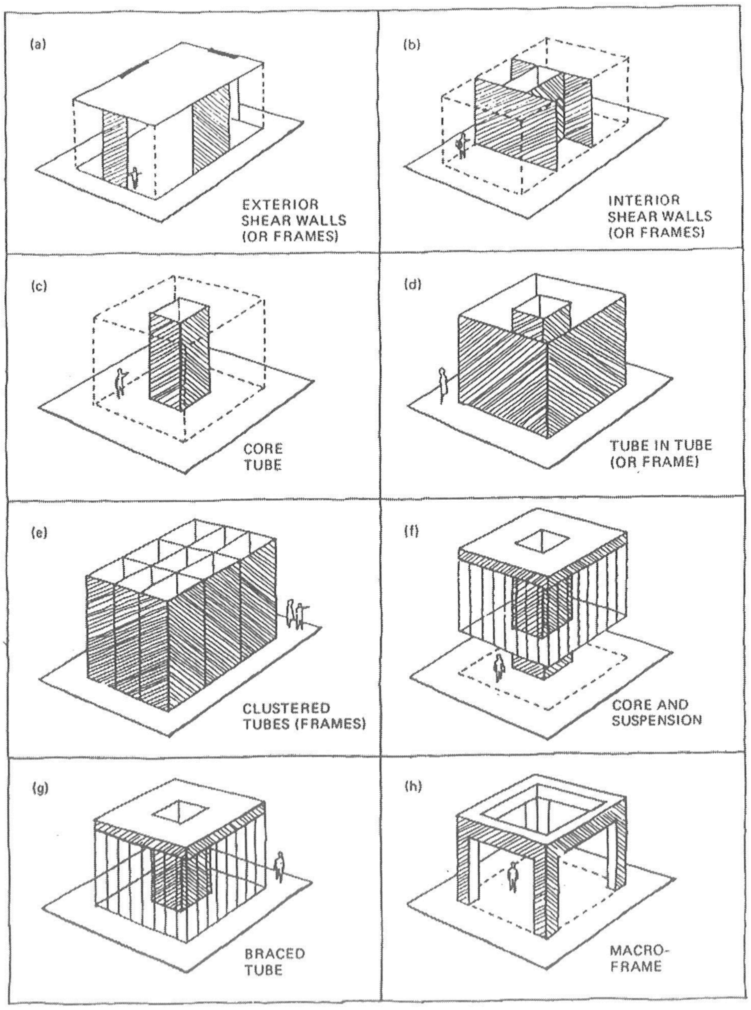

Fig. 3.4 Structural systems [19]

Figure 3.4 shows graphically a range of possible structural systems. The arrangement of horizontal and vertical planes to a three dimensional structure can be done in many ways. A very important type is the core system.

As the horizontal loads from wind and earthquakes can come from any direction the structural system of shear walls must be designed independently from the direction of the horizontal loads. Also the thermal expansion of a building must be taken into account. Figure 3.5 illustrates eight different plan views of share wall layouts.

[19] GREINER, R.: Baustatik 2. Bauwerkssicherheit. Skriptum 2007. p. 66

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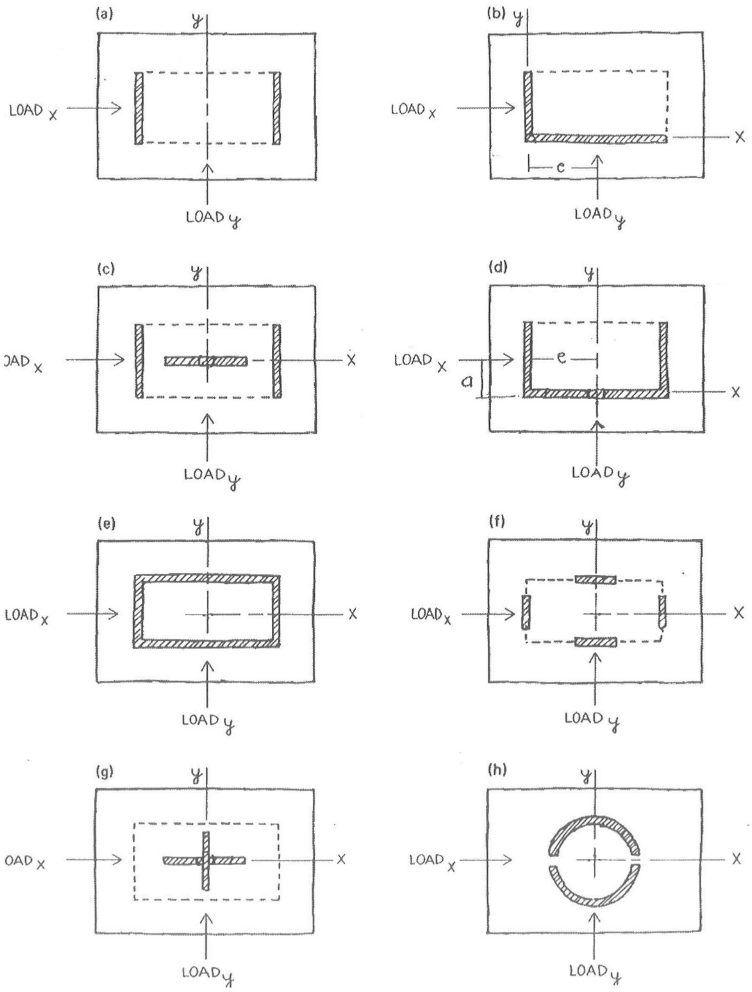

Fig. 3.5 Plan views of share wall layouts [20]

3.2.1 Bearing Wall System

Bearing wall systems are comprised of planar, vertical elements. They usually form the exterior and interior walls and transfer vertical and horizontal loads through these walls.[21]

3.2.2 Concrete Core System

A very commonly used structural system is the core system. It is comprised of load-bearing walls arranged in a closed form, usually with

[20] GREINER, R.: Baustatik 2. Bauwerkssicherheit. Skriptum 2007. p. 65

[21] Cf. FALCONER, D.: Classification of all building systems. Thesis. Lehigh University 1981. p. 23

mechanical systems concentrated in this vertical shaft. This gives the building flexible space beyond the core.[22] It allows that the periphery supporting structure of a building is designed in a light-weight way.

3.2.3 Framed System

A frame structure is a structural system comprised of columns, girders, and/or beams arranged to resist both horizontal and vertical loads. It is the most adaptable structural form in terms of material and shape due to the many ways of combining structural elements to adequately support the building.[23]

3.2.4 Tube System

Tube systems consist of closely spaced exterior structural elements, arranged to respond to a lateral load as a whole, rather than separate elements. However, the columns need not be spaced too closely. As long as the building responds similar to a cantilever, it is called a tube. This allows for more flexibility in interior space use due to the lack of vertical interior structural elements.[24]

3.2.5 Combined System

There is a variety of possible combinations of structural systems for high-rise buildings as shown in Figure 3.3. Combining structural systems may lead to better economic solutions and to stiffer systems.

3.3 Parts of High-rise Buildings

In principle, most of the high-rise buildings are designed in a very similar way. First comes the foundation. Usually, the basement levels are flat-roofed buildings where car parks or shops are located. Then, construction of the regular floors with same floor heights is next. Depending on the building, mechanical floors are installed in certain levels and at the top, there is a roof construction. In this chapter, the main parts of a high-rise building are explained.

[22] Cf. FALCONER, D.: Classification of all building systems. Thesis. Lehigh University 1981. p. 23

[23] Cf. FALCONER, D.: Classification of all building systems. Thesis. Lehigh University 1981. p. 23

[24] Cf. FALCONER, D.: Classification of all building systems. Thesis. Lehigh University 1981. p. 23

3.3.1 Foundation

The foundation is the lowest part of a building. All acting loads are transferred into the foundation, thus, the foundation must be capable of bearing all these loads. It is not uncommon that a deep foundation must be made because of the soil condition. In some cases such deep foundations are deeper than 100 metres. For example, the foundation of the Petronas Towers in Kuala Lumpur (Malaysia) needed to be driven 120 m deep until they reached the bedrock.

Deep foundations are commonly bored piles, which consist of reinforced concrete. For the construction of bored piles, huge drilling devices are mounted to an excavator. After a soil with sufficient bearing capacity has been reached, a reinforcement cage is inserted into the drilled hole. Then it is filled with concrete. Depending on the soil condition, there is a huge variety of drilling technologies available. Also the amount of bored piles to be installed depends on the soil condition. Once all bored piles are constructed, a concrete cap, which is connected to the bored piles, can be done. In this way, all the acting loads are transmitted into the soil layer which is able to bear the loads, and so, safety can be assured. The concrete cap can have a thickness of several metres.

3.3.2 Basement Level

Many high-rise buildings do not start with the regular floors from ground. Often, the first floors are used as a basement area, where car parking houses, entrance halls, shops and hotels are integrated. These levels are used to have different floor heights. They are rather irregular and thus, execution is more complicated. Usually, they are also different in the ground plan and the roofs are designed as flat-roofed buildings. But not all high-rise buildings have basement floors. Sometimes these buildings are separated.

3.3.3 Core

The core is definitely one of the most important parts of a high-rise building. Here, all the service elements, like elevators, staircases, water pipes, cooling and heating pipes, etc. are installed. The second major function is the structural system. Through the core, all loads are transferred to the foundation. Therefore, the core must be capable of resisting these loads.

The core starts already in the basement area and goes until the top of the building. It should be as small as possible but as big as necessary. Such cores are usually constructed with slipforms or jumpform systems.

3.3.4 Slabs and Columns

Once the core is approximately three floors high, the construction of the slabs can be started. There are two possible construction methods to construct the slabs:

- Core ahead
- Slab and walls together

The common way of constructing a high-rise building is to make the core ahead. In this case, the slabs are connected afterwards to the core. But there are also formwork systems where the core is casted simultaneously with the slabs. This procedure is only possible with jumpform systems whereas the slipform technology does not allow doing so.

Slabs can either be cast in situ reinforced concrete slabs or composite slabs with precast elements. The latter is advantageous for the formwork and, additionally, it is a fast method. The connection between the core and the slabs is provided by back-bending reinforcement boxes.

After the slab is finished, the columns can be constructed. Also here it can be chosen between prefabricated columns and cast in situ reinforced concrete columns. Another possibility is to construct composite columns which are steel tubes combined with concrete.

Regular Floors

Above the basement level, a continuous construction process can be started. Usually, all following floors have the same floor height. Those floors include offices, flats, hotel rooms, etc.

Mechanical Floors

An exception is the mechanical floors, which are distributed along the building. These floors often have a different floor height than the regular floors. This leads to a bigger effort in the construction phase because the continuous construction process is interrupted for only one floor. Mechanical floors are also called service-, utility- or technical floors. They include electronic equipment, the control system for heating, cooling, ventilation, water pumps, etc.

3.3.5 Cladding

The cladding is responsible for the outward appearance of a building. High-rise buildings are often equipped with a glass cladding but in the end, it is up to the architect which kind of cladding is used. For the structural design, the cladding can be allocated to the permanent loads or dead loads.

3.3.6 Roof Construction

Also the roof construction of a high-rise building can be counted as a permanent load. There are several different designs of roof constructions. Often the space at the roof is used for aerial systems or for a helicopter landing pad.

3.4 Formwork Systems for High-rise Constructions

The development of formwork systems which can be moved upwards independently of a supporting structure started in parallel to innovative construction methods and the development of big wall formwork systems. Constructional design of concrete constructions and the application of lifting gears led to formwork systems to be applied at high levels. Close to the ground, the transfer of loads is not a problem but at higher levels it becomes more cost intensive, time consuming and more complicated. Therefore, self-supporting structures, which are directly connected to the construction, were developed. Here, the load transfer is done through the construction itself. [25]

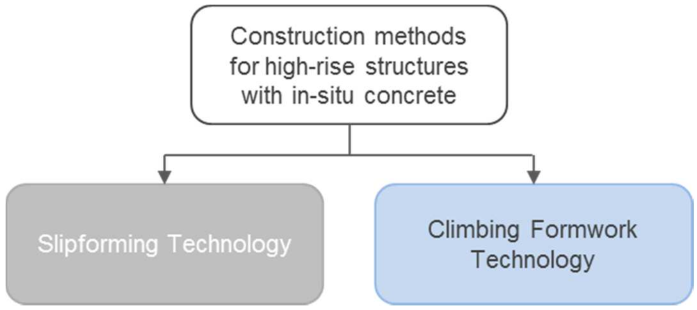

Fig. 3.6 Construction methods for high-rise structures with in-situ concrete [26]

Such self-supporting formwork methods are either **Slipform systems** or **Jumpform systems**. Both systems transfer the loads vertically into the ground. There is a wide range of application areas for these systems. Beside high-rise buildings, these formwork systems are used for constructing silos, water towers, staircases, bridge pylons etc.

[25] Cf. SCHMITT, R.: Die Schalungstechnik. Systeme, Einsatz und Logistik. Berlin. Ernst & Sohn, 2001. p. 194

[26] Cf. SCHMITT, R.: Die Schalungstechnik. Systeme, Einsatz und Logistik. Berlin. Ernst & Sohn, 2001. p. 194

4 Slipforming Technology

This chapter gives a detailed insight into how a slipform works. Initially, there is general information, including a historical part. Subsequently a precise technical description of a slipform with a list of advantages and disadvantages is provided.

4.1 General

Slipforming technology has **existed since the early 20th century** but in a more primitive form than nowadays. Early slipforms were made of timber. Hydraulic jacks and synchronized electrical equipment were not available at that time, so the formwork was lifted by hand-operated screw jacks. This made the system rather user-unfriendly and, thus, there was no significant use for the system. In the 1960s, the system got enhanced and so it was introduced into residential and commercial constructions.

In the late 1940s the company AT&T Communications Inc. (American Telephone and Telegraph), that developed the bell systems and made up a huge and complex corporate system providing telecommunications equipment and services, built a number of towers using the slipform technology. Referring to the article “Sliding Up At Sideling Hill” of Long Lines magazine in September 1949, the slipform method was called the “dramatic sliding form method”. People who were involved into this project got so amazed and obsessed by their work that they got called to have the “Tower Fever”. It was the drastic rise of the structure which gave people the motivation to work day and night.[27]

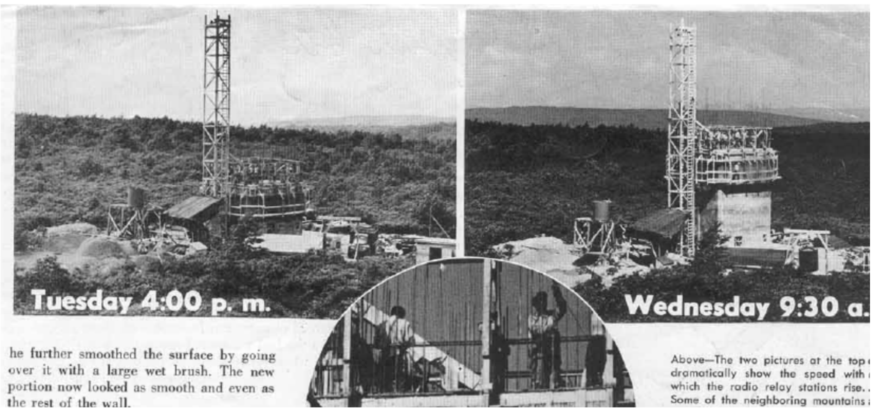

Fig. 4.1 Long Lines magazine article “Sliding Up At Sideling Hill” Sept. 1949 [28]

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[27] Cf. CHABIRS, P.D.: Long Lines magazin, September 1949, Sliding Up At Sideling Hill, p.4ff

[28] CHABIRS, P.D.: Long Lines magazin, September 1949, Sliding Up At Sideling Hill, p.5

The first remarkable application of the slipforming technology was the construction of the **Skylon Tower** in Niagara Falls, Ontario. This 160 metre high building was constructed in 1965.[29]

4.2 Fields of Application

In principle, slipforms are used for high vertical structures with a constant cross section or a regular shape. Due to the technical developments during the last years, slipforming became more flexible. Thus, also buildings with changing cross-section and inclinations can be constructed. Nevertheless, also this technology has its limitations and unfavourable properties. Even though slipforming technology became a competitive system to the climbing formwork technology in many fields of construction, concrete quality is still a big issue. To produce concrete walls with high quality of exposed concrete surfaces is still not possible. Therefore, this technology is just suited for projects with low concrete quality requirements.

The second big issue is the exact placing and adjusting of built-in parts and block-outs. Since the formwork is moving permanently, there is a risk of displacing the built-ins and block-outs.

There is no certain rule how high a building has to be to apply slipforming technology but due to the high costs of the assembling and disassembling procedure, profitable results are only reached above a certain building height.

4.3 Operating and Functional Principle

In terms of constructional operation aspects, the function of a formwork is the **shaping of an amorphous and plastic fresh concrete until it has hardened**. Additionally, it has a **guiding function** because the system is guided along the concrete.[30]

Slipforming is a continuous process where a formwork structure is lifted; reinforcement work is carried out as well as concrete is poured at the same time. There is a hanging scaffold mounted under the slipforming structure so that even the subsequent treatment of the concrete can be performed at the same time.

The formwork is rigid and about 1.2 m high. Along the climbing rods, which are located inside the wall, it is pressed upwards by approximately

[29] http://www.flickr.com/photos/wallyg/136351779/ (30.06.2013)

[30] Cf. MOTZKO, Ch.: Baubetriebliche Aspekte beim Bau turmartiger Bauwerke. Schalungstechnik - Wirtschaftlichkeit – Arbeitssicherheit. p. 8

20 to 25 mm in one stroke. Transverse yoke beams are responsible for bearing the loads. Those yoke beams consist of steel profiles. The horizontal distance between the yokes depends on the load bearing capacity of the hydraulic jack and the yoke beams. An equal distribution of the loads to all yoke beams should be considered when the slipform is designed.

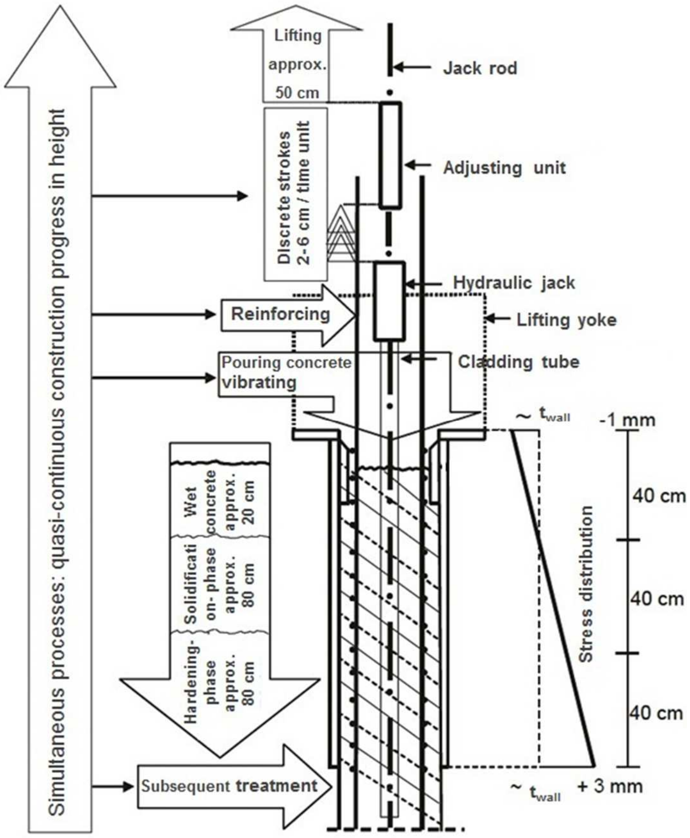

Fig. 4.2 Operating principle of a slipform [31]

To keep the formwork at the required distance, it is mounted to the yoke beams which are responsible to transfer concrete pressure because anchors cannot be installed in this procedure.

Jacks are arranged above the yokes, which are connected to the climbing rods. These climbing rods are in the middle of the wall, and they are surrounded by a cladding tube in order not to get poured in by concrete. Also the cladding tube is mounted on the yoke.

The diameter of the cladding tube is only somewhat bigger than the diameter of the climbing rod. Vertical loads are transferred from the

[31] Cf. MOTZKO, Ch.: Baubetriebliche Aspekte beim Bau turmartiger Bauwerke. Schalungstechnik - Wirtschaftlichkeit – Arbeitssicherheit. p. 9

climbing rods to the cladding tube and from the cladding tube into the hardened concrete. The climbing rods have a length between 3 m and 6 m and they are extended by a bolted connection. After reaching the building height, the climbing rods are pulled out, so they can be used again. There is also the possibility to omit the cladding tube. In this case, the climbing rods become part of the structure and cannot be used again.

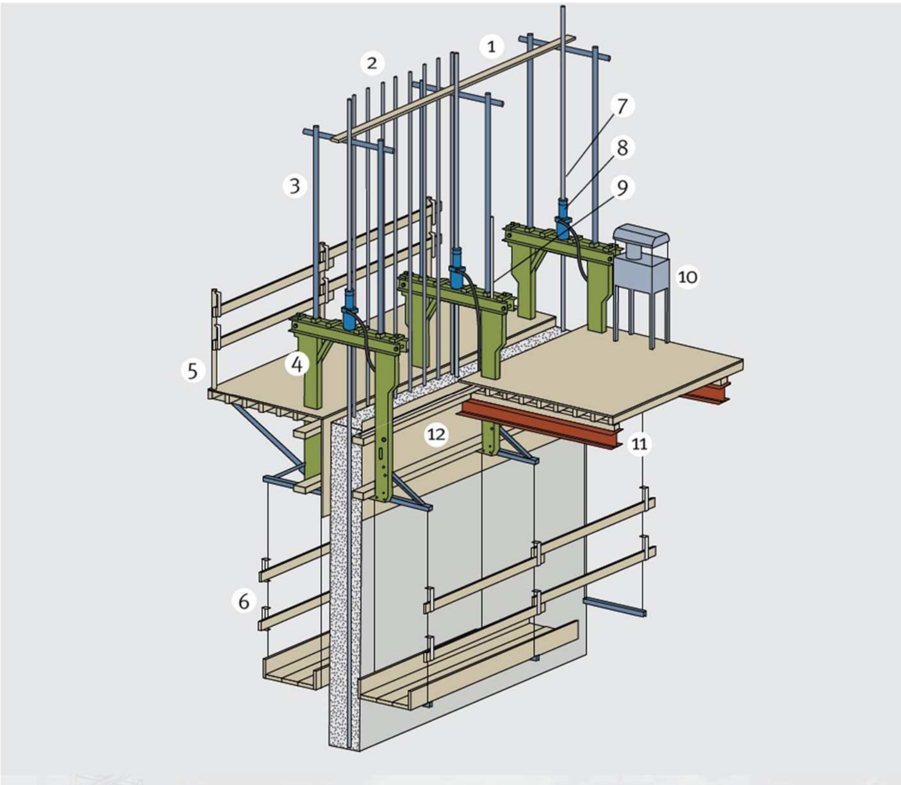

Fig. 4.3 Slipform schematic [32]

1 guide for reinforcement	**7** jack rod
2 reinforcement schematic	**8** Hydraulic 3-6 tonne jack
3 holder for reinforcement guide	**9** water hose for horizontal control
4 lifting yoke	**10** hydraulic pump
5 external work platform	**11** beam for internal work platform
6 suspended scaffold	**12** slipform with steel plates

[32] INTERFORM: Slipform brochure, p. 5

Even though the jacking procedure is done in strokes, we are talking about a continuous procedure because the jacking steps are low and the time between each stroke is very short.[33]

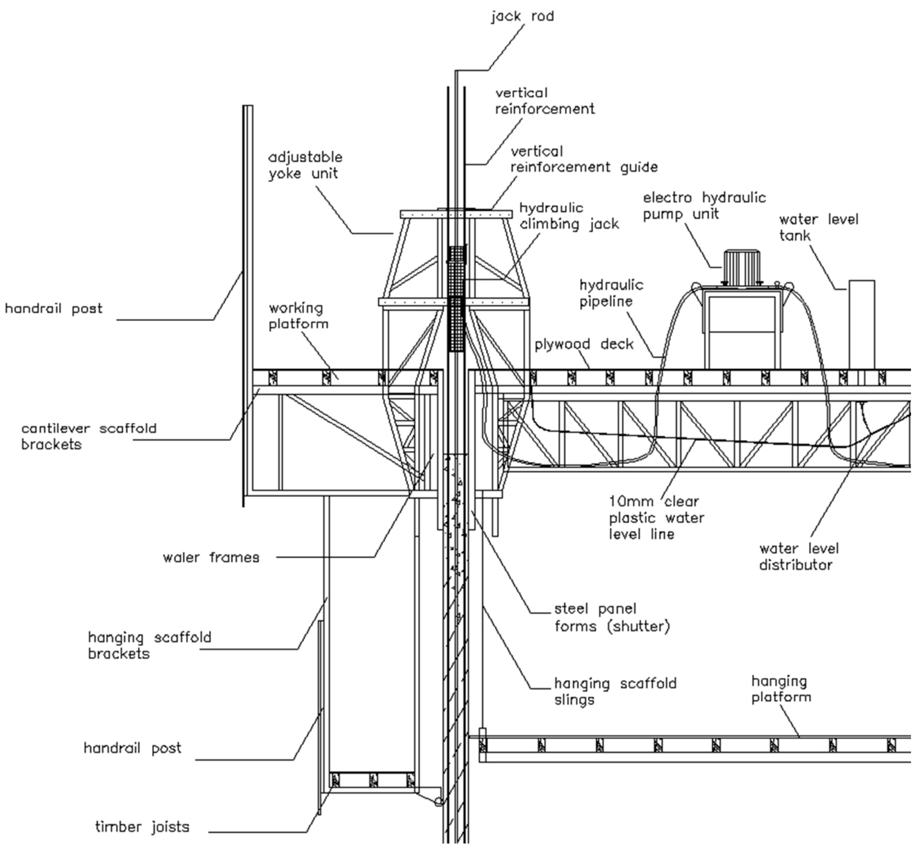

Fig. 4.4 Sectional drawing of a slipform[34]

As you can see in Figure 4.4, working platforms, which are connected to the slipform structure, are used for carrying out the reinforcement works and concrete pouring. For the subsequent treatment of the concrete hanging scaffolds are installed. From those hanging scaffolds also block-outs are removed.

A little handicap of the slipforming system is the installation of the horizontal reinforcement. The rebars can only be installed below the transverse yoke beams, which are located approximately 60 cm below the top of the formwork. Especially by installing rebars with big diameters and big lengths, efforts increase dramatically. Also the geometry of the building can make the installation of the reinforcement more problematic.

33 DUPKE, M: Einsatzgebiet der Gleitschalung und der Kletter-Umsetz-Schalung, Ein Vergleich der Systeme, p. 20

34 DOKA 2013

Pouring is done simultaneously all around the slipforming structure in layers of approximately 20 cm. According to HOFSTADLER, there is a classification of the concrete in three phases (depending on the concrete mix):[35]

- Upper layer with approximately 20 cm fresh concrete
- Middle layer with approximately 80 cm concrete in solidification process. The junction between upper layer and middle layer is achieved by vibrating the concrete.
- Lower layer with approximately 20 cm concrete in hardening process.

Because the formwork is mounted to the yoke beam it is in a rigid position and, therefore, it cannot be serviced or repaired.

4.3.1 Schematic Workflow

Below, the three phases of the slipforming technology are explained. First, there is an assembling procedure, then the continuous sliding process, and in the end the disassembling work.

Assembling Procedure

Formwork elements are prepared on an installation site and then they are put on to the foundation of the construction with a crane. Before assembling, the foundation of the structure is gauged exactly. The geometry of the construction to be built is also marked exactly with measurement points. Start of the assembling procedure is the highest point of the foundation. According to the GERMAN SOCIETY FOR CONCRETE AND CONSTRUCTION the following steps have to be executed:[36]

- Arranging supporting platform for reinforcement work
- Providing a holder for fixing the reinforcement
- Fixing horizontal steel bars on the connection reinforcement from the foundation until approximately 1.50 m above the top edge of the foundation
- Prefabrication of box-outs and built-in parts on site
- Mounting the inner platforms

[35] Cf. HOFSTADLER, C.: Schalarbeiten, Technologische Grundlagen, Sichtbeton, Systemauswahl, Ablaufplanung, Logistik und Kalkulation, 1. Auflage, Berlin, Heidelberg, 2008, p. 126

[36] DEUTSCHER BETON- UND BAUTECHNIK-VEREIN: Merkblatt Gleitbauverfahren, Slipforming Technology, Berlin 2008, p. 31

- Placing the inner formwork elements
- Placing the outer formwork elements
- Mounting the transverse yoke beams and the hydraulic jacks
- Preparing the outside hanging scaffold
- Laying the floor covering
- Fixing the railings and security elements
- Mounting the spacers
- Installation of the hydraulic tubes and testing them
- Installation of lighting
- Eventually sealing the bottom edge of the formwork in case of unevenness of the foundation
- Measuring the assembled sliding formwork. Without inspection and approval there is no sliding start
- End check and sliding start

In contrast to jumpform systems, which demand a preconstruction with a conventional formwork system of approximately three floors, the slipforming systems **can be assembled from the ground level on**. The assembling procedure is expensive and takes its time, depending on the complexity of the building and on geometry. There are standard elements to apply but for each project some special elements need to be produced which makes assembling time even longer.

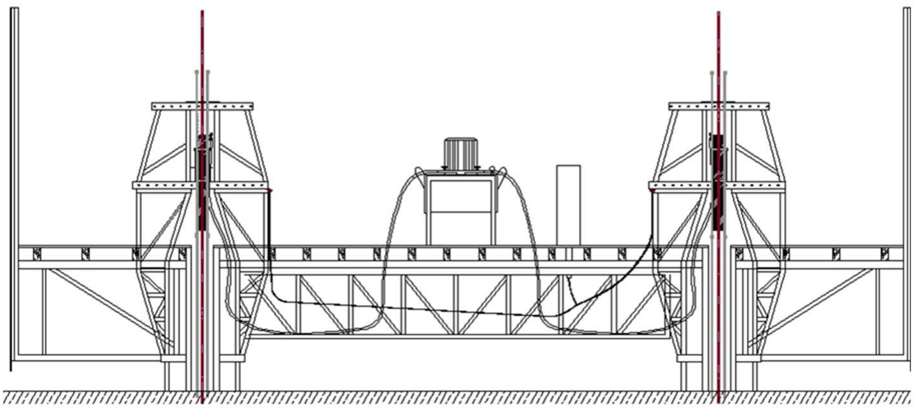

Fig. 4.5 Start - up phase – assembled rig on the raft [37]

[37] DOKA 2013

Figure 4.5 shows a slipforming system which has already been built up. There is already concrete poured in, and the first sliding stroke is done as a next step.

Continuous Sliding Process

Once the concrete has reached its initial set, the rig is jacked in regular time intervals. Stokes of approximately 20 – 25 mm can be considered as normal. According to the company Interform AS, a standard slide rate is **2.5 to 3.5 metres per day**, depending on the complexity of the construction. For simpler construction the rate can reach as much as **7 to 8 metres per day**.[38]

A very important factor for the progress of slipforms is the condition of the concrete. On the one hand concrete composition is supposed to be ductile enough so that all the corners and edges of the structure are sufficiently filled and that the pouring process can be done easily. On the other hand, the concrete should set and harden as fast as possible to be able to increase sliding speed.

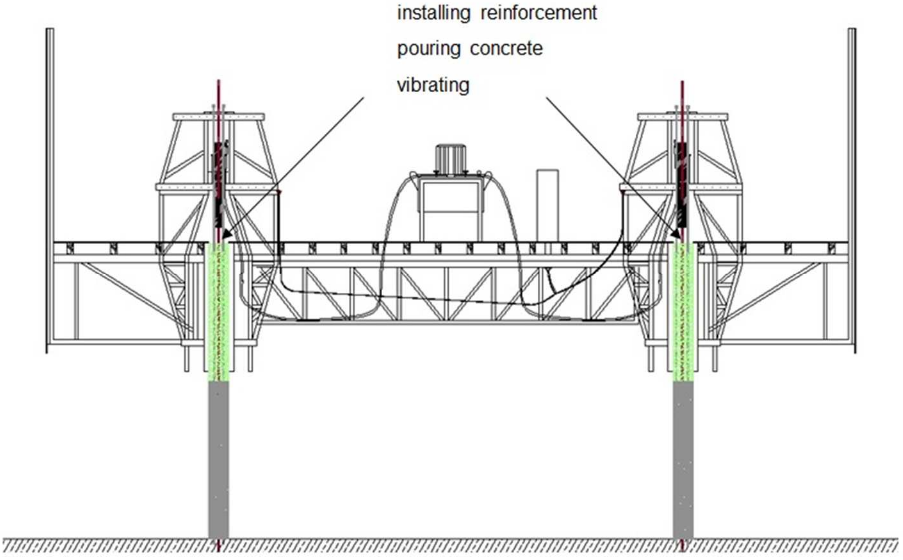

Fig. 4.6 Concreting cycle - Placing concrete and lifting the shutter [39]

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[38] Cf. INTERFORM: Slipform brochure, p. 7

[39] DOKA 2013

> *Successful slipforming depends on efficient management of the 3 main parameters; the concrete, the delivery system and the formwork. The key is control of the setting time of the fresh concrete so that the forms can be lifted at a predetermined speed and the concrete sets and hardens at the desired depth in the shallow forms. Control of the setting time is accomplished by chemical admixtures and management of the temperature regime at the batching plant and at the work face.*[40]

During the concreting cycle, reinforcement fixers must work permanently. When there is a high degree of reinforcement or a complicated geometry, the introduction of the steel rebars can be difficult and time-consuming. Thus, a good management of reinforcement works is of a big advantage to ensure that the concreting cycle does not get delayed.

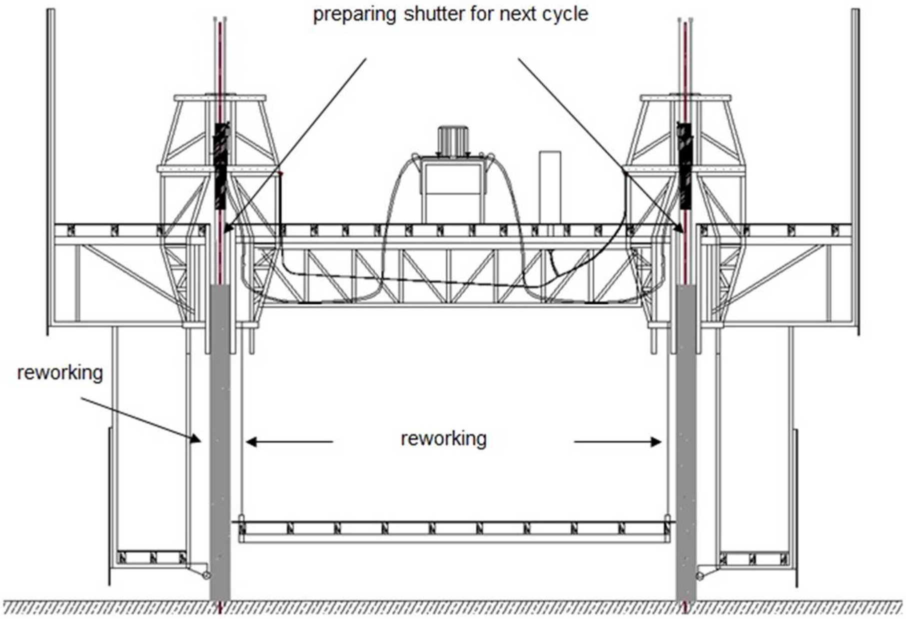

Fig. 4.7 End of cycle - preparing for the next cycle [41]

Residential or commercial buildings always have ceilings or columns which need to be constructed subsequently to the core or load bearing structure. Because of structural reasons, slipforms should be constructed ahead not more than three floors than the following slap. Thus, the slipform must be stopped at a certain height, which is usually done exactly at the height of a floor level to avoid a joint in the middle of a wall. At this stage it is possible to clean the shutter. Therefore, the shutter needs to be lifted free without pouring or fixing horizontal reinforcement.

[40] FOSSER, K. KRAINER, A. MOKSNES, J.: Slipforming of advanced concrete structure, in taylor made concrete structures, London 2008, p 836

[41] DOKA 2013

After the shutter has been cleaned, it will be possible to proceed with the normal operating sequence.

Another part of the permanent work and the cycle is the subsequent treatment of the concrete, which is explained in more detail in Chapter 3.3.10. Also the control of verticality belongs to the permanent duties and is discussed in Chapter 3.3.11.

Disassembling Process

After the concrete work for a structure is done, the slipform can be disassembled. First, the climbing rods are pulled out. Therefore, the yoke beams should be braced with some wood. Afterwards, the hydraulic tubes are removed. Openings have to be grouted. For the disassemble process a crane is needed. Demounting starts with the outer elements and subsequently the inner elements are removed. After the slipform has been dismantled, the elements are cleaned and serviced. There are strict safety conditions which have to be kept by the workforces who do the disassembling work of the slipform.[42]

4.3.2 Concrete Strength

Concrete strength depends on structural requirements. Mostly strengths like C25/30 and C30/37 are used but for buildings with more requirements high performance concrete might be demanded. Constructions with a concrete strength of C80/85 have already been built, and also slipforms with concrete strength up to 100 MPa have been tested.[43]

4.3.3 Concrete Cover

Thickness of the concrete cover depends on two factors: exposure class of the concrete and diameter of the steel bar. There is a distinction between the minimum concrete cover c_{min} and the nominal dimension c_{nom}. The nominal dimension already includes a security factor to cover wear-out cases of the concrete. Around 4 to 5 cm can be considered as standard concrete covers for slipforming systems.[44]

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[42] Cf. DEUTSCHER BETON- UND BAUTECHNIK-VEREIN: Merkblatt Slipforming Technology, Berlin 2008, p. 32

[43] Cf. DEUTSCHER BETON- UND BAUTECHNIK-VEREIN: Merkblatt Slipforming Technology, Berlin 2008, p. 10

[44] Cf. DEUTSCHER BETON- UND BAUTECHNIK-VEREIN: Merkblatt Slipforming Technology, Berlin 2008, p. 10

4.3.4 Minimum Wall Thickness

Minimum wall thickness results from structural requirements and from the feasibility to pour the concrete. Figure 4.8 shows an example of how the wall thickness and the configuration of the reinforcement can be arranged. Here, the horizontal reinforcement has a diameter of 14 mm, the vertical 10 mm, the distance from the vertical reinforcement is defined with a minimum distance of 20 mm. Depending on the maximum grain size of the aggregates in the concrete, the size of the cladding tube has to be chosen. The smaller the maximum grain size, the smaller the cladding tube can be but in this case it must be considered that a higher degree of cement needs to be used.

Adding up the minimum values in Figure 4.8, it can be assumed that for applying a slipform system a **minimum wall thickness of 18 cm** is required.

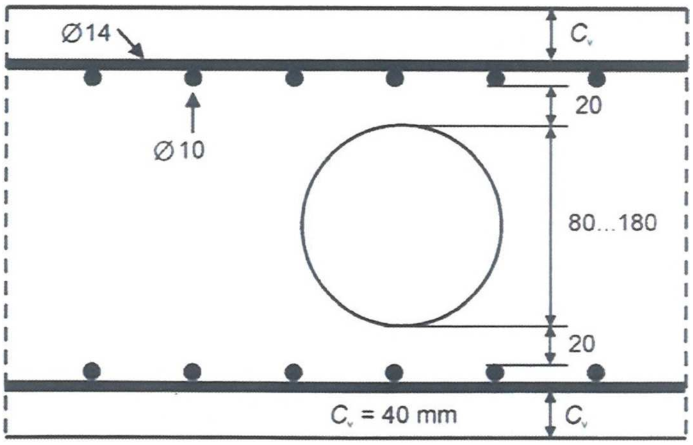

Fig. 4.8 Minimum thickness of wall for slipforming; units as mm [45]

4.3.5 Reinforcement

When designing the reinforcement for slipforms, the following items should be considered: [46]

- Basically, U-shaped reinforcement steel should be used.
- Between reinforcement layers, U-shaped reinforcement steel should be inserted to avoid the folding of the reinforcement

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[45] Cf. DEUTSCHER BETON- UND BAUTECHNIK-VEREIN: Merkblatt Slipforming Technology, Berlin 2008, p. 11

[46] Cf. DEUTSCHER BETON- UND BAUTECHNIK-VEREIN: Merkblatt Slipforming Technology, Berlin 2008, p. 12

- The reinforcement must be fixed by hand below the transverse yoke beams. Therefore, the individual weights of the steel elements should not be more than 25 kg.
- The horizontal reinforcement should always be placed on the side of the formwork outside of the vertical reinforcement.
- The maximum length of the horizontal reinforcement depends on the diameter of the steel rebar, the radius of the structure, etc. and should not exceed a size of 10 m.
- The vertical reinforcement is staggered depending on the ground plan. This is based on practical reasons for a balanced work distribution.
- The length of the vertical reinforcement should not exceed a size of 5.50 m.
- A very important point is to keep the concrete covered because this is a security layer for the reinforcement.
- For the introduction of built-in parts, additional reinforcement should be planned. In case it is not allowed to weld the reinforcement elements, the additional reinforcement should be coloured to recognize the correct position of the built-in part.

4.3.6 Formwork Sheeting

The significant feature of slipforms is that you can construct a building without joints. Normally, steel facings are used. These steel sheets have a thickness between 0.4 and 4.0 mm. Seldom plywood, coated wooden elements, synthetic materials or fibre glass are in use for formwork facings for slipforming systems. Especially for buildings with changing cross sections steel facings are of advantage.

The formwork sheets, also called shutter, are not parallel. They are inclined towards each other. At the top, the distance between the sheets is smaller than the desired wall thickness; at the bottom it is bigger. Approximately in the upper third of the shutter the desired wall thickness is reached. This is necessary to reduce the friction between formwork and concrete and is illustrated in Figure 4.9.[47]

[47] Cf. DEUTSCHER BETON- UND BAUTECHNIK-VEREIN: Merkblatt Slipforming Technology, Berlin 2008, p. 14

4.3.7 Fresh Concrete Pressure for Slipforms

Slipforms show a different stress distribution of the fresh concrete pressure than conventional formwork systems. One reason is that the rate at which the concrete rises when being poured is smaller for slipforms. It has a maximum velocity of 0.40 m/h. Another reason is that the slipform sheets are inclined towards each other and permanently moving. Also the depth of immersion of the concrete vibrator is less than in conventional formwork systems. [48]

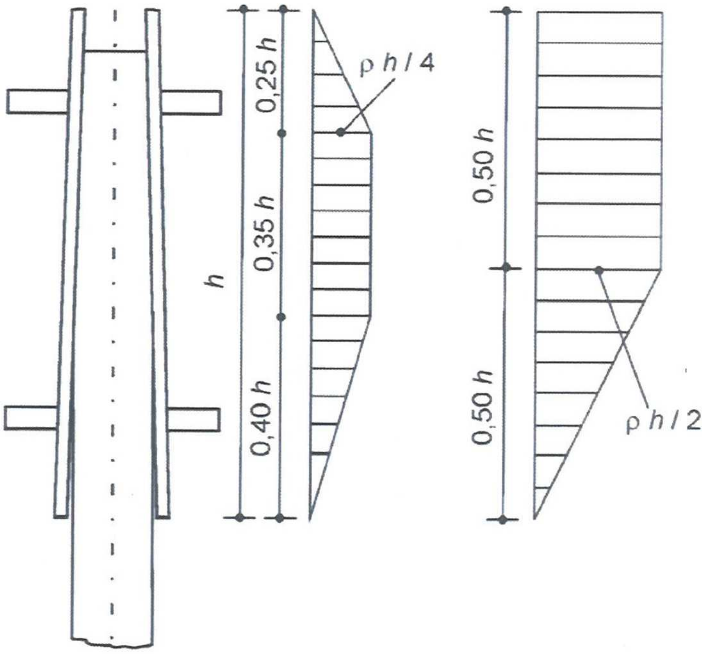

Fig. 4.9 Fresh concrete pressure on slipform [49]

The left graph in Figure 4.9 shows the stress distribution in the lower frame wood of the slipform, the right graph illustrates it for the upper frame wood. Here it can be seen that in the upper framework significant pressure acts on the formwork. This must be considered when dimensioning elements of the slipform.

4.3.8 Friction between Concrete and Formwork

Due to the sliding procedure of the slipform, a friction force occurs between the formwork facing and the concrete. An important point is that these acting friction forces do not lead to cracks in the concrete. In

[48] Cf. DEUTSCHER BETON- UND BAUTECHNIK-VEREIN: Merkblatt Slipforming Technology, Berlin 2008, p. 14

[49] DEUTSCHER BETON- UND BAUTECHNIK-VEREIN: Merkblatt Slipforming Technology, Berlin 2008, p. 15

Figure 4.10 the approximated stress distribution during the sliding process is shown. In practice, a friction value of 2.5 kN/m is realistic and is often used for designing. But the friction between formwork and concrete also depends on factors like geometry of the building, conditions and properties of the concrete mix, etc.[50]

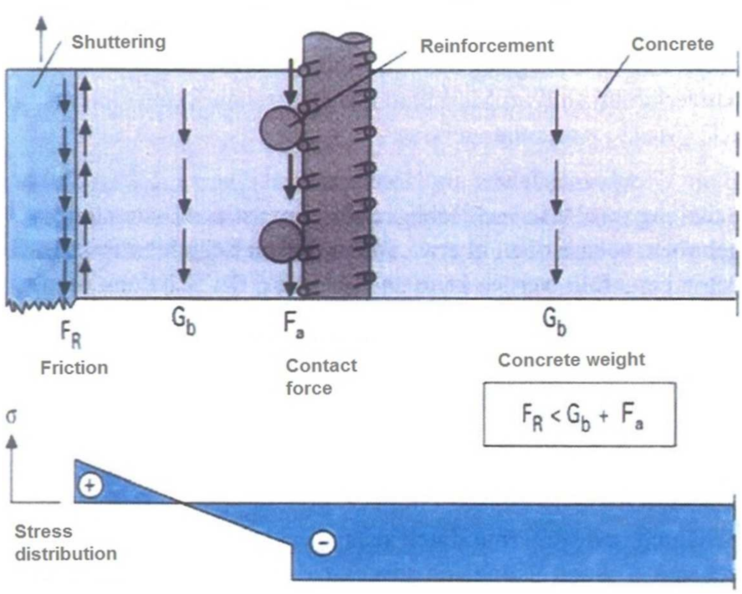

Fig. 4.10 Approximated stress distribution in a concrete wall for a slipform [51]

Due to the concrete pressure, the slipform can get elastic deformations, whereby the shutter of the slipform gets the necessary conical position as shown in Figure 4.9 by itself.

4.3.9 Built-in Parts, Block-outs

In contrast to jumpform systems, built-in parts and block-outs cannot be adjusted onto the formwork of the slipform. Since the slipform is moving permanently, these elements need to be fixed to the reinforcement. This leads to several disadvantages. First, the adjustment procedure is more complicated because built-in parts are normally welded onto the reinforcement. In some cases, they can also be fixed with steel wires. Where block-outs are positioned, additional reinforcement is required due to structural reasons. Because the built-in parts and block-outs are fixed and the slipform is moving there is always the risk of displacement of the built-in parts.

[50] Cf. DEUTSCHER BETON- UND BAUTECHNIK-VEREIN: Merkblatt Slipforming Technology, Berlin 2008, p. 16

[51] Cf. DEUTSCHER BETON- UND BAUTECHNIK-VEREIN: Merkblatt Slipforming Technology, Berlin 2008, p. 16

Fig. 4.11 Built-in part in metal, block-out in wood

There are several kinds of prefabricated built-in parts and connection joints to the reinforcement. The GERMAN SOCIETY FOR CONCRETE AND CONSTRUCTION (DEUTSCHER BETON- UND BAUTECHNIK-VEREIN) makes the following suggestions for installing block-outs:[52]

- Block-outs should be 15 mm smaller than the wall thickness
- For big block-outs the jack rods are led in support tubes
- Sufficient stiffness is of high importance
- After “stripping the formwork” after-treatment should be made

4.3.10 Subsequent Treatment of Concrete Surface

When constructing a building with slipform technology, subsequent treatment of the concrete is required. The permanent movement of the formwork has a negative influence on the concrete surface. Also the formwork sheets are not removed from its position until they have reached the full height of the building. Thus, they cannot be cleaned properly or serviced during the construction time.

[52] Cf. DEUTSCHER BETON- UND BAUTECHNIK-VEREIN: Merkblatt Slipforming Technology, Berlin 2008, p. 20

Fig. 4.12 Defective corner with slipform [53]

After-treatment of the concrete is made by a workforce working in the suspended scaffold (cf. Figure 4.3 No. 6). This suspended scaffold is normally covered by a sheet. The sheet provides security against dehydration of the concrete due to the influence of the wind. Normally, after-treatment substances are liquids.

4.3.11 Measurement of Slipform

Measurement plays a crucial role when applying slipform systems. Mostly laser for perpendicular measurements are used and the data are collected in a measurement protocol. In the protocol temperature changes must be noted. Such changes can be seasonal or caused by daytime. In case unplanned deviations occur it can be reacted on it by manipulating the slipform. [54]

Another measurement tool is the installation of a water level circuit. Here, a pipe system is mounted onto the slipform which is filled with coloured water. Once the slipform is aligned, the water level in the pipes is marked on the yokes and labelled with the present date. A surveyor is in charge of water level control. The control has to be done during the lifting process to ensure that the rig is lifted evenly.

[53] DOKA 2013

[54] Cf. HOFSTADLER, C.: Schalarbeiten, Technologische Grundlagen, Sichtbeton, Systemauswahl, Ablaufplanung, Logistik und Kalkulation, 1. Auflage, Berlin, Heidelberg, 2008, p. 127

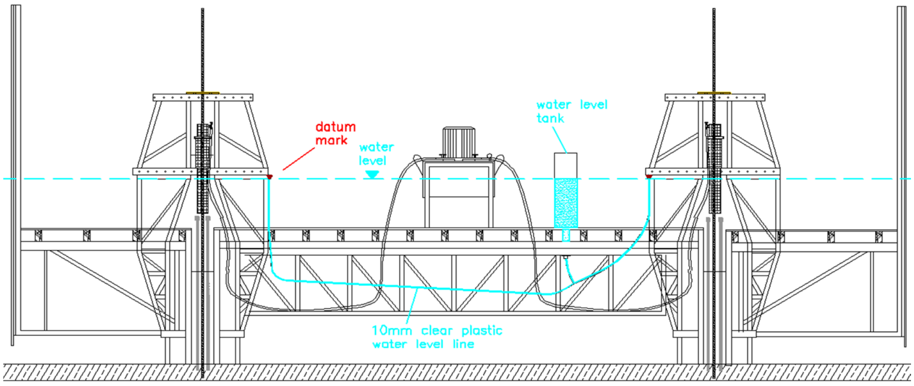

Fig. 4.13 Water level circuit [55]

Each hydraulic jack can be adjusted individually. This enables accurate control of the slipform. For the vertical control, also plumb bobs can be installed. Such plumb bobs are located at the four outermost spots of a core wall. They have to be situated in a corner to be able to make biaxial measurements. Measured is the distance from the plumb bob to the two adjacent walls. The plumb bobs are hanging directly below the shutter. At the beginning of the sliding process, an initial measurement has to be done. This measurement is the basis for following measurements and gives information about the vertical deviations of the construction.

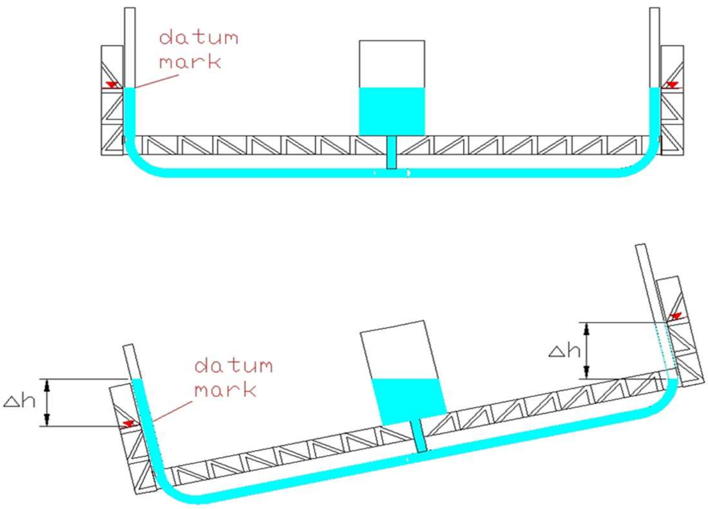

Fig. 4.14 Functional principle of the water level circuit [56]

[55] DOKA 2013

[56] DOKA 2013

4.3.12 Changing of Wall Thickness

Insertforms enable reductions of the wall thickness by using slipform systems. Changing walls need to be considered in early stages of planning. When wall reductions are expected, only steel shutters are used. Those insertforms are also steel elements which are inserted on the inside of the yoke beams. They are connected to the formwork sheet and stay in this position until further changes of the wall occur.

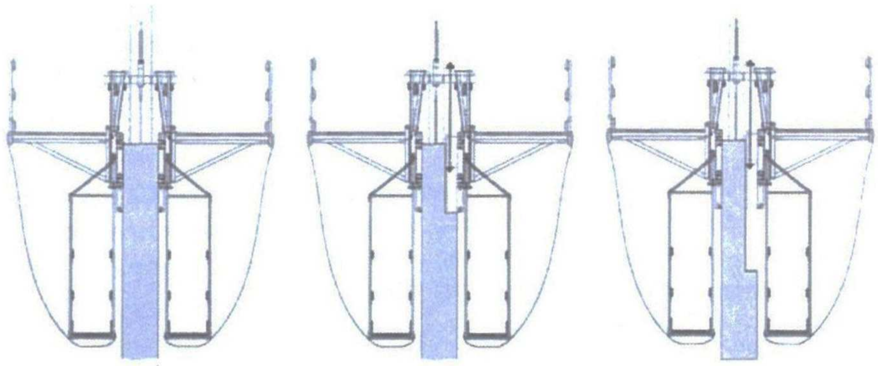

Fig. 4.15 Installation of insertform [57]

Figure 4.15 shows the principle how the installation of an insertform works. In the left sketch, the slipform is in its initial state, in the second it can be seen where the insertform is installed. The third sketch illustrates how the slipform with mounted insertform appears in later stages.

4.3.13 Inclined Constructions

For structures with an axis spatially inclined against the vertical, the conical slipform was developed. There is a significant difference between the conventional slipform in how the yoke beams are arranged. The vertical elements of the yoke construction are connected with two horizontal yoke beams. The result is a frame made of two vertical and two horizontal yoke elements, which have a distance to each other from approximately 1 metre. In kinematic terms it is a moveable parallelogram. Above the yoke beams, there is a spindle located to adjust the distance and the inclination of the vertical yoke elements to each other. In this way, the formwork can be adapted to the building geometry.[58]

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[57] Cf. DEUTSCHER BETON- UND BAUTECHNIK-VEREIN: Merkblatt Slipforming Technology, Berlin 2008, p. 23

[58] Cf. Hofstadler, C.: Schalarbeiten. 2008. p. 163

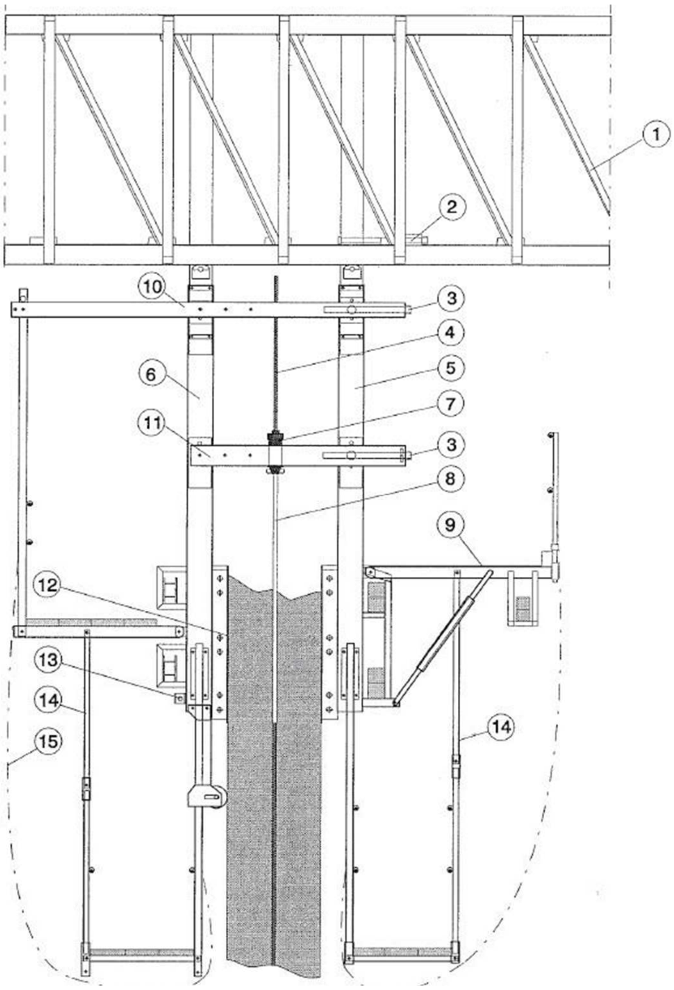

Fig. 4.16 Functional principle of a conical slipform [59]

1	lattice girder	**9**	working platform
2	radial spindle	**10**	upper yoke beam
3	spindle for wall-thickness	**11**	lower yoke beam
4	jacking rod	**12**	facing formwork
5	internal yoke frame	**13**	spindle
6	external yoke frame	**14**	suspended scaffold
7	hydraulic jack	**15**	safety net
8	cladding rod		

[59] TRITTHART, H.: Kritische Analyse und Vergleich der drei Schalungssysteme Gleitschalung – Cantileverschalung – konventionelle Schalung in technischer, baubetrieblicher und wirtschaftlicher Hinsicht. Diplomarbeit. 1994. p. 17

4.4 Advantages of Slipforming Technology

In this chapter advantages of slipforming technology are discussed. Even though economic aspects are considered as an advantage of slipform technology they are not mentioned in this chapter because costs are always project specific.

4.4.1 Shorter Construction Times

Slipforming is a continuous construction process and, if possible, three-shift operations are done. From a technological point, a progress of 7 to 8 m of building height can be done per day. Hence, the overall construction time decreases significantly compared to conventional formwork systems or to jumpform systems. Especially for structures without slabs, ceilings or other horizontal parts which have to be installed subsequently, this is a big advantage, and makes slipforms very lucrative. For residential or financial buildings where slabs and ceilings are always necessary, the formwork must be stopped either way not more than three floors above the last finished ceiling. In this case, slipforms and jumpform systems are almost equal.

4.4.2 One-time Assembling and Disassembling Process

As described in Chapter 3.3.1, a slipform needs to be assembled and disassembled only once for each structure. The continuous sliding process can start after the slipform is fully mounted. When there is a simple homogenous building (e.g. silo) to be constructed, continuous sliding can be continued until the top of the structure is reached.

4.4.3 Monolithic Construction

As a slipform is sliding continuously, concrete can be poured layer by layer. These layers are connected to each other by vibrating. Here, an important point is to pour a concrete layer before the previous layer is hardened because the connection between the concrete layers is done by vibrating. In this way, a building without joints can be constructed. Such monolithic construction cannot be reached by executing projects in jumpform technology because of the necessity of casting steps.

4.4.4 No Anchoring

Mounting suspension shoes and anchors is not only time consuming but also expensive. The fact that anchoring is not needed for slipform systems makes this a significant advantage of this technology, especially in financial terms.

4.4.5 Lifting during Wind

The independence of crane support makes it possible to proceed with the construction work also in times of stronger winds. This advantage especially counts when comparing slipform systems with crane-guided jumpform systems. Another point is the formwork itself. Due to their geometry jumpform systems have a bigger surface area exposed to wind, and wind loads are normally the determining loads for formwork jobs at high-rise buildings. Wind loads are increasing by the level above ground and lifting procedures of jumpform systems have to be stopped and postponed in case of strong wind.

4.5 Disadvantages of Slipforming Technology

There are a number of disadvantages connected with slipforming technology which are described below.

4.5.1 Necessity of Early and Definite Planning

Executing projects with slipforming technology demands accurate knowledge about the project in an early stage. Details need to be planed exactly and special elements must be fabricated. Inclinations, changes of wall thickness, built-in parts, etc. must be known from the beginning. Reacting on plan deviations is more difficult for slipforms than for jumpform systems. Unforeseen incidents or changes can lead to high additional cost. Normally, slipforms allow reacting on changes but the system is less flexible than jumpforms.

4.5.2 Quality of Exposed Surfaces

Reaching standards for exposed concrete surfaces is not possible with the present slipforming technology. Due to the sliding process surfaces are damaged and not smooth. Therefore, subsequent concrete treatment is necessary (cf. Chapter 4.3.10). Another point is the formwork sheets of the shutter. They hardly can be cleaned and a released agent cannot be applied.

4.5.3 Installing the Reinforcement

It’s a fact that buildings constructed with slipform technology require a higher degree of reinforcement than those constructed with jumpform technology. As mentioned in Chapter 4.3.5, the reinforcement must be fixed below the transverse yoke beams. This makes the mounting process much more complicated. Reinforcement cages cannot be prefabricated and reinforcement steel meshes cannot be used. The workforces have to work in an uncomfortable position with a stoop and there is always time pressure because the construction progress of the slipform depends mainly on the speed of the reinforcement workers.

4.5.4 Installation of Built-in Parts and Block-outs

Built-in parts and block-outs are fixed to the reinforcement. Thus, there is always the risk that built-ins and block-outs get displaced. This makes the technology less precise and leads to additional work to patch those inaccuracies.

4.5.5 Flexibility

With modern slipforms it became possible to execute also constructions, which are very complex in geometry, but still, slipform technology has its limits. In Chapter 4.6 the most important limits are listed.

4.5.6 Noise

In residential areas 24-hour operation cycles can be problematic because of noise generation due to construction works. In some cases this may be the reason for changing the formwork system.

4.5.7 Changing the Formwork Sheets

A problematic point in concrete surface quality issues is the difficulty to change the formwork sheets. The higher a building, the bigger is the damage of the formwork sheets. Normally, the formwork sheets do not get changed during the construction process. This leads to a lower quality of the concrete surface. Consequently, a higher effort must be spent for the subsequent treatment of concrete.

4.6 Limits of Slipforming Technology

Even though slipform technology can be applied for a big variety of structures it is less flexible than jumpform technology. There are factors which make the application of slipforms more complicated or even impossible because of technical reasons.

According to the DEUTSCHER BETON- UND BAUTECHNIK-VEREIN, slipforming reaches its limits under the following circumstances:[60]

- Significant changes in geometry of the building. That means many projections on a wall, reduction or extension of wall thickness. When the geometry of the cross-section is unsteady, alternative solutions should be considered.
- A big amount of built-in parts, especially anchor plates and screw glands which must be placed accurately.
- Construction sites where a constant, uninterrupted concrete supply in high quality cannot be ensured.
- Buildings with high quality requirements on the exposed concrete.
- Conical towers with a radius smaller than 20 metres.
- Conical towers with an axis spatially inclined against the vertical ones by more than 18°.

[60] Cf. DEUTSCHER BETON- UND BAUTECHNIK-VEREIN: Merkblatt Slipforming Technology, Berlin 2008, p. 9

4.7 Cost Distribution of Production Costs with Slipforming Technology

When using slipforms only little and low-cost material is required. Both assembly and disassembly are expensive procedures, but they only need to be done once for each project. Built-in parts and box-outs must be positioned as exactly as possible and solidly at the reinforcement. This causes high costs. The nonstop operation is expensive, too. For the accounting, the area which a slipform has slid over is the determining factor. With slipforms, construction projects can be executed very economically, provided that the structure is very high with a constant cross section and a low number of built-in parts or box outs.[61]

Figure 4.17 shows an example how production costs of the construction of a high-rise building core can be distributed when using a slipform.

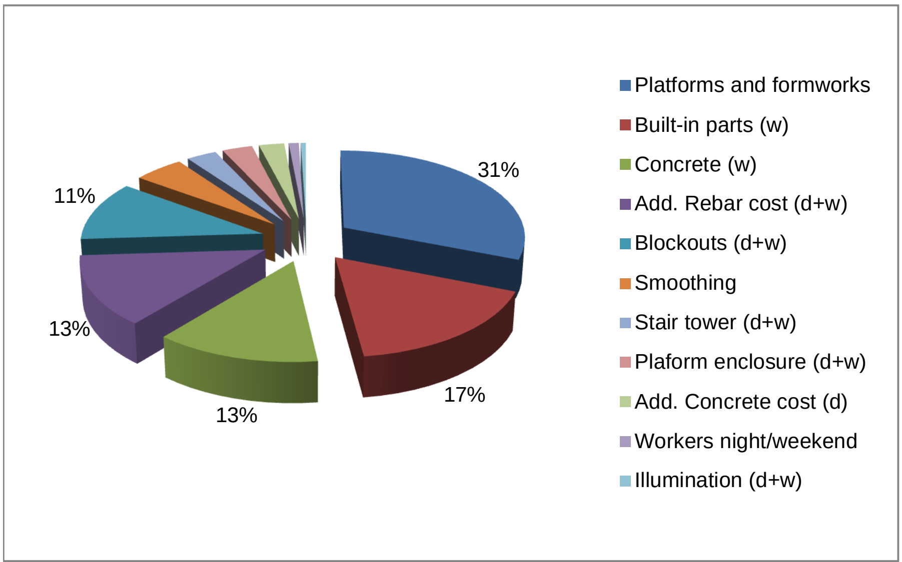

Fig. 4.17 Exemplary cost distribution for a high-rise building core [62]

d… delivery

w… work

[61] MAIER, E.: Climbing formwork, automatic climbing systems or slipforming for high walls p.173

[62] Cf. MAIER, E.: Climbing formwork, automatic climbing systems or slipforming for high walls p.174

5 Climbing Formwork Technology

Climbing technology or jumpform technology is a formwork method developed for constructing high-rise buildings. In this chapter, self-climbing systems are introduced to the reader, the functional principle is explained and the parts of a climbing unit are described.

5.1 General

Usually, slipform technology was used for 24-hour shift operations. Because of the ban on night work in residential areas in the 70s, companies started to develop a system which can be stopped without problems at a certain stage. Therefore, the jumpform system was invented.

Tall concrete structures have historically been formed with crane lifted formwork often referred to as "jump" forms. (…) Numerous improvements have led to the current generation of the Automatic Climbing System which is the state of the art in self-climbing formwork technology.[63]

5.2 Fields of Application

Basically, jump forms or automatic climbing systems can be applied for each structure to be constructed. Especially when constructions are complicated in geometry or when the design is very inhomogeneous, construction companies tend to use these technologies over slipforming technology. Also exposed concrete quality requirements can be fulfilled. There are exclusion criteria based on economic considerations for jumpform technology. For example, for homogeneous buildings with low requirements on concrete quality and a very small amount of built-in parts or box-outs, jumpforms might be uneconomic. Such projects can be silos, water tanks, chimneys, etc.

5.3 Operating and Functional Principle

The functioning of a climbing system is identical with the functioning of a slipform. The distinguishing feature is the guiding function of the slipform. A climbing system is in constant position from the stage of pouring the concrete until the concrete has reached the minimum concrete strength. Once the concrete has hardened, the climbing system can be lifted up to the next casting step. This can either be done with crane support or with

[63] PERI 2002 Nova Award Nomination

hydraulic jacks. The operating principle of a climbing system consists of a height-independent production of vertical or inclined concrete elements in strokes. Defined processes like setting up the formwork, placing the reinforcement, pouring the concrete, stripping the formwork, lifting up the climbing unit and the subsequent treatment of the concrete are sequential processes. Slipforms require these processes which are to be done simultaneously. When applying a climbing system, the central work is the setting up of the formwork. Basically, climbing systems consist of functional systems: wall formwork (framed formwork of timber beam formwork), climbing brackets and a hydraulic unit. [64]

This section provides information on how to proceed when applying a climbing system. Initially, a wall section is done by means of a conventional formwork system. For assembling the climbing system afterwards, anchors and climbing cones are integrated in the wall. Depending on the size of the climbing system, there are one or two anchor points. In the meantime, climbing consoles and working platforms are prepared and the hydraulic devices are installed. After stripping the formwork of the first casting step, guiding shoes are mounted and connected to the climbing console by hanging up.

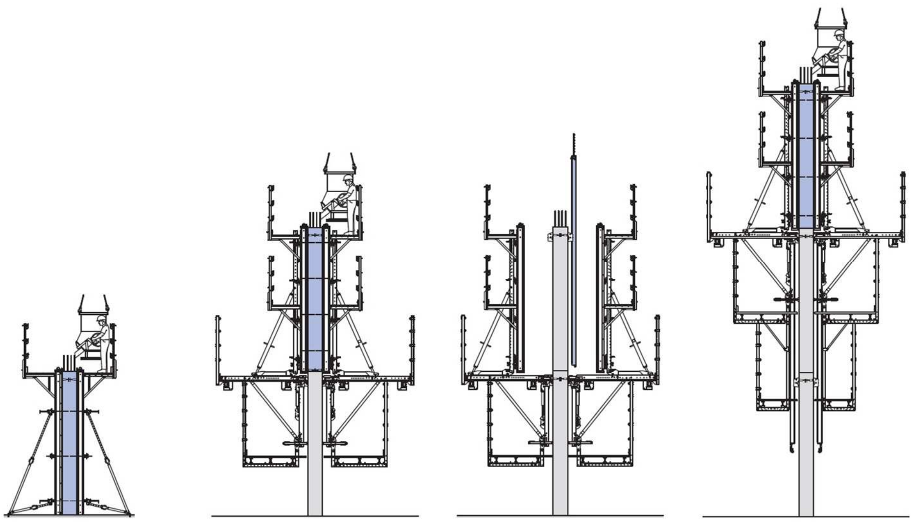

Fig. 5.1 Schematic climbing process initial phase [65]

The wall formwork is now attached to the climbing console and geometrically configured to proceed with the concrete work. Adjustments in horizontal and vertical directions are possible. Now, the reinforcement work can be done, afterwards the wall formwork is closed and it can be

[64] MOTZKO, Ch.: Baubetriebliche Aspekte beim Bau turmartiger Bauwerke. Schalungstechnik - Wirtschaftlichkeit – Arbeitssicherheit. p. 23

[65] DOKA 213

started with pouring in the concrete. As a next step, the formwork of the second concrete section is stripped, the formwork sheeting is cleaned, guiding shoes are mounted onto the climbing cones of the second section and the climbing rail is taken into its correct position. Also, the hydraulic tubes are placed and connected to the hydraulic unit. After these steps, the climbing unit can be repositioned to the next sequence. Depending on the construction conditions, the suspended platforms can be mounted during or after the lifting process.[66]

5.4 Technical Design of a Climbing Formwork System

The current state of art is the automatic climbing formwork system but crane-guided systems are still used frequently. As there is a variety of jumpform systems, standard elements were developed to enable combinations with each other. A climbing unit consists of four main parts: climbing scaffold, which can have several platforms; wall formwork; anchoring; and hydraulic unit.

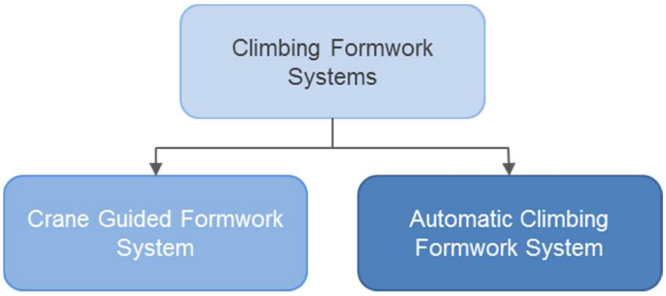

Fig. 5.2 Climbing formwork systems

Climbing systems can either be crane-guided or crane-independent. A new development of a crane-independent jumpform system is the self-climbing platform which is described in Chapter 5.7.

5.4.1 Climbing Scaffold

A climbing scaffold must consist at least of three platforms to make the concrete work possible. These platforms are the **pouring platform**, **working platform** and the **suspension platform**. On heavy climbing systems, additional platforms can be added. There are platforms to facilitate reinforcement work or to increase storing capacity. Furthermore, climbing consoles, safety railings and openings in the platforms can be counted as parts of the climbing scaffold.

[66] Cf. HOFSTADLER, C.: Schalarbeiten. 2008. p. 123 ff

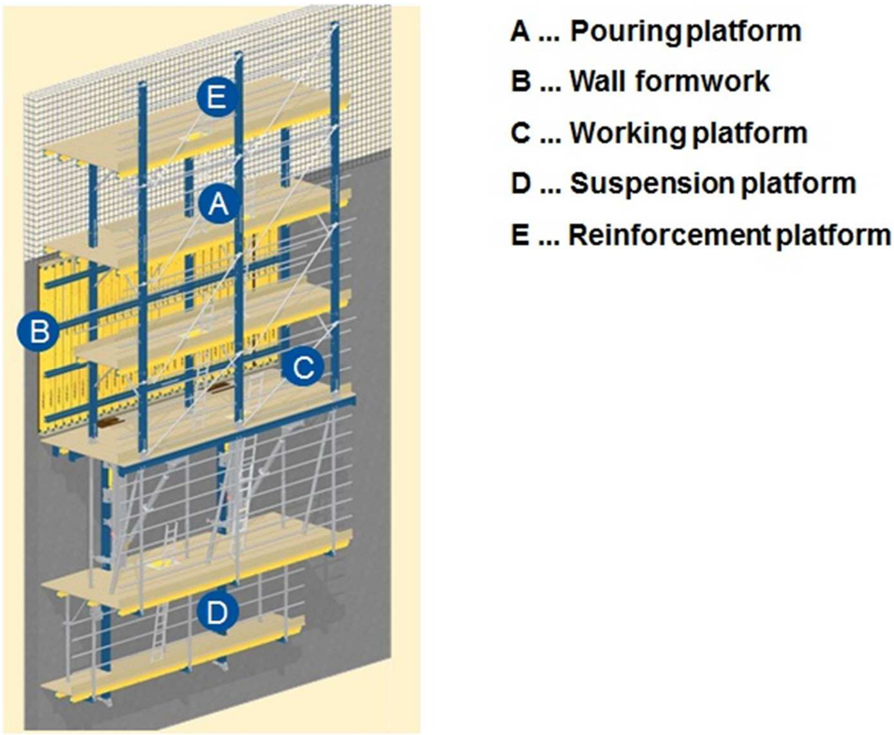

Fig. 5.3 Parts of a climbing scaffold [67]

Working Platform

Attached to the working platform is the wall formwork. Hence, it is the central working place of a climbing unit. Here, all necessary adjustments of the wall formwork are done; the formwork sheeting is cleaned and maintained. Additionally, it serves as a storing place for tools and materials. A working platform also includes an opening and a ladder so that the suspension platform can be reached.

Pouring Platform

The pouring platform is located at the top of the wall formwork. It serves as a safety working area for construction workers who are responsible for the pouring of concrete.

[67] DOKA 2013

Reinforcement Platform

To increase efficiency, heavy climbing systems include a reinforcement platform. It enables to create reinforcement cages one floor ahead.

Suspension Platform

For the recovery of anchors and the execution of subsequent works, a suspension platform must be attached to the climbing scaffold. Depending on the size of the concrete sections, it might be necessary to arrange a second suspension platform.

5.4.2 Wall Formwork

A wall formwork of a climbing unit either consists of frame formwork elements or a timber beam formwork element. For a precise positioning of the wall formwork spindles are provided. With these spindles, vertical and horizontal position as well as inclination can be adjusted. The formwork sheeting depends on the building requirements. It is even possible to reach exposed concrete quality requirement with climbing formwork systems.

5.4.3 Anchoring

To provide a safe and stable position of the climbing unit, anchor systems are applied. The climbing unit is anchored to the building and the loads of the climbing unit are transferred through the anchors into the building. According to SCHMITT, four steps are necessary to install the anchor system:[68]

1. Attaching the anchor system to the formwork sheeting.
2. Preparing the suspension point and the guiding shoe for the next concrete section after pouring and stripping the formwork.
3. Hanging up and securing the climbing console into the guiding shoe.
4. Sealing the remaining hole after repositioning of the guiding shoe.

[68] Cf. SCHMITT, R.: Die Schalungstechnik. Systeme, Einsatz und Logistik. Berlin. Ernst & Sohn, 2001. p. 214

5.4.4 Hydraulic Unit

The most important hydraulic devices of a climbing formwork are the hydraulic unit, the hydraulic cylinder and the hydraulic tubes. For the lifting of the climbing units the position of the hydraulic unit and the lengths of hydraulic tubes play a decisive role. The hydraulic system is a closed ring system: the farther away the hydraulic cylinder from the hydraulic unit, the smaller is the hydraulic pressure action in the cylinder. Because a simultaneous lifting process should be provided valves are used to regulate pressure distribution.

Fig. 5.4 Hydraulic unit, hydraulic cylinder and hydraulic tube [69]

5.5 Crane-guided Jumpform Systems

Crane-guided jumpform systems also known as crane-lifted climbing formwork are used for the erection of tall vertical buildings with a rather low complexity factor and a limitation in height. They are big formwork systems which consist of large formatted wall panels which are attached to slide carriages on working platforms. In each pouring cycle, cones must be installed in the concrete so that the formwork system can be fixed onto the wall for the following pouring step. The formwork platforms are temporary working levels and get raised floor by floor. Each climbing unit must be designed with at least two climbing brackets. There are secondary platforms below which are used to attach the devices for wind protection and to remove the cones from the concrete. Usually, the formwork system is crane-lifted as a whole unit to the next level. Some systems use vertical guiding profiles for safe lifting. Especially when strong winds occur during the lifting process such guiding profiles can be a big advantage in security issues. [70]

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[69] DOKA 2013

[70] MAIER, E.: Climbing formwork, automatic climbing systems or slipforming for high walls: Tiefbau 3/2009. p. 171

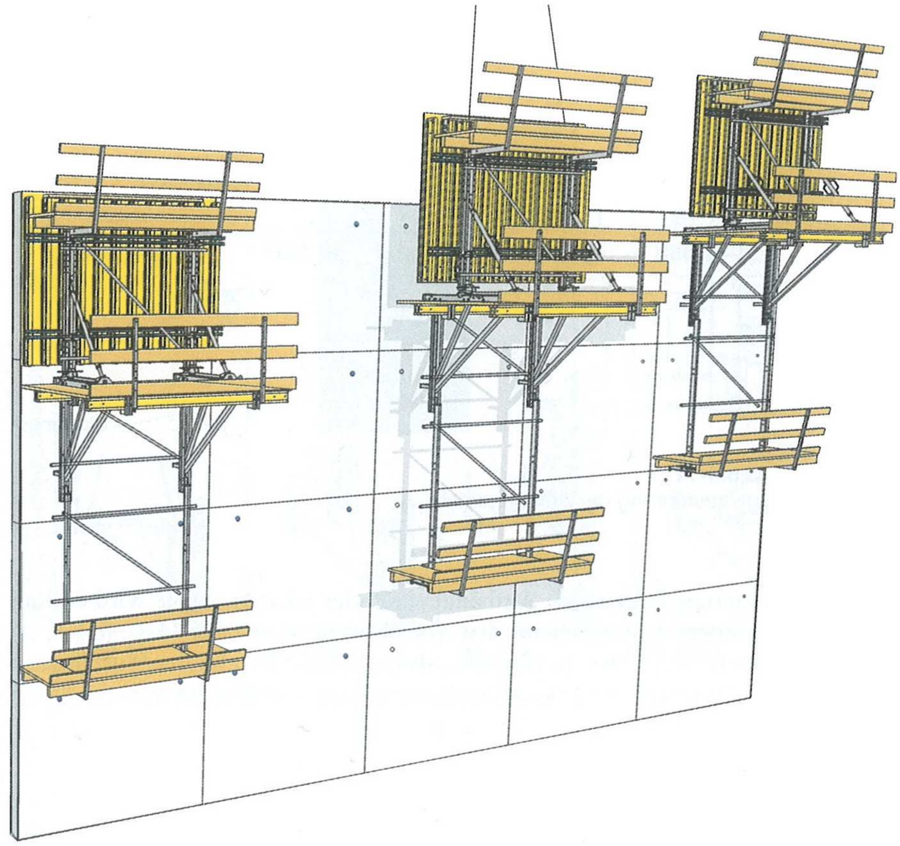

Fig. 5.5 Functional principle of a crane-guided jumpform [71]

Figure 5.5 shows the three steps of a climbing sequence when a crane-guided formwork is lifted. The system shown here is supported with the above-mentioned vertical guiding profiles.

1. Assembling of crane chains
2. Uplift by crane support
3. Disassembling of crane chains

There are several different crane-guided formwork systems offered on the market but the functional principle is always the same. The systems mainly vary in dimensions, geometry and weight but not in functionality.

[71] SCHMITT, R.: Die Schalungstechnik. Systeme, Einsatz und Logistik. Berlin. Ernst & Sohn, 2001. p. 213

5.6 Crane-independent Climbing Systems

Crane-independent climbing systems are also known as self-climbing formwork systems or automatic climbing formwork systems.

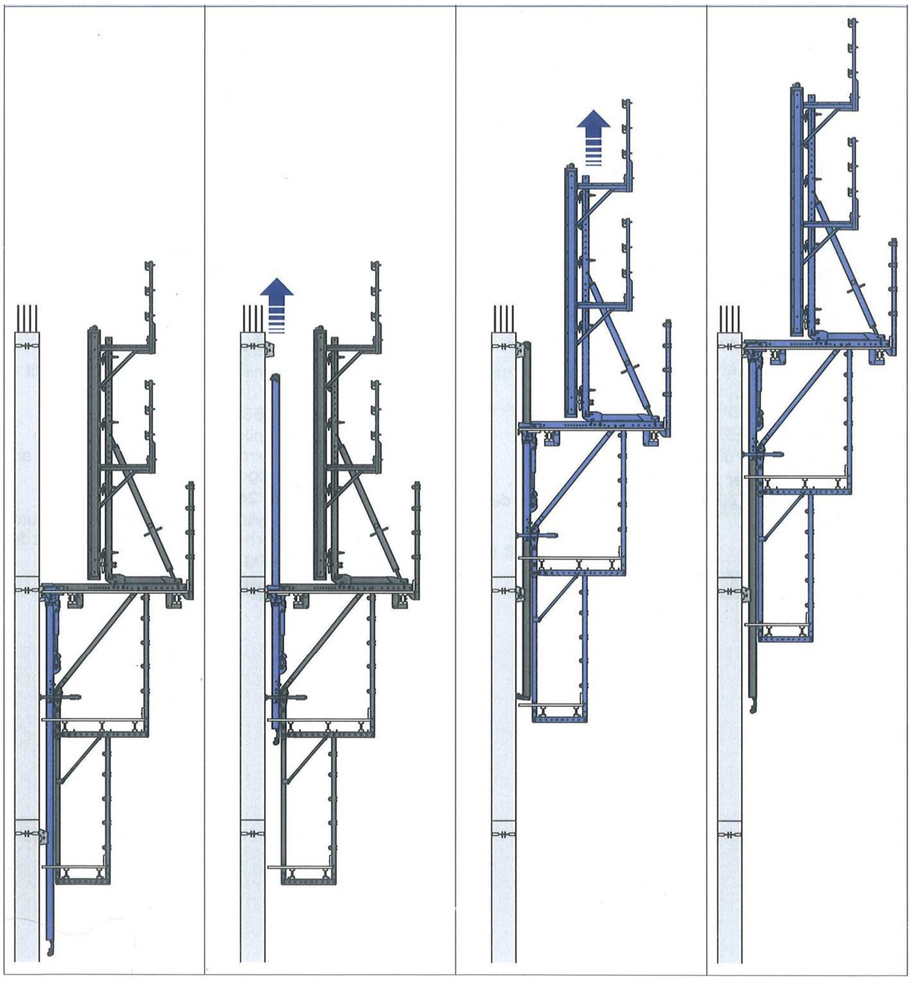

Fig. 5.6 Functional principle of crane independent jumpform of DOKA [72]

In Figure 5.6 the functional principle of a crane-independent jumpform system is illustrated starting from the left sketch:

1. Initial position
2. Climbing ahead of the climbing rail
3. Subsequent climbing of the climbing scaffold and the wall formwork.
4. New position, ready for the next casting step

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[72] DOKA 2013

There are certain circumstances where crane-guided formwork systems cannot be applied. Crane-guided jumpform systems require extensive crane time and they are too slow, unsafe and unproductive for tall structures. The higher a building the more complex and complicated is the planning of material supply. In some cases there is not enough capacity for the required cranes. This also induces to take into consideration the application of crane-independent jumpforms. Such formwork systems use hydraulic devices for the uplift of the platforms. Apart from these hydraulic devices design is very similar to crane-guided formwork systems.[73] Depending on the type of self-climbing system the climbing steps vary between 30 cm and 60 cm.

An automatic climbing formwork not necessarily needs to be lifted by climbing ahead of the climbing rail as demonstrated in Figure 5.6. There are also systems where the climbing rail is part of the climbing scaffold and the hydraulic cylinder is separated. For the lifting process, the hydraulic cylinder is connected to a guiding shoe which is mounted to the concrete wall, and to the climbing rail. Afterwards the guiding shoe is dismounted. In this way, the repositioning of the formwork is done.

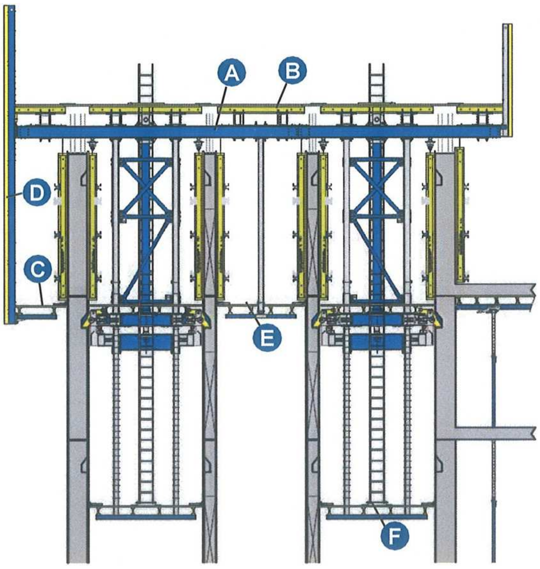
Depending on the required demands, hydraulic devices vary in their jacking capacity. Modern jumpforms with high requirements can be equipped with up to six working platforms.

5.7 Self-climbing Platforms

The latest development of self climbing formwork systems is the self-climbing platform, also known as automatic climbing platform. It is a self-climbing scaffold with integrated platforms specially designed for the production of building cores and tower-like structures. The scaffold carries the whole weight of the structure including dead and live loads. Because of the complete enclosure of the platform protection against wind is provided. Thus, working and climbing can be carried out in almost all weather situations. Additionally, fall hazard is prevented while lifting the platform.

With self-climbing platforms, the core is usually constructed in advance. The wall formwork is hanging on the top platform and the core is ahead of the slab. Walls and slabs of a section can also be poured together in one pouring step. Hence, cost-intensive installations of screw-on connectors between wall and slab can be omitted.

[73] Maier, E.: Climbing formwork, automatic climbing systems or slipforming for high walls: Tiefbau 3/2009. p. 171



A ... Platform grillage WU 300
B ... Working & Storage platform (Level +1)
C ... Facade platform
D ... Protection screen
E ... Working platform (level 0)
F … Suspended platform (level -1)

Fig. 5.7 Components of a climbing platform scaffold of DOKA [74]

In Figure 5.7 the components of the scaffold of a self-climbing platform are shown. Another important part of a self-climbing platform is the lifting system which is not described in this thesis.

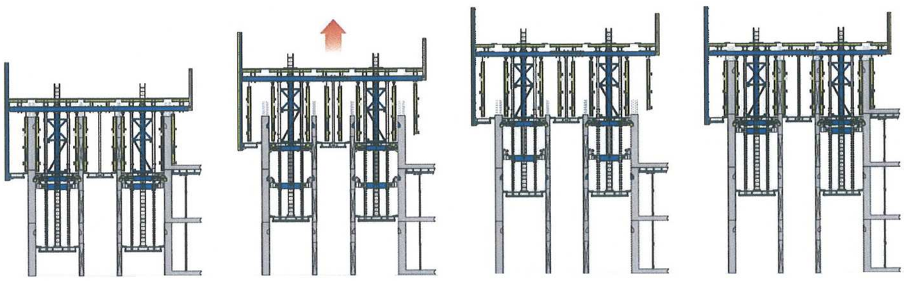


Fig. 5.8 Functional principle of Self-climbing platform of DOKA [75]

The typical operating phases of a self-climbing platform are divided into four steps, which are illustrated in Figure 5.8:

1. Starting position after pouring
2. Climbing situation
3. New working position (climbing procedure not finished)
4. Working position (climbing procedure finished)

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[74] DOKA 2013

[75] DOKA 2013

5.8 Advantages of Climbing Formwork Systems

Construction companies have different points of view regarding advantages and disadvantages of technologies. In many cases there are several factors which influence the conditions of a structure. Thus, only general statements about advantages and disadvantages can be given. Here, only technical features are discussed. Costs and economic issues are neglected because they are mostly project-specific.

5.8.1 Concrete Quality

Climbing technology works with conventional wall formworks which are commonly used for simple structures. With these wall formworks, almost all concrete quality requirements can be achieved. Even exposed concrete quality requirements are possible with climbing formworks whereas slipform technology is far away from such a quality. Concrete quality is a big issue for the selection process of formwork technologies and may be decisive in case of high concrete quality requirements.

5.8.2 Flexibility in Geometry

With modern climbing formworks almost all geometries can be executed. Even curved shapes and inclinations up to 15° are feasible. Not even corner solutions with angles bigger or smaller than 90° constitute a barrier. Normally, the wall thickness of high-rise projects decreases in height. This leads to a projection of a wall. Overcoming of such a wall projection is either done by installing an additional extension shoe which can be adapted to the size of the wall projection, or it can be climbed over. Both ways are applicable only for small wall projections. Bigger steps have to be done by crane support which causes major efforts in terms of time and, therefore, in terms of cost.

5.8.3 Flexibility in Mounting the Reinforcement

Reinforcement jobs can be executed without any barriers or time pressure because of a continuous process like in case of slipform technology. There is enough space for the workforces to assemble the reinforcement. As mentioned in Chapter 5.4.1, heavy climbing systems are even adding additional reinforcement platforms. Normally, the reinforcement cages are mounted on site but it is also possible to insert prefabricated reinforcement cages.

5.8.4 Safe Access to the Work Face

The wall formwork is connected to the working platform by rails. On these rails, the wall formwork can be moved horizontally. The formwork is retractable for about one metre. Hence, a safe working space between the concrete wall and the wall formwork is created. This working space serves for cleaning and maintaining the formwork. In case the wall formwork gets damaged it can be replaced without any problems.

5.8.5 Independence of Permanent Concrete Supply

A big advantage over the closely competing slipforming technology is the independence of permanent concrete supply. Once a section is poured, concrete supply will not be necessary until intermediate jobs like reinforcement jobs or maintaining the formwork are done. Interruptions during the normal working cycle do not lead to a bottleneck situation like in case of slipforming technology. The same conditions as for conventional concrete jobs can be assumed.

5.8.6 Accurate Placing of Built-in Parts and Box-outs

Box-outs and built-in parts are connected to one side of the formwork and not to the reinforcement. When the reinforcement work is finished and concrete is poured in and the wall formwork is closed it keeps staying in the same position until concrete has reached the necessary concrete strength. Therefore, there is no risk of displacement of built-in parts or box-outs when they are mounted accurately onto the formwork.

5.9 Disadvantages of Climbing Formwork Systems

In this chapter the most important disadvantages of climbing formwork technologies are listed and described. Like in Chapter 5.8 economic issues are not discussed.

5.9.1 Necessity of Anchors

Because climbing units are lifted along a building they need to be connected with it. This is done by means of suspension shoes which are jointed with anchors. These anchors have to be mounted very exactly while the wall formwork is adjusted and the reinforcement work is carried out. All loads which are coming from the climbing unit are transferred into the building through these anchors. The necessity of these anchors is not only cost-intensive but the mounting process is also time-consuming and, therefore, a disadvantage for this technology.

5.9.2 Non-monolithic Structure

When constructing a structure with climbing formwork technology, it is done in casting steps. This is an unavoidable characteristic of a climbing formwork system. Therefore, structures are non-monolithic. For common building cores or façades this doesn’t have any impact but structures like silos or water tanks, for example, have higher demands on building density which cannot be achieved by climbing formwork technologies.

5.9.3 Limits when Lifting during Wind

Heavy automatic climbing formwork systems are lifted in two steps. First, a rail is lifted up and fixed to the suspension shoe of the next concrete section. Subsequently, the formwork scaffold is lifted along this rail. This provides for high security during lifting because of the close contact to the structure through the suspension shoe. Nevertheless, automatic climbing systems enable lifting only up to a wind speed of approximately 70 km/h whereas slipform technology can be lifted independently of wind. Crane-guided jumpforms which are not guided along a climbing rail are not suited for areas of high wind speeds.

5.9.4 Construction Time

Applying a climbing formwork system definitely leads to longer construction times than in case of a slipform. With climbing formworks progress of approximately **six metres per week** can be achieved, with a slipform it is between **four and seven metres per day**, and even more. When constructing a building core, this does not constitute a problem because a core can only be built around three floors ahead the slabs. But for buildings without slabs, like silos, tanks, wind wheels or chimneys, climbing formwork solutions cannot compete with slipform technologies.

5.10 Limits of Climbing Formwork Technology

Climbing formwork technology is stretched to its limits when extreme situations resulting from the above-mentioned disadvantages occur. For instance, when the construction site is in areas where permanent high wind speeds are expected, or when monolithic structures are demanded. However, the most decisive exclusion criterion for climbing formworks is construction time. Long construction times lead to higher expenses and to interruptions for the users of the structure. Therefore, construction time can be considered as a limit for the application of a climbing formwork.

5.11 Cost Distribution of Production Costs with Climbing Formwork Technology

Compared with a slipform, the cost distribution of the production costs is quite different from Climbing formworks. It is necessary to consider the differences between a crane guided formwork solution and an automatic climbing system. When there is enough crane capacity to lift the formwork, crane dependent climbing formwork is usually the right choice in economic terms. Therefore, it needs to be clarified whether concrete is supplied by concrete pumps or crane support is demanded, and which type of reinforcement is used. There is a difference if steel bars, meshes of cages are installed. [76]

Figure 5.9 shows an example how production costs of the construction of a high-rise building core can be distributed when using a climbing formwork system.

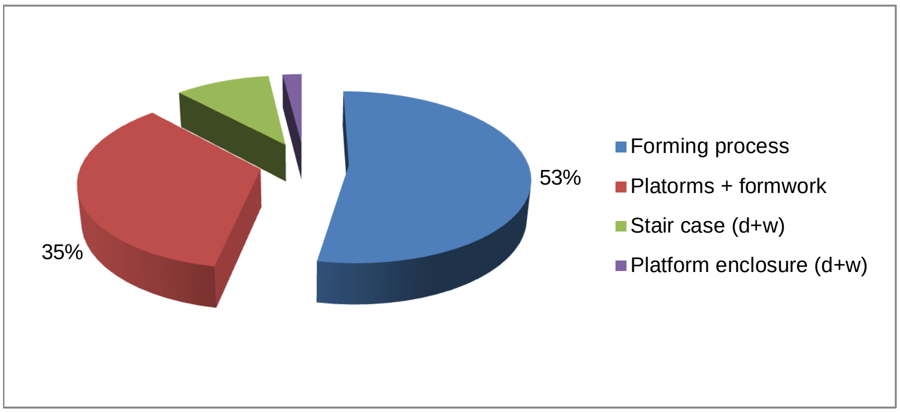

Fig. 5.9 Cost distribution for an exemplary shaft [77]

d… delivery

w… work

[76] Cf. MAIER, E.: Climbing formwork, automatic climbing systems or slipforming for high walls p.172

[77] Cf. MAIER, E.: Climbing formwork, automatic climbing systems or slipforming for high walls p.173

6 Comparison of Slipform Technology and Climbing formwork Technology

Table 6.1 Pro & Contras: Slipforming vs. Climbing System [78]

	Slipformwork	Automatic Climbing system	Crane climbing system (guided)	Crane climging system (not guided)
Concrete surface	follow-up treatment necessary	freely controllable	freely controllable	freely controllable
Concrete pressure	no anchoring necessary	anchoring necessary	anchoring necessary	anchoring necessary
Concrete sequence	monolithic	casting steps (horizontal joints)	casting steps (horizontal joints)	casting steps (horizontal joints)
Plywood	changing only possible when formwork is totally free	changing always possible	changing always possible	changing always possible
Reinforcement	single reinforcement bars	no restrictions	no restrictions	no restrictions
Working time	shift operation necessary	no restrictions	no restrictions	no restrictions
Disturbances during the working process	quality loss	no restrictions	no restrictions	no restrictions
Construction time	approx. 4-7 m/day	up to 5.50 m/week	up to 6.0 m/week	up to 6.0 m/week
Lifting during wind	no restrictions	up to 72 km/h possible	up to 72 km/h possible	up to 72 km/h possible
Building geometry	low flexibility on changes	high flexibility on changes	high flexibility on changes	high flexibility on changes
Design	early finsihed planning necessary	high flexibility on changes	high flexibility on changes	high flexibility on changes
Formwork operation	Team provided by supplier	not provided by supplier	not provided by supplier	not provided by supplier

...to be evaluated as negative

In conclusion, the best approach for formwork system selection is to check all available methods. A detailed project specific analysis of the systems shows if the necessary requirements are met. This implies the consideration of geometry, dimension tolerances, surface quality, type and number of built-in parts and block-outs, complete reinforcement planning as well as structural issues. When a certain method fulfils the technical requirements it must be checked whether the method is reasonably applicable for the construction process of the building. Therefore, the following considerations need to be done: checking the construction schedule; the expected weather; the number and types of cranes; the number, type and location of reinforcement, any jobs that must be carried out simultaneously as well as official approvals that may be necessary. After technical assessment, economic evaluation must be done. The comparison of formwork material costs only does not provide valuable information. It is necessary to do a comprehensive, project-related comparison of overall costs. Only in this way, the adequate formwork solution for a certain construction project can be properly selected. [79]

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[78] Cf. DUPKE, M: Einsatzgebiet der Gleitschalung und der Kletter-Umsetz-Schalung, Ein Vergleich der Systeme, p. 49

[79] Cf. MAIER, E.: Climbing formwork, automatic climbing systems or slipforming for high walls: Tiefbau 3/2009. p. 174

7 Systematic Selection of Formwork Systems

The selection of construction methods, machineries and technologies is of crucial importance in practice, especially in economic terms. Achieving profitable results and the aim of getting a high Return on Investment (ROI) demands the necessity of finding the most efficient and economic methods for the execution of a project.

Structured and systematic approaches are necessary to reach best solutions for each kind of project even it is only a simple organisational project. However, there are supporting tools which facilitate the execution of projects. Such a tool is for example the method of Systems Engineering, which is explained in Chapter 7.1.

Also for decision making, there is a variety of analytic methods, which make it possible to compare systems. This chapter gives an insight into the most important methods for decision making in general. Furthermore, approaches and factors for the systematic selection of formwork systems in the high-rise sector are discussed with consideration of customer requirements, contractor requirements, building requirements as well as environmental requirements.

7.1 Systems Engineering (SE)

> *Systems engineering is a methodical, disciplined approach for the design, realization, technical management, operations, and retirement of a system. A "system" is a construct or collection of different elements that together produce results not obtainable by the elements alone. The elements, or parts, can include people, hardware, software, facilities, policies, and documents; that is, all things required to produce system-level results. The results include system-level qualities, properties, characteristics, functions, behavior, and performance. The value added by the system as a whole, beyond that contributed independently by the parts, is primarily created by the relationship among the parts; that is, how they are interconnected.*[80]

7.1.1 Origin and Fields of Application

Systems Engineering evolved around 1940 in the United States of America in the Bell laboratories when the telephony service was developed. Later, it was refined and developed further by the NASA, where it was used for the development of the space shuttle in the Apollo-program. Systems Engineering also found its application in the European astronautics for the development of the Ariane-rocket. Nowadays,

[80] NASA: Systems Engineering Handbook. NASA/SP-2007-6105 Rev1. 2007. p. 3

Systems Engineering is spread all around the globe, but there are different approaches of the methodology. In 1969, a central concept was developed at the Centre for Industrial Management at Swiss Federal Institute of Technology (ETH) Zurich. This concept is used in various branches. Planning- and organisational problems are solved with the methodology of Systems Engineering, furthermore, industrial companies, the public administration and many others take use of it, but there is not yet an explicit application of Systems Engineering in fields of civil engineering.[81]

7.1.2 The Systems Engineering Concept

The **SE-philosophy** represents the spiritual superstructure of the SE-methodology, which is illustrated in Figure 7.1. It is based on a **systematic and holistic way of thinking** and the **SE-action-model** (Figure 7.2).

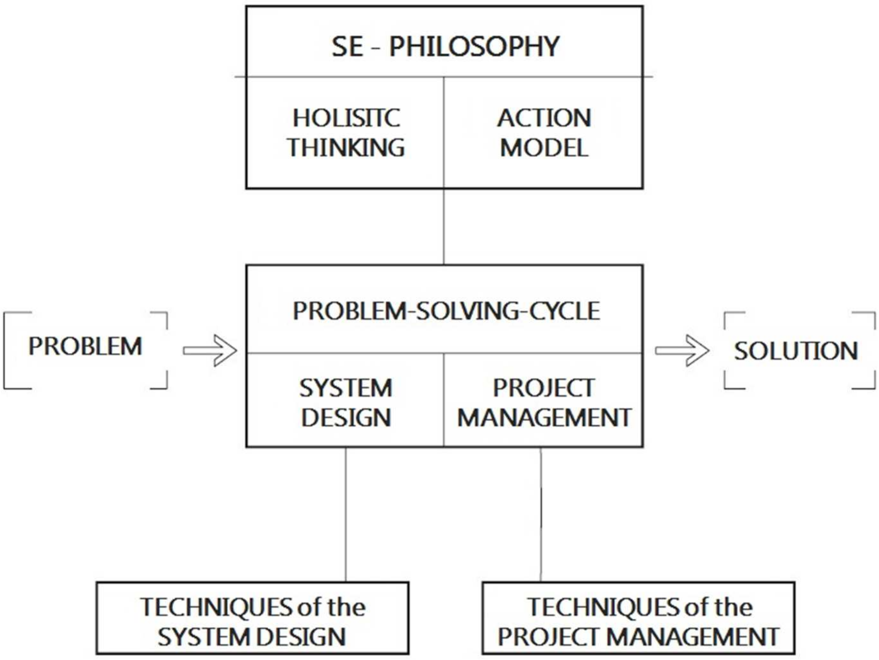

Fig. 7.1 SE-concept [82]

[81] Cf. HOFSTADLER, Ch.; SCHÜTZ, M.: In: Bautechnik 89. Heft 11. Anwendung des Systems Engineering auf die Arbeitsvorbereitung von Bauprojekten. Ernst Sohn Verlag. Berlin, 2012. p. 1 f

[82] Cf. HABERFELLNER, R. u.a.: Systems Engineering. Methodik und Praxis. 11. Auflage. Verlag Industrielle Organisation. Zürich, 2002. p.33

A systematic and holistic way of thinking is based on the approach, that complex coherences as an abstraction of the reality are illustrated as system models. It is applied in the **problem-solving-cycle** of Systems Engineering for the system design of the analysis, for the structuring and definition of the problem as well as for finding the solution.[83]

The SE-action-model, which is explained in Chapter 7.1.3, is the second idea of the SE-philosophy. It is based on following four thoughts:

- Top-down approach
- Principle of creating variations
- Principle of dividing a project into phases (macro-logic)
- Problem-solving-cycle (micro-logic)

Those four components are a coherent unit and can be combined arbitrary. The **problem-solving-cycle** is the core of the SE-methodology. It consists of the components **system design** concerning the contents and **project management** on the organisational side. System design is the application of the SE-acting model supported by the principle of thinking in a systematic and holistic way for the analysis, structuring and the solution of a problem. Project management is the organisational component and its task is the management of the problem-solving-cycle. This includes the planning, disposition as well as steering and controlling the material, personnel, financial and temporal resources. Both, the system design as well as the project management can be considered as a unit and are worked out by the same project staff.[84]

7.1.3 The SE-action-model

The SE-action-model is based on the four above mentioned principles which are now described more detailed.

Top-down Approach

The top down design is an approach breaking down a system into its compositional subsystems. First, an overview of the system is formulated, specifying but not detailing a first-level subsystem. It is a stepwise design of a project and in some way decomposition. Each

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[83] Cf. HOFSTADLER, Ch.; SCHÜTZ, M.: In: Bautechnik 89. Heft 11. Anwendung des Systems Engineering auf die Arbeitsvorbereitung von Bauprojekten. Ernst Sohn Verlag. Berlin, 2012. p. 2

[84] Cf. HOFSTADLER, Ch.; SCHÜTZ, M.: In: Bautechnik 89. Heft 11. Anwendung des Systems Engineering auf die Arbeitsvorbereitung von Bauprojekten. Ernst Sohn Verlag. Berlin, 2012. p. 2

subsystem is refined and formulated in greater detail. There may be many additional subsystem levels until the project is reduced and decomposed into its base elements.[85]

Systems Engineering suggest to operate with the top-down approach and not with the contrary bottom-up principle.

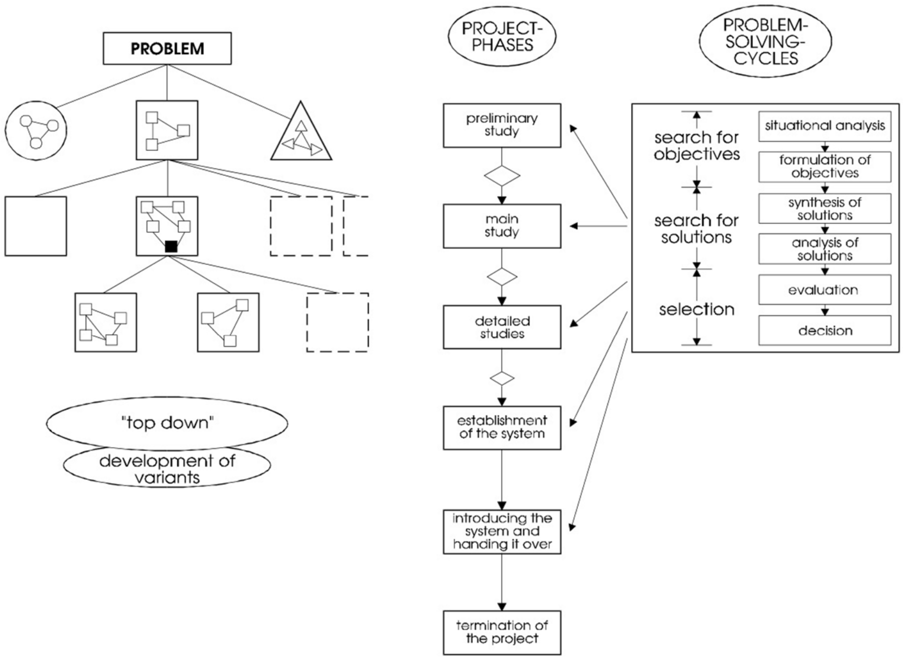

Fig. 7.2 Connection between several components of the SE-action-model [86]

Principle of Creating Variations

It is reasonable to work always with more variations. The first solution is not necessarily the best solution, thus, creating alternative variations enables to compare and to figure out pros and cons.[87]

Principle of Dividing a Project into Phases (Macro-logic)

As an extension of the first two mentioned principles, time can be introduces as a component. Structuring and arranging projects into time

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[85] http://en.wikipedia.org/wiki/Top-down_and_bottom-up_design (08.11.2013)

[86] HABERFELLNER, R.; DE WECK O.: Agile SYSTEMS ENGINEERING versus AGILE SYSTEMS engineering Incose 2005. p.4

[87] Cf. HOFSTADLER, Ch.; SCHÜTZ, M.: In: Bautechnik 89. Heft 11. Anwendung des Systems Engineering auf die Arbeitsvorbereitung von Bauprojekten. Ernst Sohn Verlag. Berlin, 2012. p. 2

and project phases enables a stepwise planning-, decision-making- and realisations process.[88]

Problem-solving-cycle (Micro-logic)

The problem-solving-cycle of the SE-action-model is based on Dewey's problem solving and represents a kind of micro-logic in each project phase. For the solution of each kind of problem, the problem-solving-cycle should be applied.[89]

7.2 Systematic Selection of Construction Machines

The acquisition of construction machines is a very important issue in practice. Construction machines became indispensable in modern construction business but they also cause high costs, thus, they must ensure their profitability. Construction companies, technical departments of entrepreneurs as well as rental companies have to grapple intensively with this subject matter in order to select the optimal construction machine from a variety of producers and manufacturers with the market. Also manufacturers and dealers should give sufficient attention to this matter to remain competitive on the market.[90]

Construction machines are of crucial importance for construction companies. They undertake tasks, which cannot be executed by handwork of the workforces, or only with a very high effort of time, personnel and costs. The application of construction machines is connected with high permanent costs and variable costs, thus, they must ensure a certain Return on Investment (ROI) to provide profitability. On the one hand, it is crucial to find a perfect combination of the construction machines and the construction method, on the other hand, to purchase the ideal construction method offered on the market. In this way, efficiency and cost-optimizing can be achieved and higher margin can be earned. The three common ways of acquiring construction machines are buying, renting and leasing. [91]

Acquisition is a continuous, complex process of a customer-orientated marketing with the target to get a profitable ROI.[92]

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[88] Cf. HOFSTADLER, Ch.; SCHÜTZ, M.: Anwendung des Systems Engineering auf die Arbeitsvorbereitung von Bauprojekten. In: Bautechnik 89. Heft 11. Ernst Sohn Verlag. Berlin, 2012. p. 2 f

[89] Cf. HOFSTADLER, Ch.; SCHÜTZ, M.: Anwendung des Systems Engineering auf die Arbeitsvorbereitung von Bauprojekten. In: Bautechnik 89. Heft 11. Ernst Sohn Verlag. Berlin, 2012. p. 3

[90] Cf. HOFSTADLER, Ch.; HILLINGER, Ch.: Systematische und nachhaltige Baumschienenwahl. In: Bau aktuell. 4. Jahrgang. März 2013. Nr:2. p. 48

[91] Cf. HOFSTADLER, Ch.; HILLINGER, Ch.: Systematische und nachhaltige Baumschienenwahl. In: Bau aktuell. 4. Jahrgang. März 2013. Nr:2. p. 48

[92] Cf. HECK, D.; SCHLAGBAUER, D.: Bauwirtschaftslehre VU (Master). Skriptum. TU Graz. 2011. p.158

7.2.1 Productivity as the Basic Prerequisite

Productivity is the essential ratio for the assessment of certain works and the whole production process. It is the relation between Output and Input, and is based on complex coherences. The aggregate productivity consists of the elementary productivity and the discretionary productivity as shown in Figure 7.3.[93]

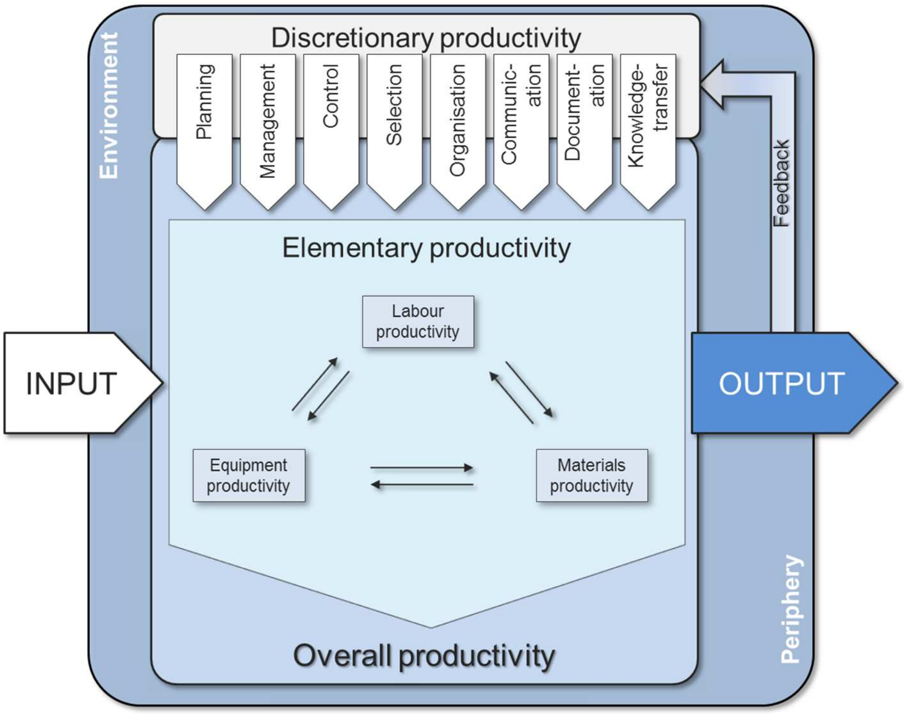

Fig. 7.3 Productivity and its elements [94]

Elementary productivity includes labour, equipment and materials and is influenced by the discretionary productivity, which is responsible for planning, managing, controlling, organising, etc. As it is illustrated in Figure 7.3, all components are coherent and cannot be optimized independently. The **labour consumption value** is the determining ratio for productivity due to labour.[95]

[93] Cf. HOFSTADLER, Ch.; HILLINGER, Ch.: Systematische und nachhaltige Baumschienenwahl. In: Bau aktuell. 4. Jahrgang. März 2013. Nr:2. p. 48

[94] Cf. HOFTADLER, Ch.: Produkivität im Baubetrieb. Bauablaufstörungen und Produktivitätsverluste. Berlin, Heidelberg. Springer. 2014. p. 15

[95] Cf. HOFSTADLER, Ch.; HILLINGER, Ch.: Systematische und nachhaltige Baumschienenwahl. In: Bau aktuell. 4. Jahrgang. März 2013. Nr:2. p. 48

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It is the **relation between the labour-time and a certain unit**. In terms of shuttering works the labour consumption value is calculated in labour hours per square meters [Lh/m²].

Increase in productivity can be a result of so called factors of rationalization. Factors of rationalization can be technical, social as well as organizational and they are influencing the elementary factors of productivity, as shown in Figure 7.4. They either occur individually or combined and can have a positive effect on productivity.[96]

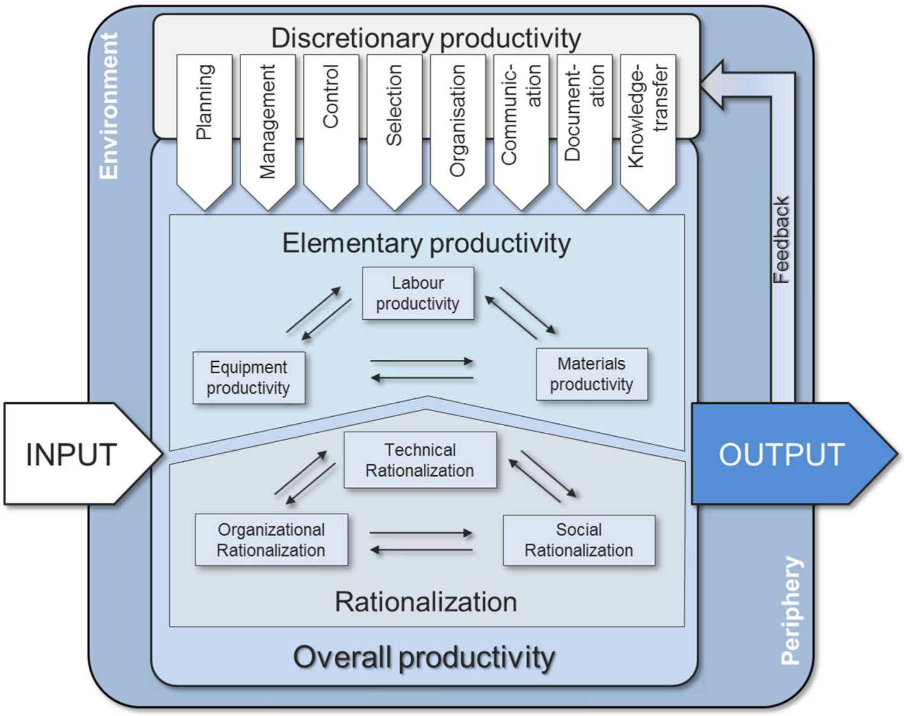

Fig. 7.4 Influence of rationalization on productivity [97]

7.2.2 Who Makes the Decision?

Generally, when purchasing construction machinery, several people from different departments with different knowledge and from a different level of information, are involved. Deciding whether a product is bought or not, is done by a single person, the decision maker. Opinions of the other involved people should not be disregarded when the decision is made. Thus, medium-sized and large companies work with a so called **Buying**

[96] Cf. GAEDE, W.; TOFFEL, R.: Zur Dynamik der Baupreise. Bauwirtschaft 12. 1985 .In:HOFSTADLER, Ch.: Bauablaufplanung und Logistik im Baubetrieb. Berlin, Heidelberg. Springer. 2007. p. 30

[97] Cf. HOFTADLER, Ch.: Produkivität im Baubetrieb. Bauablaufstörungen und Produktivitätsverluste. Berlin, Heidelberg. Springer. 2014. p. 31

Center, which includes the *user*, *buyer*, *influencer, decider* and the *gatekeeper*. MAURER presents the relation between people, who are involved in a purchasing process of construction machinery as follows: [98]

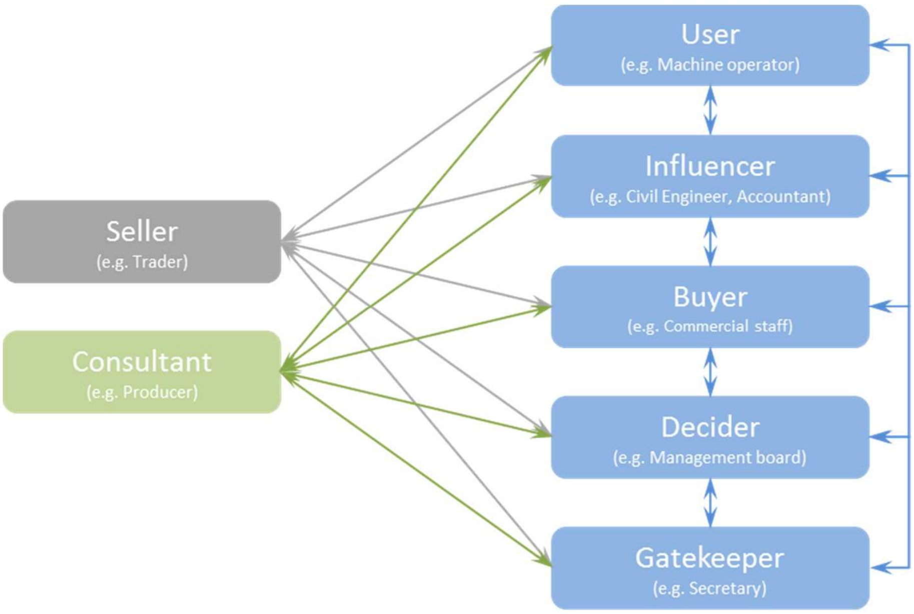

Fig. 7.5 Information exchange, purchasing process of construction machinery [99]

The arrows in Figure 7.5 symbolize how usually the interaction and communicating among members of the buying center works. Depending on the complexity of a purchasing decision, the intensity of the interaction between those people varies. In small-sized companies, a single person may hold the responsibility for more positions, thus, this person has greater influence on the purchasing decision.[100]

To give a better understanding what a buying center is, and what functions the members within a buying center have, more detailed information is provided hereinafter. Initially, the definition of a buying center is stated:

> *A buying center is a group of people in an organization who are responsible for making purchases. Centers are usually comprised of more than one individual. Each member of the buying center plays a specific role in the purchase decision.*[101]

[98] Cf. HILLINGER, Ch.: Schematischer Vergleich von Baumaschinen im Beschaffungsvorgang. Diplomarbeit. TU Graz. 2012. p.18

[99] Cf. MAURER, H.: KRACA, M.: Beschaffungsverhalten von Unternehmen der Baubranche. In: BMT Baumaschine + Bautechnik, 7-8/1996. p. 15

[100] Cf. HILLINGER, Ch.: Schematischer Vergleich von Baumaschinen im Beschaffungsvorgang. p.18

[101] http://www.wisegeek.com/what-is-a-buying-center.htm (10.12.2013)

Users

Often the users are initiating the buying process and formulate the specific purchase requirements, but their influence is not limited to those particular roles. In some cases, other members of the buying center may not be able to make a qualitative estimation of what a specific features a purchased good must include. Therefore, users can influence the buying decision in both, a positive or a negative manner. A positive way is to suggest the need for purchased goods by defining quality requirements, a negative way is to refuse a product for any reasons.[102]

Influencers

Influencers do not necessarily have a central function in the decision process, but they are often experienced staff with valuable opinions. By defining criteria which constrain the choices that can be considered in the purchasing decision or by suggestion alternative buying options and providing important information, they may have great impact on the deciding process. For example in manufacturing organisations, the technical personnel has significant impact on the purchasing decision. Other influencers can be research and development personnel, design engineers, product engineers, civil engineers as well as the manufacturing management. All of them may emphasize different factors to be considered in the buying decision, but their opinion is from significant importance.[103]

Buyers

Buyers have the formal authority for selecting suppliers and to define the purchasing conditions. But they are also restricted by the influence of other organisational members of the buying center. The operational function of a buyer may be a Purchasing Manager, Purchasing Agent, or this responsibility and authority may reside with people other than those designated specifically as buyers, a vice president-manufacturing, an office manager, or some other official for example. The buying process depends on the buying tasks. This can be a simple routine process with already known traders and buying conditions as well as a very complex process, with the need of negotiating prices and other conditions of sale, or even the necessity of defining specifications simultaneously and evaluating available alternatives in order to reach the most economical solution in the buying process.[104]

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[102] Cf. WEBSTER, F.; WIND, Y.: Organisational buying behaviour. Englewood Cliffs, NJ. Prentice-Hall, 1972. p.78

[103] Cf. WEBSTER, F.; WIND, Y.: Organisational buying behaviour. p.78

[104] Cf. WEBSTER, F.; WIND, Y.: Organisational buying behaviour. p.78

Acquiring construction machinery can definitely be counted as a complex purchasing process, because the high costs of investment demands a detailed analysis of the topic. Furthermore, the great offer of construction machinery on the market requires a comprehensive knowledge about the available products necessary. In a construction company, usually the commercial staff is responsible for the buying process. Also here, there are other parties who have an influence on the purchase of a construction machine. An important point is the consideration useful life of a construction machine. Therefore, the evaluation of the Life Cycle Cost is essential, and not the acquisition costs.[105]

Deciders

Deciders are organisational member who have the authority to determine the final selection of suppliers. It is possible that the buyer and the decider is the same person, but the decision can also be made by someone else and be left to the buyer for implementation. In praxis it is not always clear who has the responsibility for the decision and when it is actually made. [106]

Depending on the size and the organisation of a construction company, deciders may be the head of technical or commercial departments, the Managing Director, the Management Board or the CEO.[107]

Gatekeepers

Gatekeepers are responsible for the flow of information with the group. A typical gatekeeper in a formal organisation is for example the buyer or purchasing agent who manages the relationships of the firm between vendors and potential vendors. Gatekeepers are not necessarily purchasing agents. Also salesmen and the general management can be significant sources of information. Identifying buying alternatives is the central point of a gatekeepers work. They have big influence on the definition of the feasible set of buying alternatives, the outcome of the purchase decision, on scheduling as well as on all other members of the buying center.[108]

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[105] Cf. HILLINGER, Ch.: Schematischer Vergleich von Baumaschinen im Beschaffungsvorgang.. p.20

[106] Cf. WEBSTER, F.; WIND, Y.: Organisational buying behaviour. p.79

[107] Cf. HILLINGER, Ch.: Schematischer Vergleich von Baumaschinen im Beschaffungsvorgang. p.20

[108] Cf. WEBSTER, F.; WIND, Y.: Organisational buying behaviour. p.79

Decision Stages and Roles in the Buying Center

WEBSTER and WIND set up a table which make obvious the responsibilities of the members within the buying center. The table is structured in the decision stages of a purchasing process and the assignment of the roles of the members within the buying center.

Table 7.1 Decision stages and roles in the Buying Center [109]

	User	Influencer	Buyer	Decider	Gatekeeper
Identification of need	x	x			
Establishing specifications and scheduling the purchase	x	x	x	x	
Identifying buying alternatives	x	x	x		x
Evaluating buying alternatives	x	x	x		
Selecting the suppliers	x	x	x	x	

Table 7.2 Decision stages and roles in the Buying Center of a construction company according to HILLINGER [110]

	User	Influencer	Buyer	Decider	Gatekeeper
Identification of need	x	x			
Establishing specifications and scheduling the purchase	x	x	x	x	
Identifying buying alternatives		(x)	x		(x)
Evaluating buying alternatives			x		
Selecting the suppliers			(x)	x	

Following WEBSTER and WIND, HILLINGER set up a table on how a buying center in a construction company may be organized.

[109] WEBSTER, F.; WIND, Y.: Organisational buying behaviour. p.80

[110] Cf. HILLINGER, Ch.: Schematischer Vergleich von Baumaschinen im Beschaffungsvorgang.. p.21

7.2.3 When Does the Purchasing Process Take Place?

Acquiring construction machinery can either be project independent, based on strategic considerations, or project specific, because it is required by a certain construction project. When special machines are needed, long lead times need to be taken into account.[111]

7.2.3.1 Project Independent Purchase

Project independence means that there is not an upcoming project which requires the application of certain construction machine or construction equipment. There may be considerations regarding the fleet of machines, for example replacing old equipment, bringing the machines on the state of art or other strategic reasons. Such decisions are usually done based on personal experiences. As an example, operating hours of a machine can be mentioned, or quality conditions of a formwork element. Depending on the conditions of the machinery, renewing equipment can be more economic than investing in reparations and maintenance. Whether the machinery is bought, rented or leased is a strategic issue of the decision makers in the company, but certainly the size of the company, solvency as well as order situation have a significant influence on this decision. When investing in new construction equipment, it is of prime importance to know the **useful life** of the machine. The useful life of a machine is the time in which the machine can be used for operating. During this time, the machine is supposed to amortize and to achieve a high ROI. The more a construction machine can be employed, the faster it pays itself off. However, there is no certain rule as to when construction equipment has to be acquired.[112]

Many construction companies have their own formwork equipment in store. They only rent component parts of formwork equipment which are necessary for a certain project, or when their all own equipment is in use because of the order situation. Owning formwork equipment can be advantageous if the construction projects do not require any special formwork solutions; or for the workforces of a company, because they are familiar with the system and perform their work with more efficiency, but in economic terms it is not necessarily more profitable than renting. If a company has its own formwork equipment, there is the necessity of employing it. This makes a company less flexible. If the owned equipment does not match the geometric requirements of a construction or specific tender conditions, the contracting construction company cannot employ its own equipment and is forced to rent.

[111] Cf. HILLINGER, Ch.: Schematischer Vergleich von Baumaschinen im Beschaffungsvorgang.. p.22

[112] Cf. HILLINGER, Ch.: Schematischer Vergleich von Baumaschinen im Beschaffungsvorgang.. p.22

7.2.3.2 Project Specific Purchase

In contrast to project independent construction equipment purchase, project specific purchase can be assigned quite definitely to a certain time in project phases.

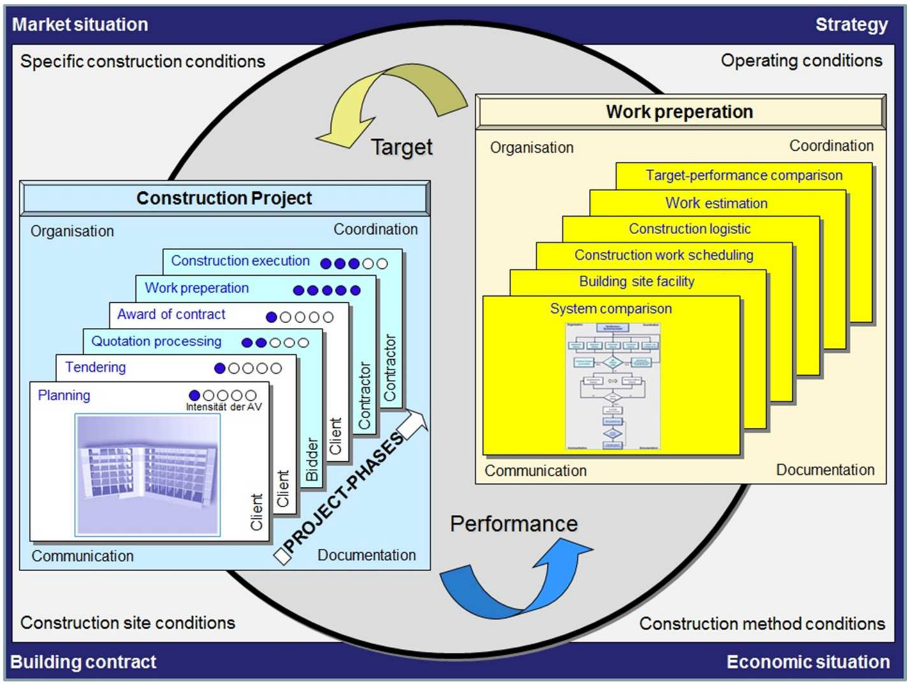

Fig. 7.6 Project phases of a construction project in connection with work preparation [113]

Figure 7.6 shows the connection between the phases of a construction project and the associated work preparation. On the left hand of the figure there is the point “construction project”. The light blue layers (quotation processing, work preparation and execution of construction work) can be assigned to the sphere of the contractor and are determining for the purchase of construction machinery. Construction companies get involved in a project during the quotation processing. Based on a preliminary costing, a quotation costing is done. Therefore, construction methods are compared in order to reach an economic construction process. Applying a certain construction method requires decisions of which construction equipment is used. At this stage of a project, first decisions regarding construction machinery purchase are done.[114]

[113] Cf. HOFTADLER, Ch.: Produkivität im Baubetrieb. Bauablaufstörungen und Produktivitätsverluste. Berlin, Heidelberg. Springer. 2014. p. 16

[114] Cf. HILLINGER, Ch.: Schematischer Vergleich von Baumaschinen im Beschaffungsvorgang.. p.23

After getting the contract, a construction company has to do the work preparation. For shuttering works, HOFSTADLER suggests following steps to be taken:[115]

- Selecting the most economic formwork solution after comparing the systems with regard to aesthetic, technical, safety, environment-specific as well as construction operational boundary conditions
- Planning the construction process
- Planning the usage of resources like workforces, machines and material (formwork logistic)
- Planning of the building site facilities for the formwork

Furthermore, the target-performance comparison needs to be planned. When doing the calculation for the upcoming work, guidelines for the construction work execution are defined (labour consumption value, performance ratios, equipment costs, material costs, etc.). This stage includes all changes regarding the execution of construction.[116]

If there is a need to change construction machinery during the execution of construction, high additional cost can be expected. An example for changing the formwork systems of a construction is the DC Tower in Vienna. Initially, the project was started with a slipform, but during the construction execution it became obvious that the building was not suited for slipform technology based on technical reasons. Thus, the slipform was disassembled and the construction was continued with an automatic climbing formwork system, which led to a big delay in construction time and consequently to additional costs.

7.2.4 Flow Chart for Construction Machinery Purchase

When a construction company plans to invest in new construction machinery, a systematic and strategic approach is indispensible in order to avoid unnecessary effort in work and additional costs. Therefore, HILLINGER established a flow chart, which should serve as a guideline for the purchase process of construction machinery.

[115] Cf. HOFSTADLER, C.: Schalarbeiten, p. 11

[116] Cf. HOFSTADLER, C.: Schalarbeiten, p. 11

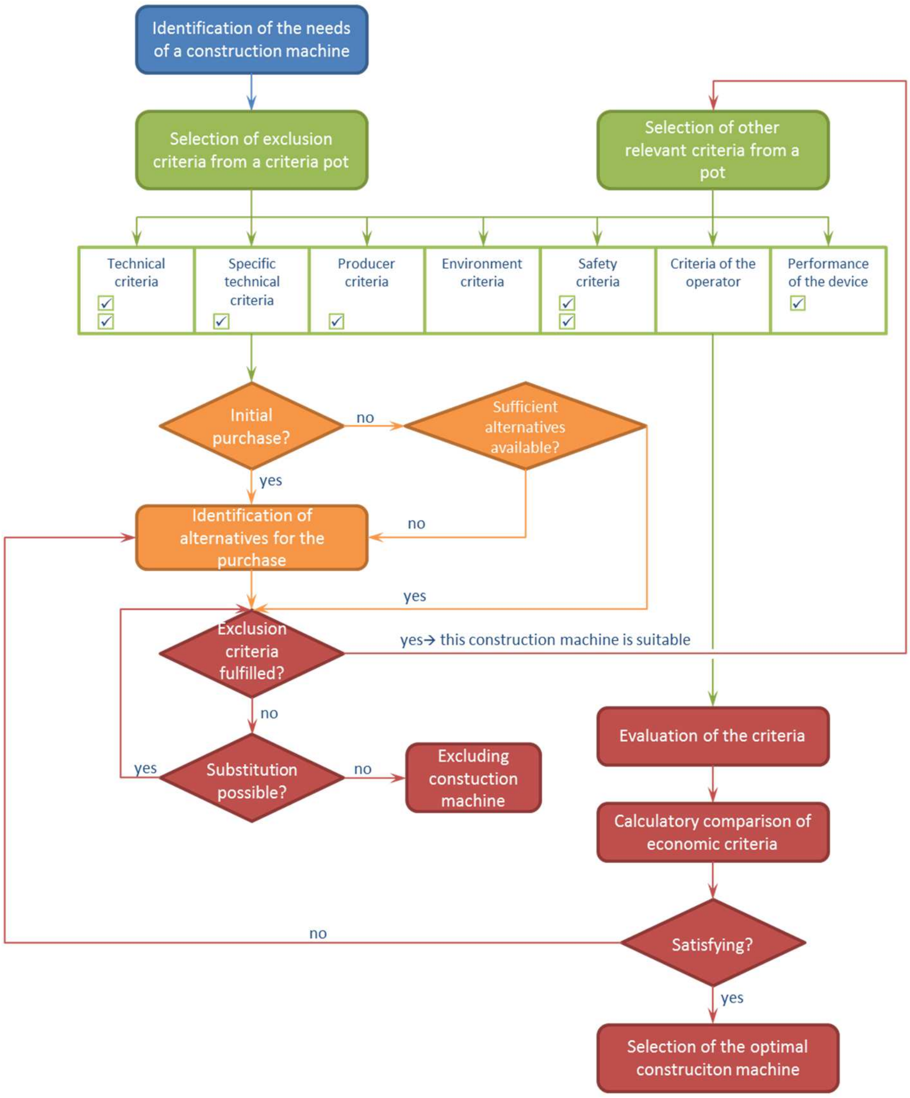

Fig. 7.7 Flow chart for optimal construction equipment selection [117]

WEBSTER and WIND describe the purchasing process as a multi-stage model divided into phases, which is shown in Figure 7.8. HILLINGER attuned the colours of the flow chart for optimal construction equipment selection to this model, to clarify the connection between the stages of his flow chart and the model of WEBSTER and WIND.

[117] Cf. HILLINGER, Ch.: Schematischer Vergleich von Baumaschinen im Beschaffungsvorgang. p.31

The flow chart includes all necessary steps in determined order, which need to be considered for the acquisition of construction machinery.

Fig. 7.8 Model of organisational decision process of WEBSTER and WIND [118]

The charts held in green deal with the selection and determination of certain criteria. That means, for the decision-making process all relevant criteria are selected from an existing criteria pool. Initially, this is done for the so called exclusion criteria. If only one exclusion criterion is not fulfilled, it is reason enough to exclude this variant.[119]

The orange charts deal with the buying behaviour of a company. After buying alternatives are identified, it is asked if it is an initial purchase or a repeat purchase.[120]

For all construction machines which fulfil the exclusion criteria, further relevant criteria are selected from a criteria pool. Those aspects must be evaluated, therefore the last charts deal with the evaluation process. Apart from economic criteria, which are evaluated by means of investment analyses, those criteria are very difficult to determine in monetary terms. Instead of that, a cost-utility analysis, which is based on point system, may lead to sufficient results. [121]

7.2.5 Criteria for the Selection of Construction Machinery

There is a range of criteria which can be compared and evaluated in the selection process of construction machinery. HILLINGER made intense literature researches to this topic, identified comparison criteria, allocated them to groups and integrated them in a mind map which is illustrated in Figure 7.9.[122]

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[118] Cf. WEBSTER, F.; WIND, Y.: Organisational buying behaviour. p.31

[119] Cf. HOFSTADLER, Ch.; HILLINGER, Ch.: Systematische und nachhaltige Baumschienenwahl. In: Bau aktuell. 4. Jahrgang. März 2013. Nr:2. p. 51

[120] Cf. HOFSTADLER, Ch.; HILLINGER, Ch.: Systematische und nachhaltige Baumschienenwahl. In: Bau aktuell. 4. Jahrgang. März 2013. Nr:2. p. 51

[121] Cf. HOFSTADLER, Ch.; HILLINGER, Ch.: Systematische und nachhaltige Baumschienenwahl. In: Bau aktuell. 4. Jahrgang. März 2013. Nr:2. p. 51

[122] Cf. HOFSTADLER, Ch.; HILLINGER, Ch.: Systematische und nachhaltige Baumschienenwahl. In: Bau aktuell. 4. Jahrgang. März 2013. Nr:2. p. 51

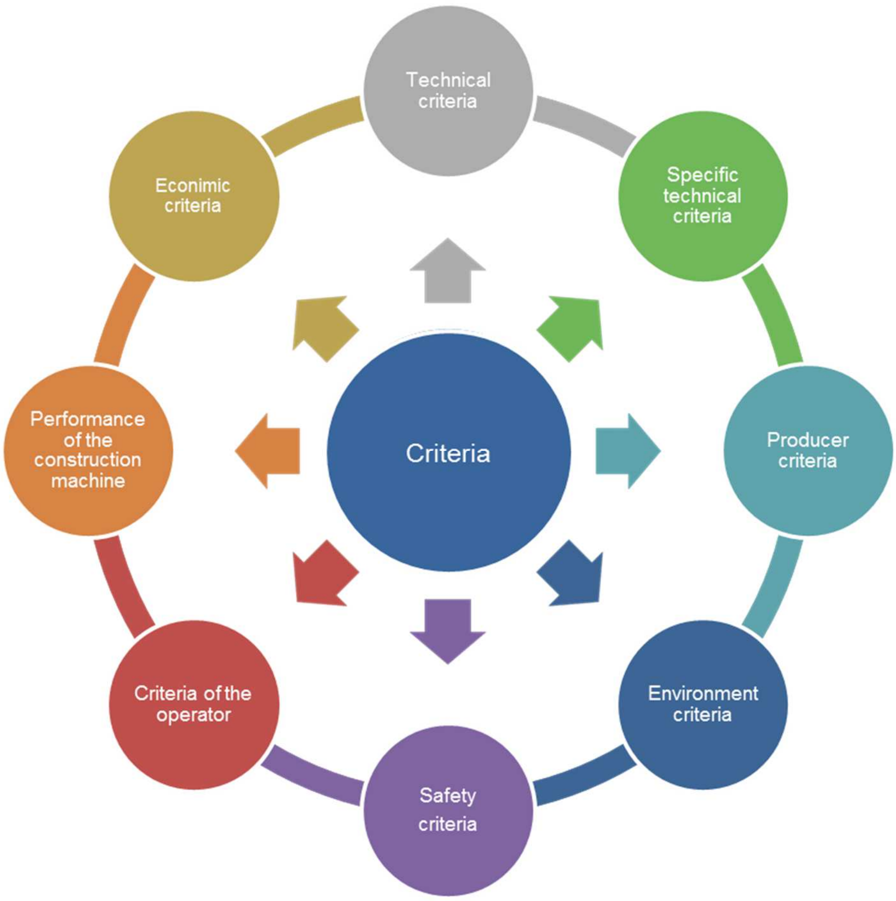

Fig. 7.9 Structuring of selection criteria [123]

7.2.6 Methods for System Comparison

At the beginning of construction progress scheduling, detailed investigation of the available construction methods is of prime importance. Especially in terms of time and economy, the decision for a certain construction method plays a crucial role. There is a variety of factors which influence the decision process of a construction method; that is why system selection became a very complex problem in the construction industry. This complexity as well as the fast growing construction industry and its developments are the reason why only calculatory system comparisons are not sufficient for construction system selection anymore. Construction companies are forced to make differentiated system comparisons of the available construction systems in order to get an economic positive result at the end of a construction

[123] Cf. HILLINGER, Ch.: Schematischer Vergleich von Baumaschinen im Beschaffungsvorgang. p.36

project. Therefore, systematic approach and detailed definition of the desired targets and criteria are necessary.[124]

According to the magazine BAUTECHNIK 11/2008, in praxis, construction companies do not give particular consideration to the system selection process. Reason therefore might be: [125]

- Certain procedures have become established in a construction company; therefore, alternatives are not considered (fear of change).
- Often, there is not enough time for the work preparation.
- Missing knowledge of diverse methods for system comparison.

Depending on the amount of influencing factors for the system selection, two methods can be distinguished:

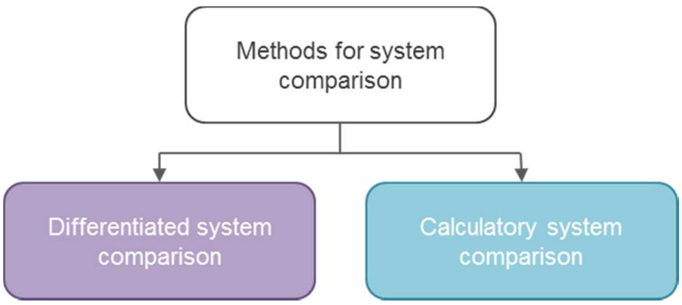

Fig. 7.10 Differentiated and calculatory system comparison

Independently of the chosen method, following targets should be met:[126]

- Fulfilling technical and aesthetical requirements
- Producing with minimum production costs
- Avoiding changes of the contract
- Minimizing company internal organisational problems
- Exclusion or reduction of dangers of accident

Hereinafter, an introduction of the calculatory as well as of the differentiated system comparison is done.

[124] Cf. NIKAS, G.: Systematische Verfahrenswahl – Anwendung einer Entscheidungsmatrix bei der Auswahl der Schalung für horizontale Bauteile im Hochbau. Diplomarbeit. 2010. p. 6

[125] Cf. BAUTECHNIK, Magazin: Artikel, Verfahrensvergleiche: Die Kombi macht's. 11/2008. p.25

[126] Cf. HOFSTADLER, Ch.: Bauablaufplanung und Logistik im Baubetrieb. Berlin, Heidelberg. Springer. 2007. p. 74

7.2.7 Calculatory System Comparison

A calculatory system comparison is nothing else than a methodically implemented cost comparison. In principle, each system comparison is based on assumptions, therefore, it is only a supporting tool for the decision process, which may help to reduce risks but does not exclude them at all.[127]

Methods of calculatory system comparisons are also known as economic comparison. When doing a calculatory system comparison, comparative cost determinations are done for each analysed construction method.[128] Conditions of clients as well as company internal conditions and construction site circumstances must be considered. Such conditions can be due to:[129]

- **Client**: Quality requirements, construction time requirements, working time conditions and construction conditions
- **Contractor**: Equipment, machinery, workforces, materials and available assets
- **Construction site**: Topographical conditions, infrastructure, main services

According to HOFFMANN, the following points must be taken into account when comparing systems on calculatory basis:[130]

- Fundamental differences of the construction methods
- Different choice of materials or components, including its production and arrangement
- Local construction site conditions like weather conditions, infrastructure, supply possibilities
- Operating conditions for workforces, materials and machinery of the contractor, spare capacity, shift operation, overtime as well as assets and financing base
- Special demands of the client regarding construction time, terms of acceptance as well as construction conditions
- Special possibilities of the contractor to make subsequent offers

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[127] Cf. BERNER, F.; KOCHENDÖRFER, B.; SCHACH, R.: Grundlagen der Baubetriebslehre 2. Baubetriebsplanung. 1. Auflage, Wiesbaden. B.G. Teubner Verlag. 2008. p.127

[128] Cf. HOFFMAN, M.: Zahlentafeln für den Baubetrieb. 6. vollständig aktualisierte Auflage. Stuttgart, Leipzig, Wiesbaden. B.G. Teubner Verlag. 2002. p.481

[129] Cf. BERNER, F.; KOCHENDÖRFER, B.; SCHACH, R.: Grundlagen der Baubetriebslehre 2. 2008. p.128

[130] Cf. HOFFMAN, M.: Zahlentafeln für den Baubetrieb. 2002. p.481

Basically, the acquisition of construction machinery is an investment, but this does not count for formwork systems and its equipment. In a financial statement, construction machines and equipment can be found under the point non-current assets, assumed that they are not rented or leased. In economic terms, investment decisions are some of the most important decisions. They should not be made intuitively or based on technical criteria only. Therefore, a variety of methods for investment appraisals were developed. With these methods, investment decisions can be done with regard to economical and operational aspects. Furthermore, the influence of risks and uncertainties on the decision process is reduced. In general, the features of investment alternatives are cut down to a single feature, a ratio, which should have a significant meaning.[131]

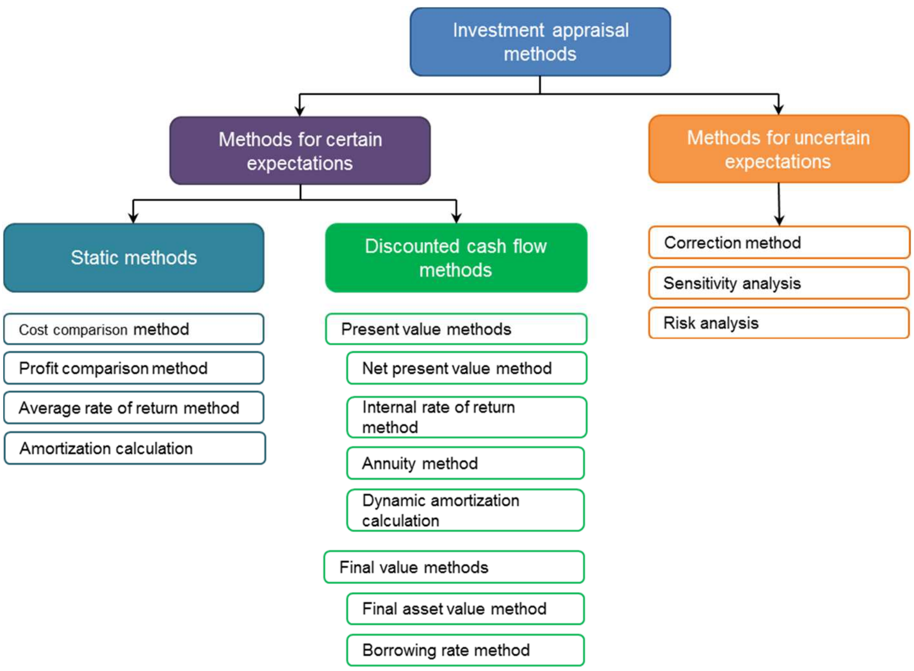

Fig. 7.11 Methods of investment calculations [132]

Figure 7.11 gives an overview about the methods for investment appraisals. The first step is to identify whether the expectation is certain or uncertain. In case of certain expectations, the investment appraisal can be divided into **static methods** and **dynamic appraisals**, so called **discounted cash flow methods.**

[131] Cf. Bauer, U.: Betriebswirtschaftslehre Bau. Skriptum. p. 7-3ff

[132] Cf. Bauer, U.: Betriebswirtschaftslehre Bau. Skriptum. p. 7-17

7.2.7.1 Static Investment Methods

Static analysis methods focus only on a single financial measure by assessing the profitability of an investment for a time span of one (average) period. It is assumed that alternative investment projects are comparable in regard to their project type, the amount of capital tie-up and their economic lives. That means, identical amounts of invested capital are required as well as identical economic lives for all investment alternatives. Comparability can also be achieved by including additional factors to balance differences in the capital tie-up and the economic lives. [133]

Static investment models ignore the passage of time, they explicitly consider only one period (e.g. a year). This period is assumed to be representative of all such periods. The average date is derived from the anticipated life of the investment. Depending on the target measure (costs, profit, average rate of return and payback time) of a static investment method, there is a differentiation of following methods:[134]

- Cost comparison method
- Profit comparison method
- Average rate of return method
- Static payback method (static amortization calculation)

As the name suggests, with the **Cost Comparison Method (CCM)**, the target measure is the costs of an investment project. To make a valuable cost comparison, it must be ensured that revenues of mutual exclusive investment alternatives are identical. The only difference can be in the costs. Several cost components may be included:

- personnel expenditures (wages, salaries, social expenditure etc.)
- cost of raw materials
- depreciation
- interest
- taxes and fees
- costs of outside services (such as repair or maintenance).

[133] Cf. GÖTZE, U.; NORTHCOTT, D.; SCHUSTER, P.: Investment appraisal. Methods and Models. Berlin, Heidelberg, Springer Verlag. 2008. p.31

[134] Cf. GÖTZE, U.; NORTHCOTT, D.; SCHUSTER, P.: Investment appraisal. 2008. p.32

Summing up all these cost components gives a total cost for each alternative investment. For the cost comparison method, very simple calculations are required.[135]

In contrast to the cost comparison method, the **Profit Comparison Method (PCM**) considers both the costs and revenues of investment projects. The average profit, which is the target measure, is determined by making the difference between revenues and costs. All other assumptions are identical to the cost comparison method.[136]

The **Average Rate of Return Method (ARR**) adds up the average profit and the average interests and puts them into relation to the average capital tie-up. In this way, the return of the invested capital can be calculated.

$$Average\ rate\ of\ return = \frac{Average\ profit + Average\ interest}{Average\ capital\ tie\ up}$$

With the **Static Payback Period Method (SPP)**, the amortization time of the capital invested in a project can be calculated. This method provides a measure of risk of an investment. The static payback method is only suitable as a supplementary appraisal method, because any costs and revenues occurring after the payback period are completely ignored.[137]

$$Payback\ period = \frac{Capital\ tie\ up}{Average\ cash\ flow\ surpluses}$$

Conclusively it can be said that the longer the payback period or amortization time, the higher is the risk that the investment is not rentable.

[135] Cf. GÖTZE, U.; NORTHCOTT, D.; SCHUSTER, P.: Investment appraisal. 2008. p.32

[136] Cf. GÖTZE, U.; NORTHCOTT, D.; SCHUSTER, P.: Investment appraisal. 2008. p.39

[137] Cf. GÖTZE, U.; NORTHCOTT, D.; SCHUSTER, P.: Investment appraisal. 2008. p.44

7.2.7.2 Discounted Cash Flow Method

Discounted cash flow methods, also called dynamic investment appraisals, consider more than only one time period explicitly and acknowledge the time value of money. The economic life of an investment project usually extends over different periods and is characterized by the streams of (expected) cash inflows and outflows. These cash inflows and outflows describe all relevant effects of the alternative investment projects, thus, for evaluating investments, only cash flows need to be considered whereas other effects can be neglected. It must be ensured that all cash flows can be forecast and allocated to defined periods of identical lengths. [138]

Cash flows from different periods can only be compared by integrating the **time value of money**. Because the values of the cash flows depend on the time at which they take place, the cash flows must be transformed by either discounting or compounding them. This makes it possible to compare them at specific points in time. When discounting a value, future cash flows are converted to their equivalent value at the beginning of the investment project; when compounding it, the cash flows are converted to their equivalent value at the end of the investment project. The factors for discounting and compounding are described with following terms:[139]

- Discounting factor : $(1 + i)^{-t}$
- Compounding factor : $(1 + i)^{t}$

For dynamic investment methods, the interest or discount rate "i" is of prime importance. The "t" stands for the number of time periods for which the cash flows are discounted or compounded.

Using discounting or compounding amounts to the **Present Value (PV)**, which can be described as follows:

> *Present value, also known as present discounted value, is a future amount of money that has been discounted to reflect its current value, as if it existed today. The present value is always less than or equal to the future value because money has interest-earning potential, a characteristic referred to as the time value of money.*[140]

The following calculation examples are modelled after GÖTZE, NORTHCOTT and SCHUSTER, [141] and they should give a better

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[138] Cf. GÖTZE, U.; NORTHCOTT, D.; SCHUSTER, P.: Investment appraisal. 2008. p.51

[139] Cf. GÖTZE, U.; NORTHCOTT, D.; SCHUSTER, P.: Investment appraisal. 2008. p.51

[140] http://en.wikipedia.org/wiki/Present_value (22.11.2013)

[141] Cf. GÖTZE, U.; NORTHCOTT, D.; SCHUSTER, P.: Investment appraisal. 2008. p.52

understanding of how the computation works. Assuming there is a net cash flow of 100.000 € with an interest rate (i) of 8% and a time period of 5 years, the present value is 68.058,32 € at the end of the period. This result can be explained by following calculation:

$$PV = \frac{Net\ cash\ flow}{(1+i)^t}$$

$$PV = \frac{100.000\ €}{(1+0{,}08)^5} = 68.058{,}32\ €$$

That means, a cash flow of 100.000 € with an interest rate of 8% has a monetary value of 68.058,32 € in five years; in other words, today, 68.058,32 € has the same value as 100.000 € in five years.

The same can be done the opposite way by compounding cash flows. Using the same interest rate of 8% and the same time period of 5 years, a future value (FV) of 146.932,81 € is attained.

$$FV = Net\ cash\ flow\ \cdot (1+i)^t$$

$$FV = 100.000\ \cdot (1+0{,}08)^5 = 146.932{,}81\ €$$

When there is a stream of identical cash flows over a certain period of time, the present value must be calculated with the **Capital Recovery Factor (CRF)**, also called **annuity factor**.

$$PV = Annuity\ \cdot \frac{(1+i)^t - 1}{(1+i)^t \cdot i}$$

$$PV = 100.000\ \cdot \frac{(1+0{,}08)^5 - 1}{(1+0{,}08)^5 \cdot 0{,}08} = 399.271{,}37\ €$$

Again, using the same values as in the former calculations, an annuity of 100.000 € over a time span of 5 years and with an interest rate of 8 leads to a present value of 399.271,37 €.

In order to attain the annuity, the formula can be transformed. Therefore, the **annuity factor** is needed, which is the inverse vale of the above mentioned capital recovery factor.

$$Annuity = PV \cdot \frac{(1+i)^t \cdot i}{(1+i)^t - 1}$$

$$Annuity = 100.000 \cdot \frac{(1+0{,}08)^5 \cdot i}{(1+0{,}08)^5 - 1} = 25.045{,}65\ €$$

Applying again the same values as in the other calculations, an annuity of 25.045,65 € is calculated. This means, getting 25.045,65 € at the end of each year of a five years period with an interest rate of 8%, has the same value as receiving 100.000 € today.

The scheme of an investment project is always the same. It is characterized by cash inflows and outflows over several periods of time. At the beginning (time 0) there is usually an outflow, the initial investment. Cash inflows and further outflows follow in later years.[142]

For the acquisition of construction machinery, it is important to know about the life cycle costs (LCC) of a machine. LCC give information of the outflows, which is indispensable information for making an investment in construction machinery.

> *Summarising, it can be said that discounting and compounding calculations capture and reflect time preferences – that is, they are an expression of the preference an investor shows for receiving income, or consuming resources, at particular times.*[143]

Below, the most important discounted cash flow methods are listed again. However, a description of these methods is not done in this Master Thesis.

- Net present value method
- Annuity method
- Internal rate of return method
- Dynamic payback period method

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[142] Cf. GÖTZE, U.; NORTHCOTT, D.; SCHUSTER, P.: Investment appraisal. 2008. p.53

[143] GÖTZE, U.; NORTHCOTT, D.; SCHUSTER, P.: Investment appraisal. 2008. p.53

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7.2.8 Differentiated System Comparison

The selection of construction methods sometimes leads to incorrect results, in case the decision is only based on calculatory system comparison, especially when external and internal conditions of an enterprise are not sufficiently considered.[144]

In contrast to the calculatory system comparison, which only focuses on economic aspects (the costs) when deciding for a construction method, the differentiated system comparison also considers other factors. LANG mentions four important criteria to be considered when selecting a construction method:[145]

- Economic criteria
- Technical criteria
- Organisational criteria
- Environment criteria

HOFSTADLER developed the so called **Decision Matrix** as a supporting tool for system selection. This matrix has a high degree of complexity and is divided in two parts: **exclusion criteria** and **criteria** regarding the **construction management**. Additionally, there is a differentiation between **soft facts** and **hard facts**:[146]

Exclusion criteria:

- Environmental criteria
- Technical criteria
- Safety criteria
- Construction specific criteria
- Aesthetic criteria

Construction management criteria:

- Criteria regarding construction management
- Criteria regarding construction operation

[144] Cf. LANG, W.: Verfahrensvergleich zur optimalen Auswahl von Bauverfahren. Grundlagen, Methodik und Anwendung. Diplomarbeit. Institut für Baubetrieb und Bauwirtschaft. TU Graz. 2008. p.127

[145] Cf. LANG, W.: Verfahrensvergleich zur optimalen Auswahl von Bauverfahren. 2008. p.106

[146] Cf. Entscheidungsmatrix nach HOFSTADLER

An example in Chapter 7.3 gives more detailed insight in how the decision matrix of HOFSTADLER works and illustrates how system selection can be carried out systematically by applying the matrix.

The differentiated system comparison is more complex than the calculatory system comparison, but then a bigger amount of data is needed which requires more effort. One advantage is that the systems are evaluated in a holistic way, which minimizes the risks when selecting construction machinery.[147]

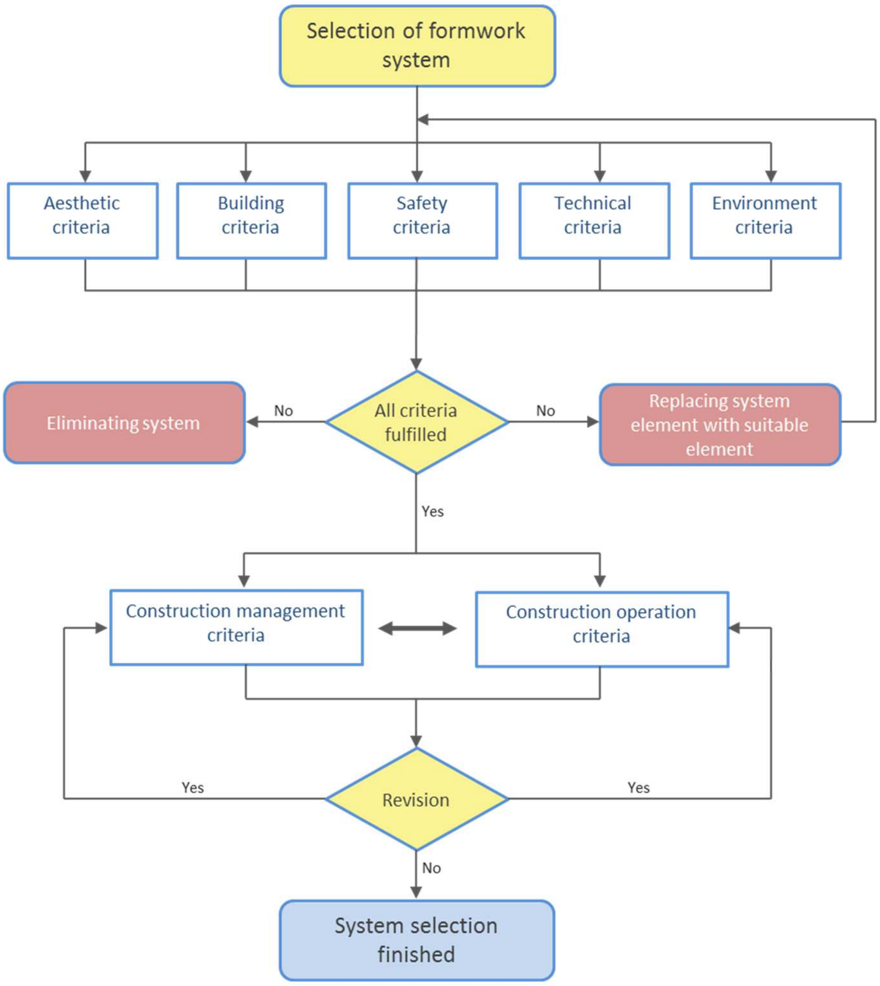

Fig. 7.12 Flow chart for the approach of differentiated formwork system selection according to HOFSTADLER [148]

[147] Cf. HOFSTADLER, Ch.: Schalarbeiten. 2008. p. 345

[148] Cf. HOFSTADLER, Ch.: Schalarbeiten. 2008. p. 346

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The flow chart in Figure 7.12 illustrates the steps which need to be done chronologically for selection a formwork system. In principle, these steps can also be applied for the selection of any other construction system in a very similar way, and are explained as follows:[149]

1. Definition of sub-criteria of the exclusion criteria under consideration of tendering criteria and contract conditions
2. Doing a cost-utility analysis, which is based on a score system (part 1)
3. Controlling if criteria are fulfilled. If sub-criteria are not fulfilled, substitution of elements within the system is necessary
4. Excluding all systems which are not fulfilling the criteria after substitution
5. Definition of criteria regarding construction management and construction operation
6. Determining costs and construction time under consideration of resources and logistical aspects
7. Estimating the risk of the systems in respect of the defined criteria
8. Doing a cost-utility analysis, which is based on a score system (part 2)
9. Discussing, controlling and revising the results
10. Finial risk estimation of the systems
11. Decision for a system

7.2.8.1 Hard Facts

Usually, hard facts are comprehensible data which can be expressed by means of ratios. In economic terms, these are for example costs or the asset turnover. For the selection process of construction methods, besides the economic criteria mostly technical criteria are determining. But also other hard facts such as environmental criteria, safety criteria as well as aesthetical criteria must not be neglected. For example, if a high-rise project requires exposed concrete quality, the aesthetic criteria become determining because such quality requirements can only be achieved by applying climbing formwork technology, not with slipforming technology.

[149] Cf. HOFSTADLER, Ch.: Schalarbeiten. 2008. p. 345

7.2.8.2 Soft Facts

On the other hand, soft facts deal with personal preferences. This can be personal knowledge and experiences, emotional behaviour, personal habits, interpersonal relations, etc. In the selection process for construction machinery, the brand of a machine for example can be decisive for the decision, assuming that costs and performance of competing systems are at the same level.

In the formwork selection process, it might be that workforces prefer to work with a climbing formwork instead of a slipform, or vice versa. Such facts are not necessarily determining for decision-making, but they definitely have an influence on the selection process and should not be under estimated.

7.2.8.3 Methods for Decision-making

When going beyond calculatory methods for making decision and selection systems, additional facts as soft facts, hard facts etc. have an influence on the final decision. Using methods with for example score systems enables a numerical comparison also for such methods. To get representative and comparative numbers, weighting of each criterion is often necessary. However, there is a range of different methods with different approach. Here is a list of the most common methods, but without detailed description:

- Cost- utility analysis,
- Cost- benefit analysis
- Cost- effectiveness analysis
- Morphological analysis
- SWOT analysis
- Potential analysis
- Brainstorming method
- Decision tree
- Decision Matrix

7.3 Finding the Optimal Formwork Solution for a High-rise Building

This chapter deals with formwork solutions for the high-rise sector only. It should be mentioned that whenever the expression “formwork system” is used, there is either talk about climbing formwork systems or slipform systems, not conventional formwork systems like frame- or timber beam formworks.

As described in earlier chapters, there are many factors which influence the selection process of construction machinery and construction equipment. Also in the formwork sector, there is a big offer of different formwork systems. In contrast to other construction equipment, formworks mostly are rented by contracting companies. Renting a formwork system has the advantage that only project specific elements are used on the building site. Contracting companies do not have the pressure to employ their own formwork equipment, and therefore, the best suited formwork solution for the project execution can be chosen.

But what is the best suited formwork solution? From the technical point of view, for every project a variety of formwork solutions is applicable, but they differ in costs on the one hand and in technical conditions on the other hand.

7.3.1 Analysis of Requirements

Finding the optimal formwork solution for a specific project is the task of the engineers of a formwork supplying company. Formwork suppliers make their offers based on plans and technical building descriptions, which they receive from their clients. Before starting with the formwork design for a construction, certain prerequisites must be clarified. Usually these are:

- Costumer requirements
- Building requirements
- Environmental requirements
- Contractor requirements

All these requirements must be considered in order to get the optimal solution for the client. Providing more solutions gives a better basis for further discussions. In principle, the most economical solution, the best technical solution and alternatively a combination of these variants should be offered.

Usually, it is possible to combine different formwork systems from the same supplier. Therefore, higher flexibility is provided and more economic solutions can be achieved.

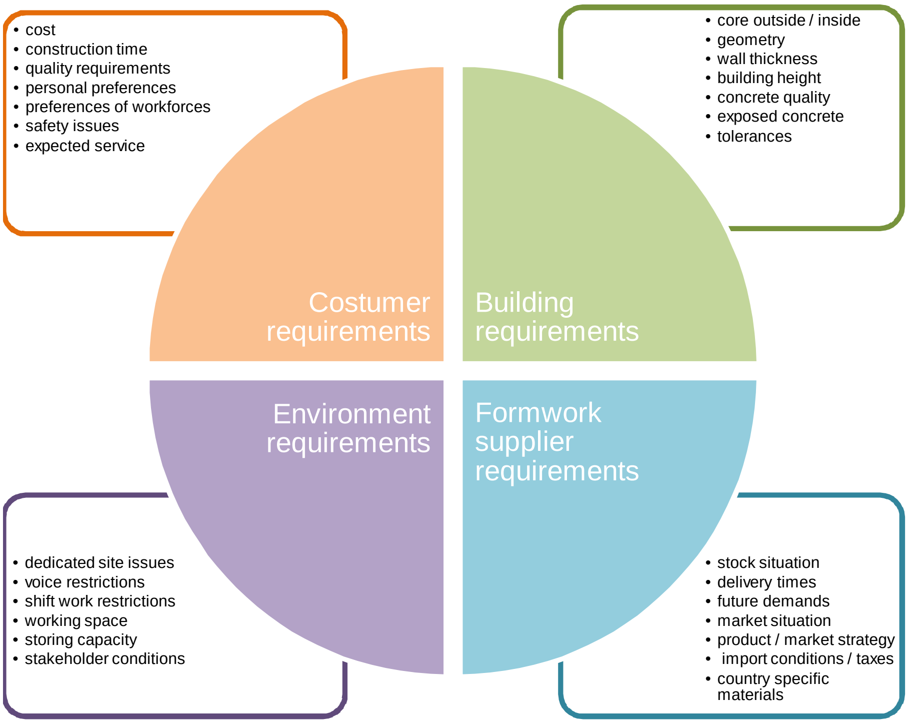

Fig. 7.13 Requirements for a high-rise formwork solution design

7.3.2 Formwork Selection

Once all requirements are determined and other conditions are clarified, the planning for the formwork system can be done. Dimensions and geometry such as building height, wall thickness, inclinations as well as the complexity of a building can be derived from plans and building drawings. Also the structural design of a high-rise building plays a crucial role for the system decision. The most common structural system is a core-system, for which both slipforming as well as climbing formwork technology is appropriately applicable. But a core system can be constructed in two ways: the core walls ahead or in in a monolithic construction. The latter would be an exclusion criterion for slipforming technology, because the core walls and slabs are poured in on step, which is not possible with a slipform.

The decision for a certain formwork system depends on the height of a building on the one hand and on the complexity of a building on the other hand. Figure 7.15 shows the field of application for Crane guided climbing formwork systems, automatic climbing formworks systems, heavy automatic climbing formwork systems as well as for slipform systems schematically. The complexity factor has a score from 1 - 7. It is not practical to allocate a certain factor to a certain number. Therefore, 1 can be considered a very simple construction, 7 a very complex construction. Influencing factors on the complexity of a building are: changes in wall thickness, wall changes, wall inclinations, changing inclinations, extraordinary casting steps, etc. In this example, the complexity factor is manly based on geometric conditions, factors like the degree of built-in parts, box-outs and the degree of reinforcement is not considered, otherwise it would not make sense to integrate the slipform system in the graph.

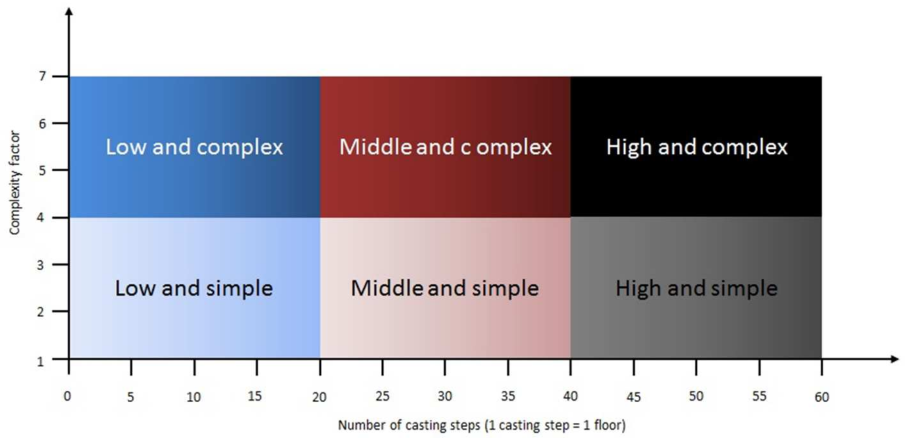

Fig. 7.14 Schematic complexity distribution over a high-rise building height

Figure 7.14 serves as a map legend for figure 7.15. It is a classification based on the height and complexity of a high-rise building by putting them into a relation.

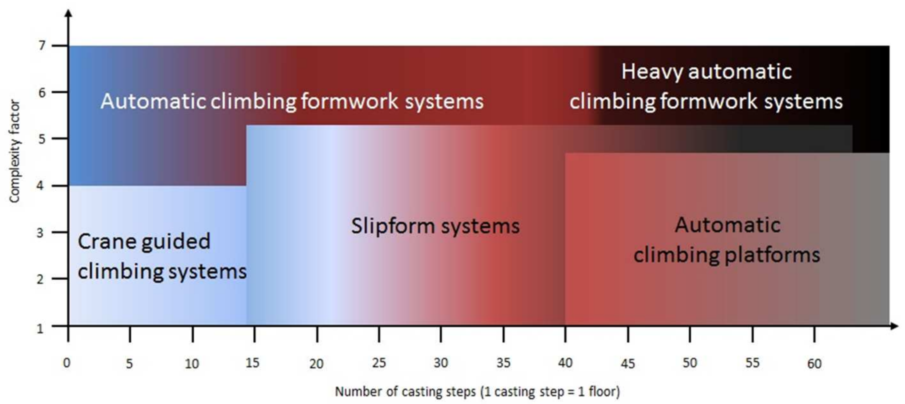

Fig. 7.15 Schematic fields off application of different high-rise formwork systems

Figure 7.15 illustrates that different systems are overlapping. Especially slipforming technology has a wide range of application. It must be mentioned that **this figure only counts for high-rise buildings**, and not for other constructions.

7.3.3 Exemplary Application of the Decision Matrix [150]

According to HOFSTADLER, differentiated system comparison methods are expediently applicable for the comparison of different technologies.[151]

At this point, the decision matrix, as a differentiated system comparison method, is introduced. A fictive example comparing a crane guided climbing formwork system, an automatic formwork system and a slipform system should give an insight how the decision matrix works and how it can be applied.

As mentioned in Chapter 7.2.8, the decision matrix in based on weighted exclusion criteria and construction management criteria. Initially, the essential criteria must be determined. These criteria underlie a system of score distribution. It can be scored from 0 to 5, where 5 is the highest score and 0 the lowest (5 = criterion totally fulfilled, 0 = criterion not fulfilled). Additionally to the score system, the criteria get weighted. There is a weighting in percentages for criteria groups as well as for single criteria. In the end, the weighted scores of all criteria get added up, and the system with the highest score is the most appropriate.

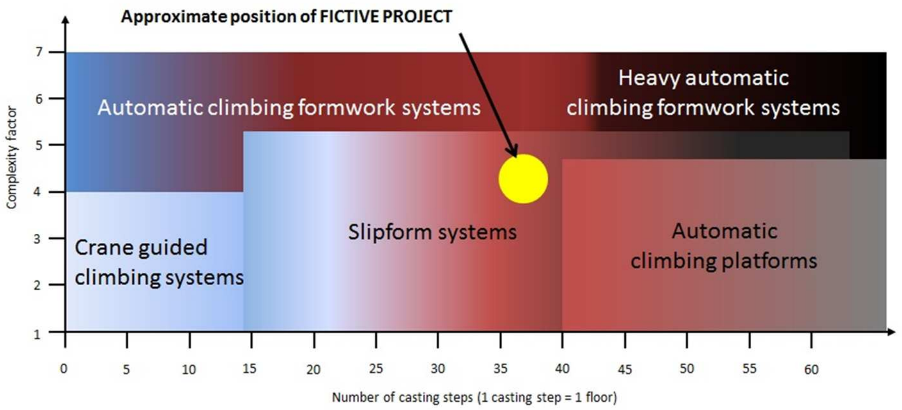

Fig. 7.16 Allocation of position of the fictive project

Figure 7.16 shows an approximate position where the fictive project is located. Based on this position, the score distribution in the decision matrix of Figure 7.17 is done. It must be mentioned, that this example should give a rough overview about how the decision matrix can be applied in the high-rise sector, but the here used values are all fictive and without any connection to a real project. Values which cannot be derived from Figure 7.16 are chosen randomly (e.g. environment criteria).

[150] Cf. HOFSTADLER, Ch.: Schalarbeiten. 2008. Kapitel 13.2.2.1

[151] Cf. HOFSTADLER, Ch.: Bauablaufplanung und Logistik im Baubetrieb. 2007. p. 54

Below, criteria groups with the most important sub criteria for the high-rise sector are listed. The groups are divided into exclusion criteria and construction management criteria and can be complemented by a range of other criteria.

Exclusion Criteria

Aesthetic criteria:

- Construction joints
- Anchor joints
- Corner solutions
- Concrete surface
- Concrete structure

Specific building criteria:

- Repeating ground plans
- Constructions without joints
- Degree of reinforcement
- Reinforcement distribution
- Diameters of reinforcement
- Concrete strength
- Building height
- Constant/changing ground plans
- Constant/Changing cross section of the building
- Vertical/inclined constructions
- Modifications during construction

Safety criteria:

- Country specific requirements
- Safety work in all construction stages
- Special safety elements
- Sensitivity to wind occurrences
- Subjective feeling

Technical criteria:

- Structural requirements
- Installation of built-in parts and box-outs
- Working space
- Type of reinforcement
- Installing the reinforcement
- Flexibility in positioning of anchors
- Storing capacity on the formwork
- Admissible concrete pressure

Environmental criteria:

- Neighbours
- Geographical conditions
- Geological conditions
- Topographical conditions

Construction Management Criteria

Construction management criteria:

- Discretionary works (planning, controlling, coordinating)
- Market situation
- Rental charges
- Availability of equipment
- Achievable daily performance
- Salary level of workforces

Construction operation criteria:

- Logistic aspects (infrastructure, concrete supply, etc.)
- Requirements concerning planning
- Requirements concerning work forces
- Qualification of work forces
- Crane capacity
- Requirements regarding building site facilities
- Available construction time

Decision Matrix											Line
Criteria			Weighting		System						
1	2	3	4	5	6	7	8	9	10	11	
Project:			Total	Single	Crane guided		Automatic Climbing		Slipform		
Consultant:		Version: v1.0	[%]	[%]	Score	Total	Score	Total	Score	Total	
Exclusion Criteria	Aesthetic criteria	Corner solution	10	30	5	0,15	5	0,15	2	0,06	1.1
		Anchor joints		15	1	0,015	1	0,015	5	0,075	1.2
		Concrete surface		15	5	0,075	5	0,075	2	0,03	1.3
		Geometrical accuracy		40	5	0,2	5	0,2	3	0,12	1.4
	Score - Sub criteria			100		0,44		0,44		0,285	1.20
	Specific building criteria	Inclined walls	30	10	4	0,12	4	0,12	4	0,12	2.1
		Building height		50	0	0	5	0,75	4	0,6	2.2
		Changing wall thickness		10	5	0,15	4	0,12	3	0,09	2.3
		Degree of reinforcement		10	5	0,15	5	0,15	2	0,06	2.4
		Modifications during construction		20	5	0,3	4	0,24	1	0,06	2.5
	Score - Sub criteria			100		0,72		1,38		0,93	2.20
	Safety criteria	Danger caused by wind	10	50	2	0,1	4	0,2	5	0,25	3.1
		Safety elements		50	5	0,25	5	0,25	5	0,25	3.2
	Score - Sub criteria			100		0,35		0,45		0,5	3.20
	Technical criteria	Installation of built-in parts	40	40	5	0,8	5	0,8	2	0,32	4.1
		Installation of anchor joints		20	1	0,08	1	0,08	5	0,4	4.2
		Installing the reinforcement		20	5	0,4	5	0,4	3	0,24	4.3
		Flexibility in type of reinforcement		20	5	0,4	5	0,4	3	0,24	4.4
	Score - Sub criteria			100		1,68		1,68		1,2	4.20
	Environment criteria	Neighbours	10	10	1	0,01	1	0,01	1	0,01	5.1
		Shift operation		90	1	0,09	1	0,09	5	0,45	5.2
											5.3
											5.4
	Score - Sub criteria			100		0,1		0,1		0,46	5.20
			100			3,29		4,05		3,38	
Exclusion factor (multiplicative: 1 all criteria fulfilled, 0 at least 1 criterion not fulfilled):						0		1		1	
Individual factor (multiplicative: between 0 und 1):						1		1		1	
Total score of exclusion criteria:						0,00		4,05		3,38	
Construction Management Criteria	Construction operation	Infrastructure (permanent concrete suppy)	40	30	5	0,6	5	0,6	3	0,36	14.1
		Cranage capacity		20	2	0,16	4	0,32	4	0,32	14.2
		Requirements concerning work forces		20	4	0,32	2	0,16	3	0,24	14.3
		Requirements concerning planning		30	4	0,48	3	0,36	2	0,24	14.4
	Score - Sub criteria			100		1,56		1,44		1,16	14.20
	Construction management	Rental charges	60	40	4	0,96	2	0,48	3	0,72	15.1
		Discretionary works (planning, control, etc.)		20	4	0,48	2	0,24	3	0,36	15.2
		Availability of equipment		40	4	0,96	4	0,96	4	0,96	15.3
											15.4
	Score - Sub criteria			100		2,4		1,68		2,04	15.20
			100			3,96		3,12		3,20	
Total score of system:						3,96		7,17		6,58	
Risk factor (multiplicative: 1 no aggravated risk, 0 insuperable risk):						1		1		1	
End score:						0		7,17		6,58	
Decision (ranking):						3		1		2	

Decision matrix: ©ChristianHOFSTADLER

Fig. 7.17 Decision matrix according to HOFSTADLER

In this example, the decision matrix shows that the best suited system for this fictive project would be an automatic climbing formwork. But slipforming is competing strongly, thus, other factors should be considered additionally. Even though the crane guided formwork system wins the category *construction management criteria*, it is ranked at the last position in the total ranking. This is because of the building height, which according to Figure 7.16 is approximately 125 meters. Although it is possible to construct buildings of this height with crane guided formwork systems without any problems, it was scored with 0, because of the required crane capacity (fictive reason). If only one parameter of the group exclusion criteria is scored with 0, then the system gets 0 points in the total score of exclusion criteria (cf. Figure 7.17). Comparing the result of the decision matrix with the position of the project illustrated in Figure 7.16, it can be seen that they are corresponding.

The result of the decision matrix depends on one side on the weighting factor of the parameters, on the other side on the distribution of the score. To achieve valuable results, persons who enter the data must have profound knowledge and experience in their field. If the weighting factors are not chosen realistically, the results of the decision matrix will be distorted; the same happens if the score is entered inappropriately.

In conclusion, the decision matrix of HOFSTADLER is a practical and useful supporting tool for selecting formwork systems in the high-rise sector, assumed that the consultant who enters the data is advised by people with profound experience and knowledge about the available techniques, the market and all other factors which influence the selection process. Additionally it must be mentioned that such supporting tools should not be determining for the selection process of formwork systems, but they provide a good discussion basis, facilitate the selection process and make it more effective.

8 Questionnaire Design

This chapter discusses the significance of market research with special focus on questionnaire development. It should serve as a basis for Chapter 9, the practical part of this research work, to give a better understanding about the approach to the principles on which the present questionnaire was designed.

8.1 Marketing and Market Research

Nowadays, market research is a very important tool for active enterprises. Proper forecasts, correct estimation of the market situation, detailed research of costumer behaviour as well as the evaluation of strengths and weaknesses of the competitors are essential issues market research has to deal with. Market research is very important for enterprises to reach their targets in the desired target market.[152]

The Master Project „*Grundlagen der Marktforschung für die Fragebogenentwicklung*“ serves as a basis for this Master Thesis, therefore, facts about market research can be looked up there.

8.2 Questionnaire Definition

There are several methods and techniques to collect data. If the data are not collected following specific guidelines, the data will not be comparable. Questions and research methods must be arranged in a standard way of asking in order to make a valuable analysis of the recorded answers. A standardized questionnaire fulfils these prerequisites. It ensures comparability of data, increases the speed and the accuracy of recording and additionally facilitates the data processing.[153]

A questionnaire can be defined as a **formalized set of questions for obtaining information from participants**. It is also called a schedule, interview form or measuring instrument. Any questionnaire has three specific objectives:[154]

1. The necessary questions must be translated to a set of specific questions which participants can and will answer. The right way of asking questions is very difficult. Asking a question in two

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[152] STELZL, Th.: Master Projekt. Grundlagen der Marktforschung für die Fragebogenentwicklung. TU Graz. 2013

[153] Cf. MALHOTRA, N.; BIRKS, D.; WILLIS, P.: Marketing Research. An applied approach. 4th Edition. London. Pearson Education Limited, 2012. p. 452

[154] Cf. MALHOTRA, N.; BIRKS, D.; WILLIS, P.: Marketing Research. 2012.p. 452

different ways may lead to two different results. Hence, designing questions is a big challenge and special attention must be given to this point.

2. Participants must get involved in a questionnaire. Therefore, it must uplift, motivate and encourage the participants to cooperate and to complete the task. To illustrate this, a basic marketing model of the exchange of values between two parties is shown in Figure 8.1. The first step of a researcher must be the evaluation of what the participants are going to get out of this. He must be able to estimate what they think when they read the questions. The researcher must have empathy with the target participants. The way participants are approached by a questionnaire is strongly affected by the appreciation of what participants go through. Additionally, the stated purpose of the questionnaire, the rewards of taking part as well as the whole process of questioning and the question design are affected by this.

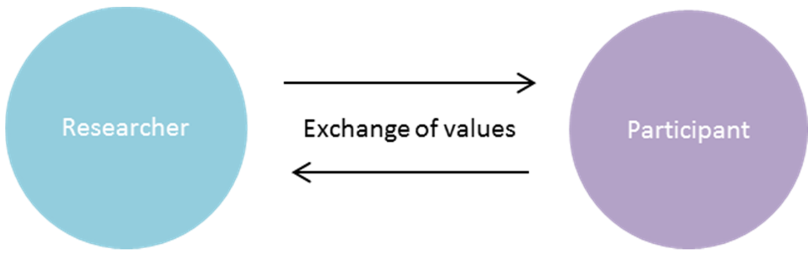

Fig. 8.1 Exchange of values between researcher and participants [155]

What the participant may want from the researcher:

- Tangible reward
- Confidentiality
- Interesting subject and experience
- Personal benefits from seeing the research completed
- Social benefits from seeing the research completed
- Being chosen as a participant with expertise on a subject
- Research organisation known for excellence in research
- Rapport and trust

[155] MALHOTRA, N.; BIRKS, D.; WILLIS, P.: Marketing Research. 2012. p. 452

What the researcher may want from the participant:

- Honesty

  That the participant:

- Takes in reasons for the study
- Follows the instructions in completing the study
- Thinks through the issues before forming an answer
- Social benefits from seeing the research completed
- Says good things about the rationale for marketing research
- Says good things about the research process

3. A questionnaire should be designed in a way that the error of responses can be hold minimized. Errors arise when participants give inaccurate answers, when their answers are recorded wrongly or when they are mis-analysed.

8.3 Questionnaire Design Process

Several guidelines support researchers when designing a questionnaire. The way of asking, the overall design, the structure of the questionnaire as well as many other factors influence the quality of a questionnaire, but there is no scientific rule that guarantees optimal answers or the ideal questionnaire. Designing a questionnaire is a skill acquired through experience.[156]

This chapter deals with the questionnaire design process in general. Specific features like the way of asking or the design itself are not described.

Questionnaire designers are confronted with some trade-offs which make the design process problematic. According to MALHOTRA, BIRKS and WILLIS such trade-offs are:[157]

- The source of idea
- The question purpose
- Actual questions

[156] Cf. MALHOTRA, N.; BIRKS, D.; WILLIS, P.: Marketing Research. 2012. p. 453

[157] MALHOTRA, N.; BIRKS, D.; WILLIS, P.: Marketing Research. 2012. p. 453

- Question analyses

Each research project has different demands and emphases, but the above mentioned trade-offs cannot be avoided.

Marketing decision makers are supported effectively by the information provided by the results of market research. Questionnaire design, as a part of market research, is therefore of prime importance for making new decisions and investments.

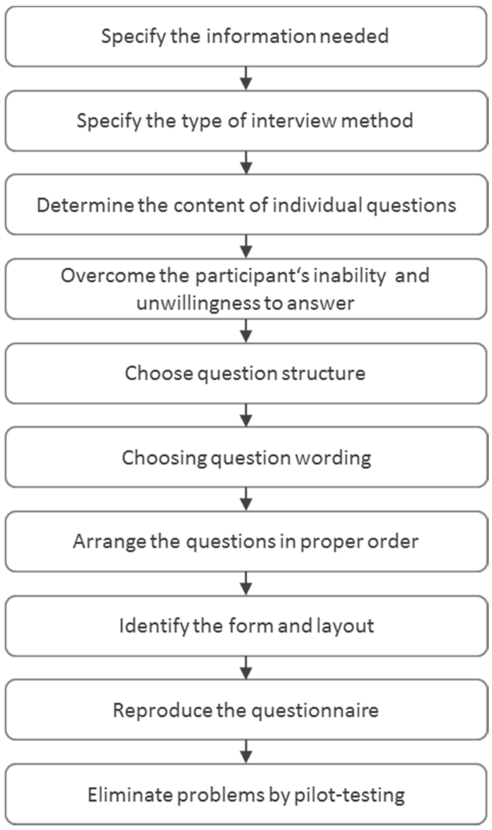

Fig. 8.2 Questionnaire design process [158]

A chronological approach of how a questionnaire design should be done is illustrated in Figure 8.2. In practice, the steps are interrelated; iterations and interconnections between the stages are prerequisites for developing a questionnaire.

The present questionnaire (cf. Chapter 9) was designed in a similar way to this process. It was partly combined with face-to-face interviews, and also one telephone interview.

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[158] MALHOTRA, N.; BIRKS, D.; WILLIS, P.: Marketing Research. 2012. p. 456

9 Statistical Evaluation of the Questionnaire

This chapter describes the questionnaire about system decision for slipforming technology and climbing technology; also, the statistical evaluation of the closed questions is done. Additionally, the open questions are interpreted, based on the results of the questionnaire and the information which was delivered through the interviews.

9.1 Introduction

The structure of the questionnaire falls into three parts. It starts with the personal experience in the high-rise sector and the use of slipforming and climbing technologies. The participants are also asked for their expectations and requirements, because they act as end users of these competing technologies. Furthermore, the selection factors for deciding in favour for a technology over another are asked. Lastly, the participants are requested to give their opinion of future demands for these technologies.

The majority of the questions are multiple choice questions with a score system, but there are also open questions (question 28-31, 33 a-d and 39) which are not statistically evaluated, but the results are summarized.

Questions 5-19, 20-24, 32, 33 e-f, 37 and 38 are designed with a six point ordinal scale. Questions 17-19, 22-24, 32 and 33 e-f additionally have a multiple priority choice option.

An ordinal scale is characterized by the fact that the measured object additionally underlies a ranking which is interpreted empirically.[159] The numbers of an ordinal scale include a hierarchy and must not be mixed up. The score values can be interpreted as follows: 1 = very low, 2 = low, 3 = medium (-), 4 = medium (+) 5 = high 6 = very high. The figures are evaluated in percentages.

Question 20, 21, 25-27 and 34-36 are evaluated with nominal numbers (0 = no, 1 = yes). In this way the answers can be distinguished. The modal value serves to give information in which category the highest frequency occurs.

Because of the low number of participants, only the medians and standard deviations were calculated in the statistical evaluation, which serve as the basis for the interpretation of the results.

[159] Cf. HÄDER, M.: Empirische Sozialforschung. Eine Einführung. Wiesbaden. VS Verlag für Sozialwissenschaften. 2006 p.99

Median

In statistical evaluations, the median is a numerical value which separates a data collected in its higher half and its lower half, in other words, it is exactly the value which stands between the upper and lower 50% of the data collection. E.g. the median of (1, 2, 2, 4, 5, 6, 6) is 4.

Standard Deviation

The standard deviation is statistical measure and gives information how much dispersion from the mean or expected value exists.

It was decided to set the score system without mean value because participants have the tendency to choose the mean value in case of uncertainty. The questions are structured in a way to obtain statistically evaluable results. In addition to the questionnaire, a face-to-face interview was planned, but only six participants were willing to take part. With one participant a telephone interview was held.

9.2 The Questionnaire

In total, **fifteen participants** took part in the research work. Because of the low number of participants, the statistical results can only be interpreted as tendencies. The distribution of the participants over countries is as shown in Figure 9.1.

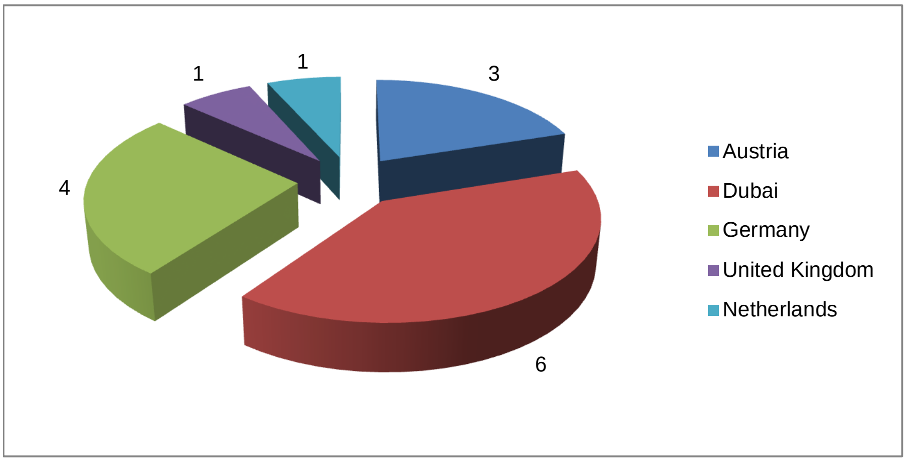

Fig. 9.1 Number of participants

With the six participants of Dubai, a face-to-face interview was held, with one participant of Germany a telephone interview was held, the others delivered the questionnaire without giving an interview.

I. Personal experience with Slipforming and Climbing Formwork Technology

1. *What is your **position within the firm?***

One participant is a **Professor from a German Technical University**, the other fourteen are employees of construction companies. The majority of the participants were Project Managers. These people are responsible for the decision making process, but generally they work in teams to find the best formwork solution for an upcoming project. The exact position of the participants within the firm is stated below:

4 Participants: Senior Project Manager (Dubai)

1 Participant: Deputy Director (NL)

1 Participant: Contract Manager (UK)

1 Participant: Formwork Manager (Dubai)

1 Participant: Method Manager (Dubai)

1 Participant: Work Preparation Manager, formworks / scaffolds (GER)

3 Participants: Head of department (2 AUT, 1 GER)

1 Participant: Employee of the department of formwork Management

1 Participant: Civil engineer

2. *How many years have you worked in this field?*

In average, the fourteen participants (exclusive the German Professor) worked in the high-rise sector for approximately **20 years** with a standard deviation of around 7 years. The lowest value was 11 years, the highest 34 years.

3. *How many projects have you executed using either **Slipforming or Climbing** Technology?*

Table 9.1 Projects in Slipforming or Climbing Technology in total

Slipforming or Climbing	***2***	***4***	***5***	***7***	***8***	***22***	***40***	***48***	***55***	***115***
Frequency distribution	*1*	*1*	*3*	*2*	*2*	*1*	*1*	*1*	*1*	*1*

The mean value of executed projects using either slipforming or climbing technology is **around 24** projects. With a lowest value of only 2 executed projects and a highest value of 115 executed projects, the standard deviation is quite high with 32 projects. This high standard deviation can be explained by the deviation of executed projects.

Table 9.2 Projects in Slipforming or Climbing Technology in the last 3 years

Slipforming or Climbing	***0***	***1***	***2***	***3***	***5***	***8***	***10***	***15***
Frequency distribution	*1*	*1*	*4*	*3*	*1*	*1*	*1*	*1*

In average, **around 4 projects** were executed during the last three years. The lowest value is 0 projects and the highest is 15 projects; the standard deviation comes to 4 projects.

4. *How many projects have you already executed in **Slipforming** Technology?*

Table 9.3 Projects in Slipforming Technology in total

Slipforming	***0***	***1***	***2***	***4***	***5***	***10***	***12***	***23***	***25***
Frequency distribution	*1*	*2*	*5*	*1*	*1*	*1*	*1*	*1*	*1*

The mean value of executed projects using slipforming is **around 6** projects. The lowest value is 0 executed projects and the highest value is 25 executed projects, the standard deviation comes to 6 projects.

Table 9.4 Projects in Slipforming Technology in the last 3 years

Slipforming	***0***	***1***	***2***	***4***
Frequency distribution	*5*	*5*	*2*	*1*

With slipforming technology **1 project** was executed in average during the last three years.

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5. *How much time and effort do you have to spend in the **selection process?***

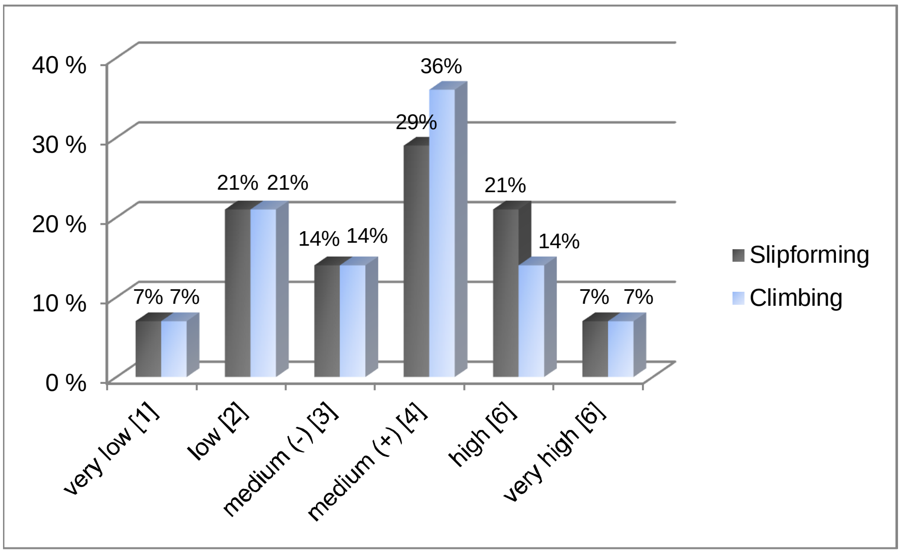

Fig. 9.2 Time and effort spent in the selection process

	Slipforming	Climbing
Median:	4.00	4.00
Standard Deviation:	1.45	1.40

The median comes to 4,00, which means that the effort which has to be spent for the selection process of **slipforming** technology is a little bit above the average and can be evaluated with **medium (+).**

The effort in the selection process for **climbing** formwork technology is very similar to slipforming technology, and reaches also a median of 4,00. the standard deviation, which is quite high, is very similar in both technologies.

Conclusion

According to these results it can be said that the effort in the selection process is equal for both technologies.

6. *How much **effort and resources** are required in the **start-up-phase** of the **construction of the high-rise element?***

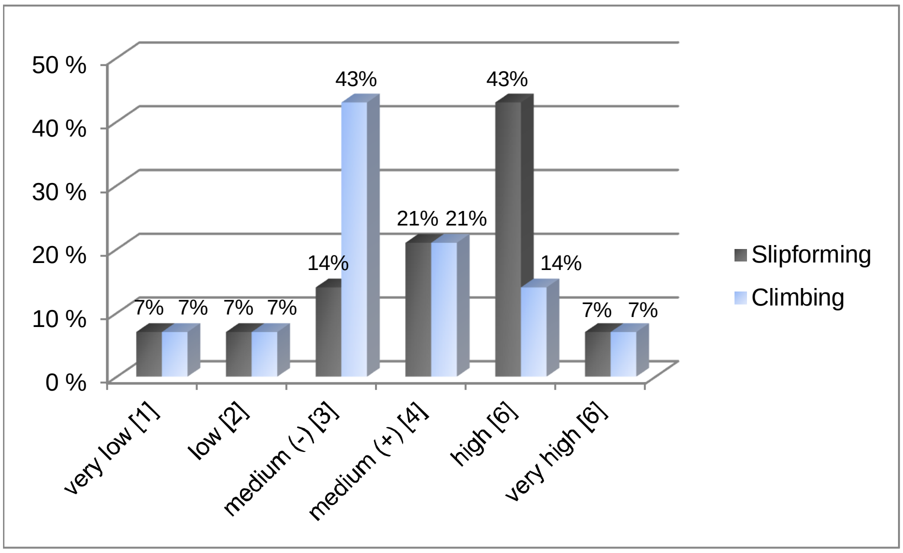

Fig. 9.3 Effort and resources required in the start-up phase

	Slipforming	Climbing
Median:	5.00	3.00
Standard Deviation:	1.48	1.29

Due to the median of 5.00, the start-up phase can be evaluated with **high** for **slipforming** technology. The standard deviation is 1.48, and 43% of the participants said that the effort and the necessary resource are rather high.

Climbing formwork technology with a value of 3.00 can be evaluated as **medium (-).** The standard deviation is lower than of slipforming technology, 43% of the participants said that the effort is rather medium (-).

Conclusion

According to the medians, slipforming technology requires a bit more effort and resources than climbing formwork technology in the start-up phase.

7. *How much **effort and resources** are required in the **main phase** of the **construction?***

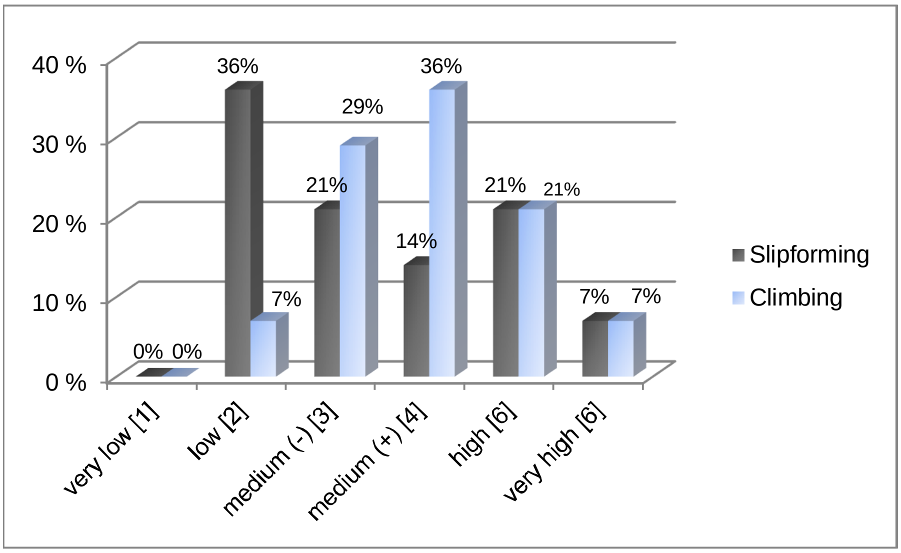

Fig. 9.4 Effort and resources required in the main phase

	Slipforming	Climbing
Median:	3.00	4.00
Standard Deviation:	1.40	1.07

Due to the median of 3.00, the main phase can be evaluated with **medium (-)** for **slipforming** technology. The standard deviation is 1.40, and 36% of the participants said that the effort and the necessary resource are rather low.

Climbing formwork technology comes with a median of 4.00 to **medium (+)** effort. The standard deviation with 1.07 is explicitly lower than of slipforming technology. 36% of the participants said that the effort is rather medium (+).

Conclusion

Climbing formwork technology tends to require a bit more effort and resources to be spent in the main phase.

8. *How much **effort and time** is spent in the **end phase** of the **construction of the high-rise elements?***

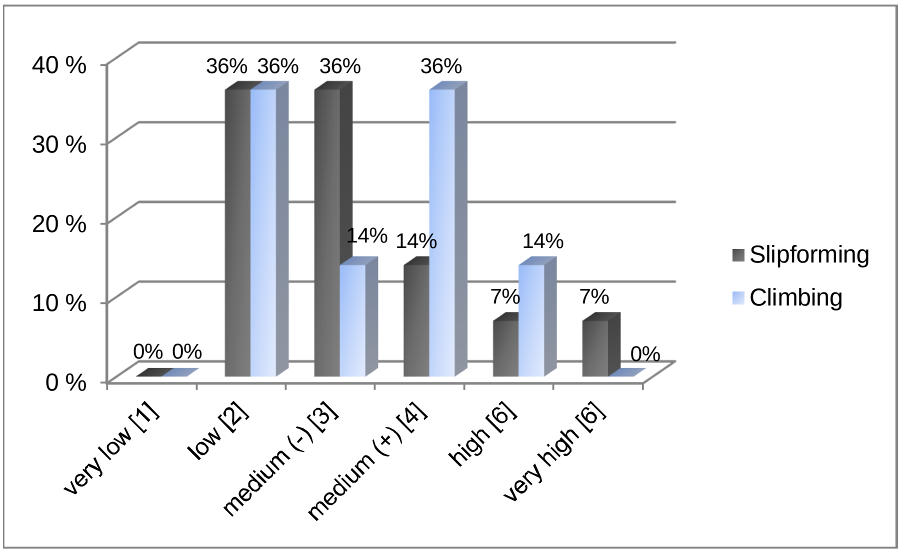

Fig. 9.5 Effort and time required in the end phase

	Slipforming	Climbing
Median:	3.00	3.50
Standard Deviation:	1.23	1.23

Due to the median of 3.00, the main phase can be evaluated with **medium (-)** for **slipforming** technology. The standard deviation is 1.23 and 36% of the participants said that the effort and the necessary resource are medium (-) or low.

Climbing formwork technology is with a median of 3.50 exactly in the middle of **medium (+)** and **medium (-)** effort. Also the standard deviation is equal to slipforming technology with 1.23.

Conclusion

Effort and time which need to be spent in the end phase of a project can be evaluated a bit higher for climbing formwork technology.

9. *How complicated are **changes of the ground plan** (dimensions, wall thickness, etc.)?*

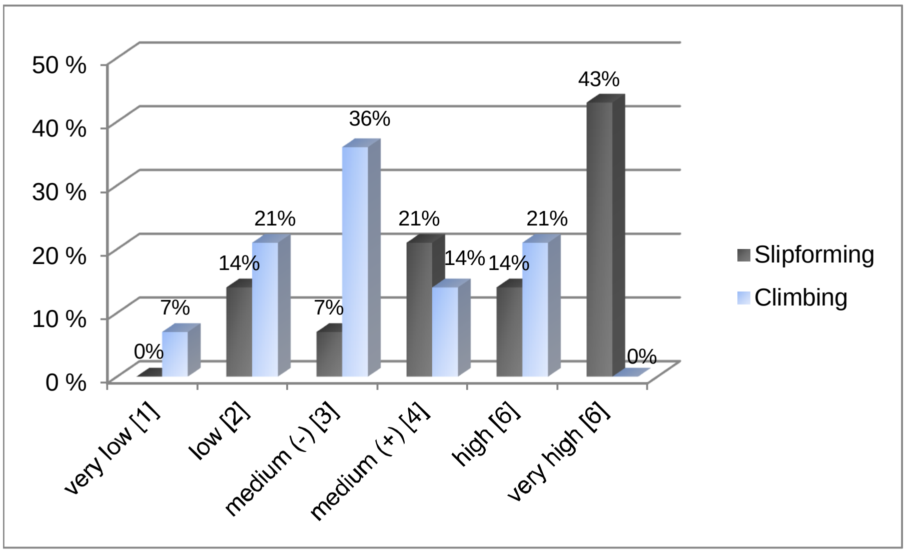

Fig. 9.6 Changes of the ground plan

	Slipforming	Climbing
Median:	5.00	3.00
Standard Deviation:	1.50	1.25

With a median of 5.00, changes of the ground plan with **slipforming** technology can be evaluated as **high**. Although the standard deviation is rather high, there is an explicit tendency that such changes might lead to complications. Even 43% of the participants evaluated changes of the ground plan as very high.

In this category, the median of **climbing** formwork technology with 3.00 lies clearly beyond the median of slipforming technology and can be evaluated as **medium (-).**

Conclusion

According to the expert opinions, changes of the ground plan are unambiguously more complicated with slipforming technology than with climbing formwork technology.

10. *How complicated are **changes** in **geometry** of the building during the construction phase?*

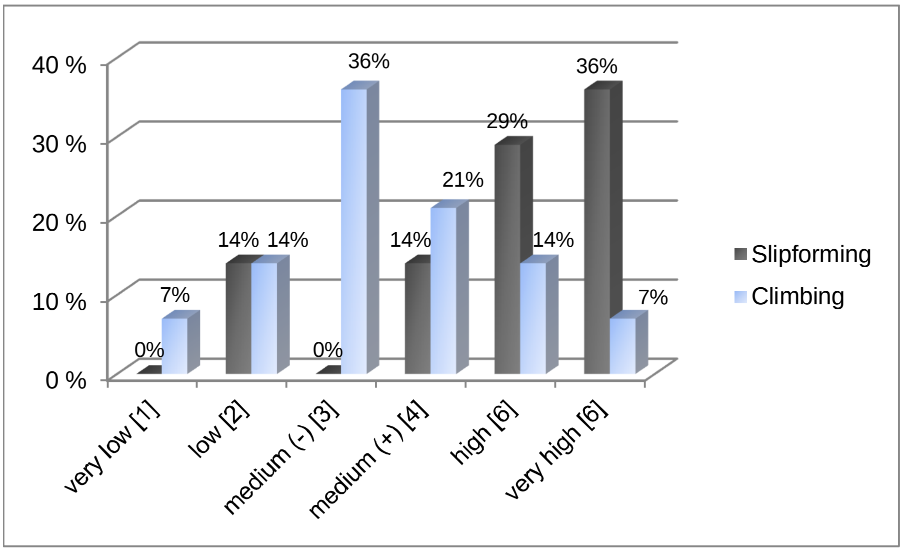

Fig. 9.7 Changes in geometry

	Slipforming	Climbing
Median:	5.00	3.00
Standard Deviation:	1.42	1.34

The result of the changes in geometry is similar to changes of the ground plan. With a median of 5.00, **slipforming** technology can be evaluated as **high**. Even 36% said that it is very complicated and evaluated it as very high. When adding up the number of percentages of slipforming technology, a total sum of only 92.9% can be calculated. This is because only 13 participants evaluated this question.

A median of 3.00 and the answer frequency of 36% lead to a result of **medium (-)** for **climbing** formwork technology.

Conclusion

According to the expert opinions, changes in geometry are unambiguously more complicated with slipforming technology than with climbing formwork technology.

11. *How **expensive is the specific concrete mix** for each formwork solution?*

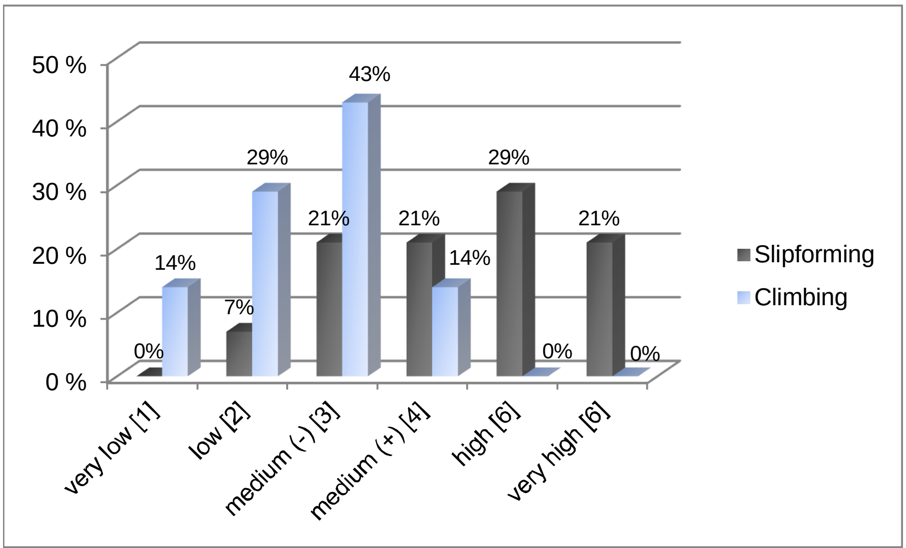

Fig. 9.8 Prizing of specific concrete mix

	Slipforming	Climbing
Median:	4.50	3.00
Standard Deviation:	1.28	0.94

Due to the median of 4.50, the specific concrete mix can be rated between **medium (+)** and **high** expensive for **slipforming** technology. But it must be mentioned that the highest number of percentages with 29% goes to the score high. Even 21% evaluated the prizing for a specific concrete mix as very high. Because of the low number of participants and the standard deviation of 1.28, the author would evaluate this point rather **high** than medium (+).

Due to the median of 3.00 and a rather low standard deviation of 0.94, **climbing** formwork technology can be evaluated as **medium (-).**

Conclusion

The specific concrete mix seems to be more expensive when using slipforming technology than climbing formwork technology.

12. *How complicated is it to fix **box-outs for openings or embedments** in the concrete?*

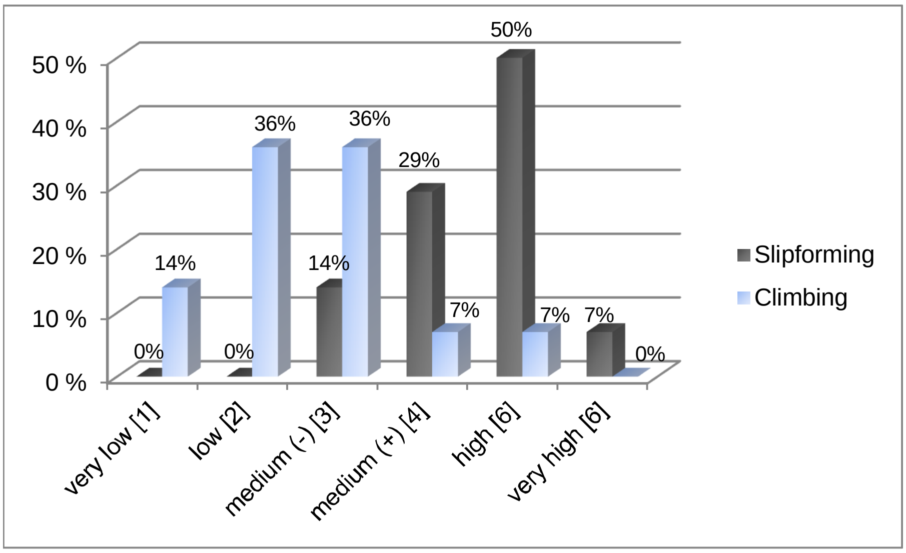

Fig. 9.9 Installation of box-outs and embedment's

	Slipforming	Climbing
Median:	5.00	2.50
Standard Deviation:	0.86	1.09

Installing box-outs and embedments in the concrete with **slipforming** technology has a median of 5.00 and can therefore be evaluated with the score **high**. Also the low standard deviation and the percentage high percentage value of 50% indicate this score.

The installation of box-outs and embedments is explicitly less complicated with **climbing** formwork technology and can be evaluated between **low** and **medium (-)** or even as low.

Conclusion

According to the opinion of the experts, fixing box-outs and embedments in the concrete is definitely more complicated with slipforming technology.

*13. How much effort and resources are required in **fixing the reinforcement?***

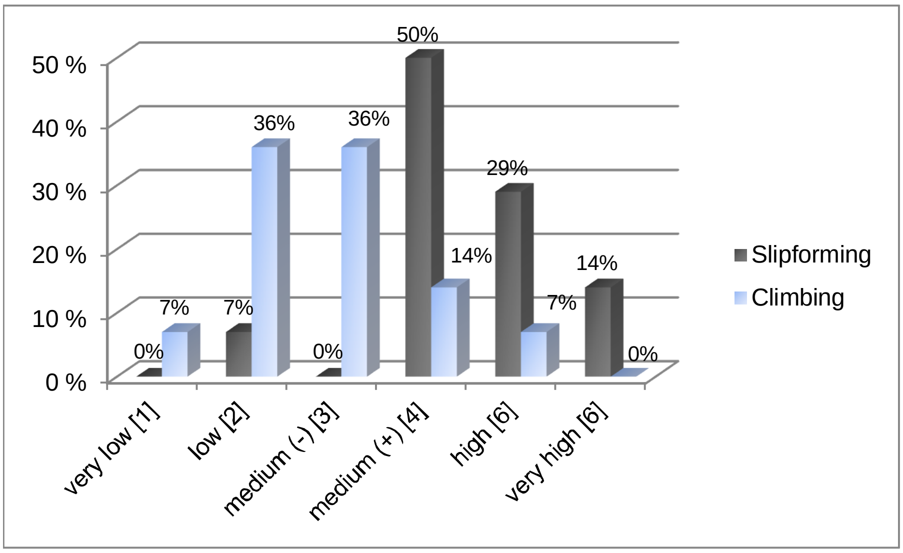

Fig. 9.10 Effort and resources required for fixing the reinforcement

	Slipforming	Climbing
Median:	4.00	3.00
Standard Deviation:	1.02	1.05

50% of the participants evaluated the fixing of the reinforcement using **slipforming** technology as **medium (+),** the same result is indicated by the median of 400.

Climbing formwork technology comes to the average result **medium (-)**.

Conclusion

For fixing the reinforcement, there is a tendency that more effort and resources are required with slipforming technology.

14. *How would you assess the* ***cost expenditure*** *for the* ***reinforcement work?***

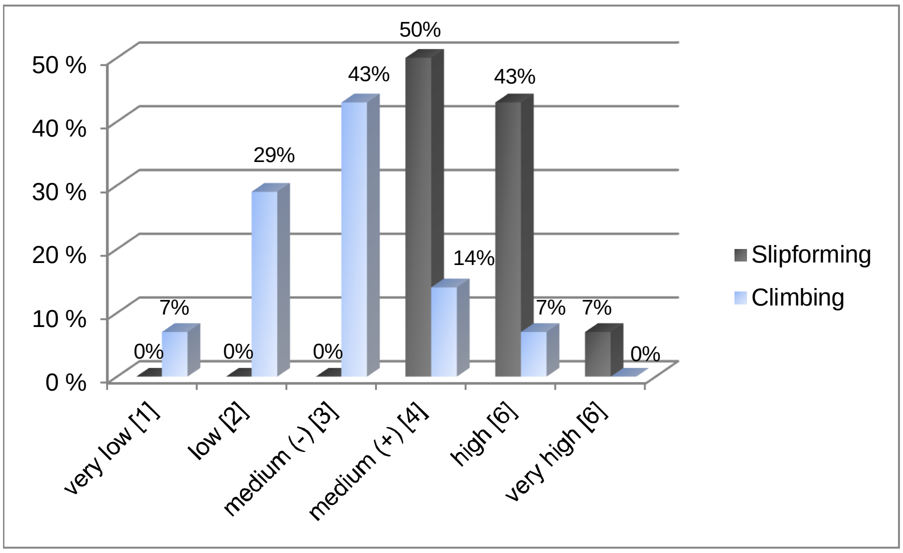

Fig. 9.11 Cost expenditure for reinforcement work

	Slipforming	Climbing
Median:	4.50	3.00
Standard Deviation:	0.65	1.03

There is a conspicuous low standard deviation with 0.65 for the result of **slipforming** technology. The categories very low, low and medium (-) did not get a single vote. 50% evaluated the cost expenditure as medium (+), 43% as high and 7% as very high. Therefore it can be categorized between **medium (+)** and **high**.

The cost expenditure for the reinforcement is lower with **climbing** formwork technology. The maximum percentage value of 43% for medium (+) and the median of 3.00, lead to a final result of **medium (+).**

Conclusion

In the opinion of the experts, the cost expenditure for the reinforcement work is clearly higher with slipforming technology.

15. *How much **effort** do you have to spend in terms of **logistical aspects** (permanent concrete supply, other material supply and storing capacity)?*

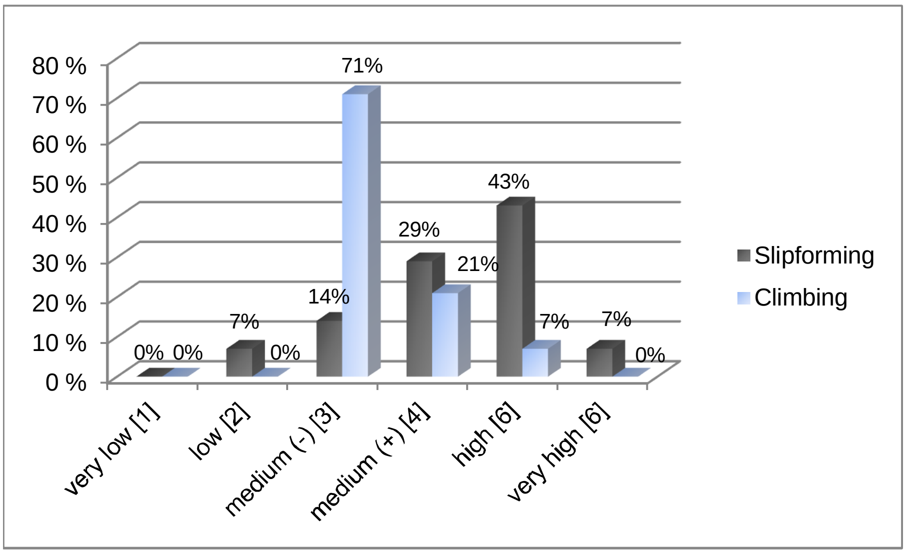

Fig. 9.12 Effort of logistical aspects

	Slipforming	Climbing
Median:	4.50	3.00
Standard Deviation:	1.07	0.63

According to the participants, permanent concrete supply is a big issue for **slipforming** technology. This explains the quite high median of 4.50. 43% of the participants evaluated logistic aspects as high. The result can be interpreted between **medium (+)** and **high**.

A high percentage value of 71% evaluated the logistic aspects of **climbing** formwork technology as **medium (-).** Also the median indicates this.

Conclusion

Especially the necessity of permanent concrete supply makes logistical aspects more complicated for slipforming technology.

16. *How much **more effort** do you have to spend in terms of **safety construction issues?***

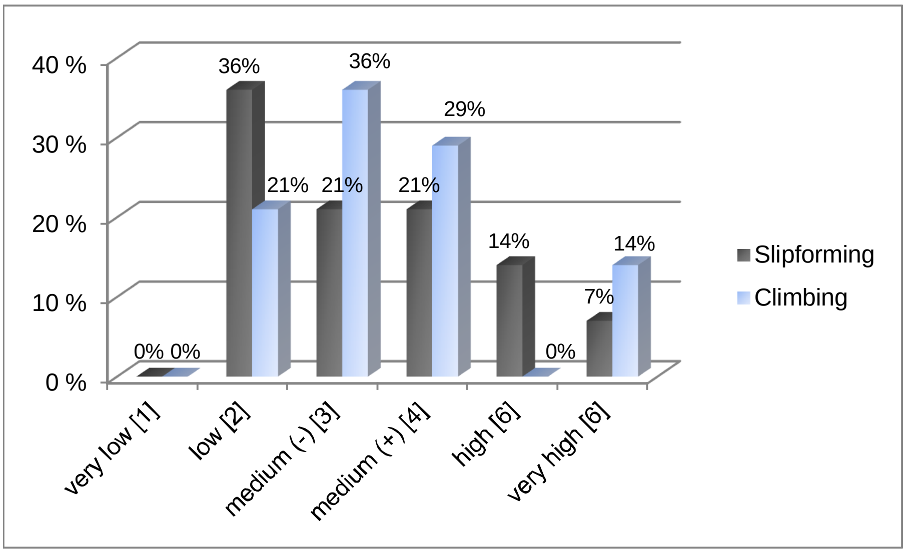

Fig. 9.13 Safety construction issues

	Slipforming	Climbing
Median:	3.00	3.00
Standard Deviation:	1.34	1.29

Due to the median of 3.00, the effort of safety construction issues can be evaluated with **medium (-)** for **slipforming** technology. The standard deviation is quite high and the percentage distribution too.

Climbing technology comes to a median of **medium (+)**. Also here, the standard deviation is rather high, same as the percentage distribution.

Conclusion

The effort to be spent in terms of safety construction issues seems to be equal for slipforming technology and climbing formwork technology.

17. What are in your opinion the biggest **advantages** of **Slipforming** Technology?

Table 9.5 Advantages of slipforming technology

	yes definitely	yes certainly	yes generally (+)	Yes generally (-)	Yes moderately	Yes but not essentially	No
Construction time	54%	31%					15%
No anchoring	14%	14%	14%	21%			36%
Monolithic construction	7%	14%		14%	7%	7%	50%
Crane independence	14%	14%	7%	7%	14%	7%	36%
Assembling procedure			7%	14%	7%		71%
Material costs		7%	14%	7%			71%
Total costs	7%	7%	21%	14%			50%
Lifting during wind		14%	21%	14%	7%		43%
Others		7%					93%

According to the participants, the low **construction time** is the biggest advantage of slipforming technology. With a median of around 6 it can be evaluated with **Yes definitely**. Followed by **now anchoring** which can be evaluated with **Yes generally (-).**

Even though most of the participants who took part in a face-to-face interview said that the total costs very often are determining for the decision over a formwork system, the point **total costs** was only evaluated with a median of 1.50. That means it is exactly between **Yes but not essentially** and **Yes moderately**. This result might be explained with the quite high number of participants who do not consider the total costs as an advantage for slipforming technology.

All other factors were evaluated with less decisive than Yes generally (-). 93% of the participants said that there are no other advantages, one participant mentioned that no plywood is also of prime importance and rated it with 5, which equals with Yes certainly.

The standard deviations of all factors are quite high, which means that the participants have very different points of view regarding the advantages of slipforming technology.

18. *What are in your opinion the biggest **disadvantages** of **Slipforming** Technology?*

Table 9.6 Disadvantages of slipforming technology

	yes definitely	yes certainly	yes generally (+)	Yes generally (-)	Yes moderately	Yes but not essentially	No
Lower flexibility	21%	21%	21%		7%	7%	21%
Lower durability			7%	14%			79%
Quality of exposed concrete surfaces	14%	21%	7%	21%			36%
Only steel bars applicable	7%		7%	14%	7%		64%
Necessity of early and definite planning		23%	8%	15%	8%		46%
Installing the reinforcement		31%	23%	15%			31%
Low concrete strength			21%	7%			71%
Noise			21%	7%			71%
Problems by installing built-in parts		29%	14%		21%		36%
Difficulties to change the plywood		7%	7%	14%	7%	7%	57%
Others	14%		7%				79%

As the biggest disadvantages are mentioned the **low flexibility** and the **installation of the reinforcement**, both are evaluated with a median of 4.00. Therefore, they can be rated with **Yes generally**. Exposed concrete quality is number three of the biggest disadvantages with a median of 3.00 and therefore a rating of Yes generally. An interesting point is that the installation of built-in parts, with a median of only 2.00, was rated quite low. Two participants mentioned other factors. One person rated initial complications in the setting up stage of a slipform with 4, the other person said that the biggest disadvantage of slipforming technology is the quality.

Also for the opinion of disadvantages, the standard deviations are high.

*19. Which factors define in your opinion the **limits** of **Slipforming** Technology?*

Table 9.7 Limits of slipforming technology

	yes definitely	yes certainly	yes generally (+)	Yes generally (-)	Yes moderately	Yes but not essentially	No
Concrete surface quality	21%	7%		21%	7%		43%
Concrete pressure	8%		15%	15%	8%		54%
Reinforcement	15%	8%	23%	8%			46%
Shift operation in residential areas	21%	14%	7%		7%	7%	43%
Building geometry		14%	21%	21%	7%		36%
Building height	7%	7%		7%		7%	71%
Amount of built-in parts		14%	21%	7%	14%		43%
Necessity of early and definite planning		21%		21%			57%
Others	7%						93%

According to the mean values, slipforming technology has no definite limits. The **reinforcement** and the **building geometry** came to the highest median evaluated with **Yes generally (-).** One participant said in the interview that the limits of technology only depend on the operator on site.

Again, the standard deviations are quite high.

*20. Where are the **limits** of **concrete quality** and **strength** of **Slipforming** Technology?*

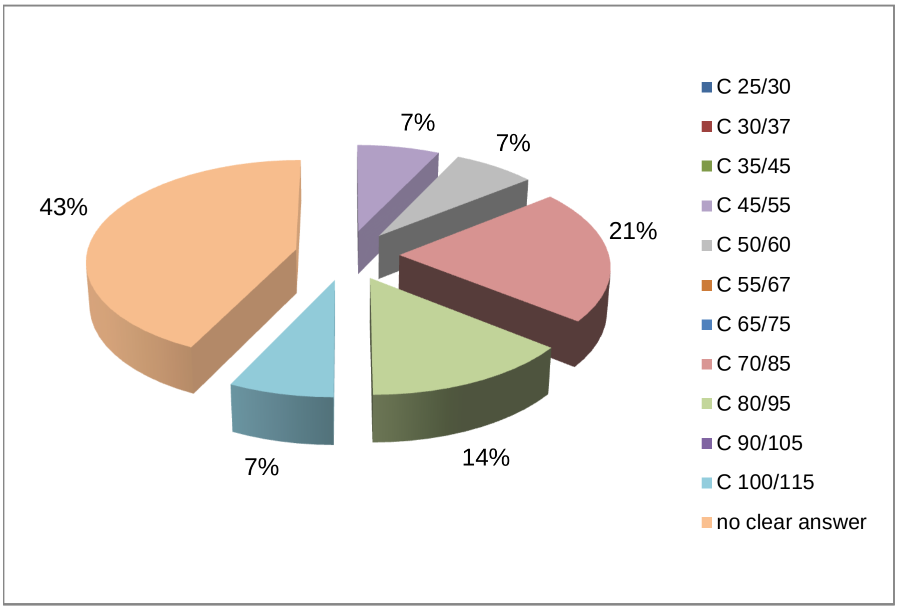

Fig. 9.14 Limits of concrete quality and strength

For the limits of the concrete quality and strength, the opinions of the participants vary strongly. 43% of the participants were not able to give an answer, 2 participants named a quite low concrete strength (C45/55 and C50/60) as the limit. The majority of the participants who answered this question agreed that the **limits of slipforming technology** lie approximately between **C70/85 and C80/95**.

One participant mentioned that 100MPa concrete pressure were tested, nevertheless, he rated the limit with C70/80. Another person said the C80/95 is possible but very rare.

According to the expert opinions, for slipform projects, concrete strengths between C30/37 and C35/45 are used.

*21. What would you define as **exclusion criteria** for **Slipforming** Technology?*

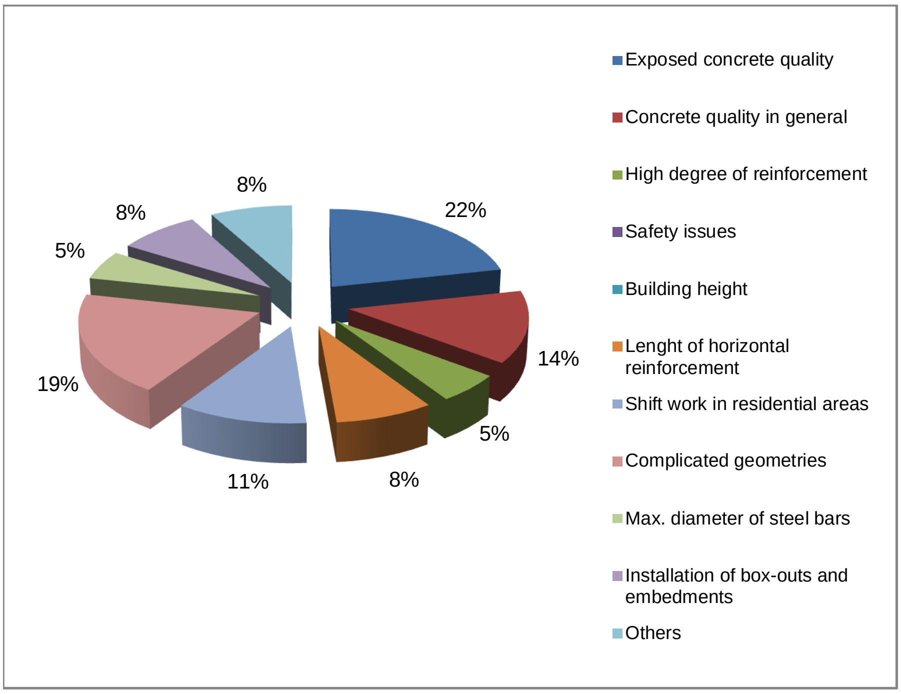

Fig. 9.15 Exclusion criteria for slipforming technology

With 22%, the exposed concrete quality is the most decisive exclusion criteria for slipforming technology, followed by complicated geometries with 19%. It is interesting that the result does not fit with the result of question *19. Limits of slipforming technology*. Here, a high degree of reinforcement is more essential and the exposed concrete quality does not influence the limit of slipforming technology strongly.

Because the standard deviations of question 19 are quite high, and also some participants rated the exposed concrete quality with a high score as a limit of slipforming technology, it can be presumed that the three factors **exposed concrete quality, high degree of reinforcement** and **complicated geometries** are determining the **limits for slipforming** technology and can also be exclusion criteria, even though only 5% of the participants rated the high degree of reinforcement as an exclusion criteria.

It must be mentioned that this question is evaluated with nominal number and question 17, for example, with a six point ordinal scale. That means, there is no graduation, it is only distinguished if it is an exclusion criteria or not. Thus, the percentage values of those questions cannot be compared directly.

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22. *What are in your opinion the biggest **advantages** of **Climbing Formwork** Technology?*

Table 9.8 Advantages of climbing formwork technology

	yes definitely	yes certainly	yes generally (+)	Yes generally (-)	Yes moderately	Yes but not essentially	No
Quality of exposed surfaces	36%	14%	7%	14%			29%
Flexibility in geometry	15%	15%	23%	15%			31%
Flexibility in mounting the reinforcement	15%	23%	15%	15%			31%
Safe access to work face	21%		21%	14%			43%
Concrete quality	14%	7%	14%	7%			57%
Independence of permanent concrete supply		36%	7%	7%	7%		43%
Independence of cranage	7%	7%	21%	7%		7%	50%
Others	14%	7%					79%

With a median of 4.50, the **quality of exposed concrete** is the biggest advantage of climbing formwork technology and can be rated as **Yes certainly**. Followed by the **flexibility in geometry** and by the **flexibility in mounting the reinforcement**, which have both a median of 4.00, therefore they are rated with **Yes generally**. The other factors are evaluated with less than average and thus, they are not considered as significant advantages.

One participant said that climbing formwork is more user-friendly and implies fewer problems than slipforming technology. He also mentioned as advantage that workforces can be trained to work with climbing formwork technology within one month.

Similar to the answers of the advantages and disadvantages of slipforming technology, the standard deviations of the answers here are quite high.

23. *What are in your opinion the biggest* ***disadvantages*** *of* ***Climbing Formwork*** *Technology?*

Table 9.9 Disadvantages of climbing formwork technology

	yes definitely	yes certainly	yes generally (+)	Yes generally (-)	Yes moderately	Yes but not essentially	No
Material costs	14%	14%	14%	7%			50%
Construction time	7%	21%	21%	7%	7%		36%
Casting steps		31%	15%	15%			38%
Total costs	7%	21%	29%	14%			29%
Non-monolithic construction		14%				7%	79%
Limits by lifting during wind		21%	7%	14%	7%		50%
Others							100%

The **total costs** with a median of 4.00 can be evaluated with **Yes generally (+)** as the biggest disadvantage of climbing formwork technology. It is interesting that in question *17. Biggest advantages of slipforming technology,* the total cost are rated only with a median of 1.50. The answers do not fit together, but according to the face-to-face interviews, the total costs play a crucial rule in the decision process and thus, the result of question 17 might be inaccurate. With a median of 3.50, the **construction time** is located exactly between **Yes generally (+)** and **Yes generally (-)**. It is evaluated as the second biggest disadvantage of the participants, considering the mean values.

It must be mentioned that also here the standard deviations have high values, because the answers of the participants are varying strongly.

*24. Which factors define in your opinion the **limits** of **Climbing Formwork** Technology?*

Table 9.10 Limits of climbing formwork technology

	yes definitely	yes certainly	yes generally (+)	Yes generally (-)	Yes moderately	Yes but not essentially	No
Material costs	14%		7%				79%
Construction time	14%		21%	7%			57%
Casting steps	8%		23%	8%			62%
Technical issues			14%	7%		7%	71%
Total in-use costs		36%	7%				57%
Non-monolithic construction	8%	8%					85%
Limits by lifting during wind			7%	7%	7%		79%
Others							100%

Even though some participants evaluated some factors with Yes, unexceptionally, in all categories the median is 0. The reason therefore is the fact that such a high percentage of participants did not evaluate the factors as a limit of climbing technology. Considering only the mean values, there are **no limits** for **climbing** formwork technology.

But in practice, there are definitely projects where climbing formworks cannot compete with a slipform. Constructions like silos, or monolithic buildings with a low number of embedments are best suited for slipforming technology. Especially the construction time and the fact that it is not possible to construct a non-monolithic construction with climbing technology brings this system to its limits.

Again, the answers have high standard deviations.

25. *What would you define as **exclusion criteria** for **Climbing Formwork** Technology?*

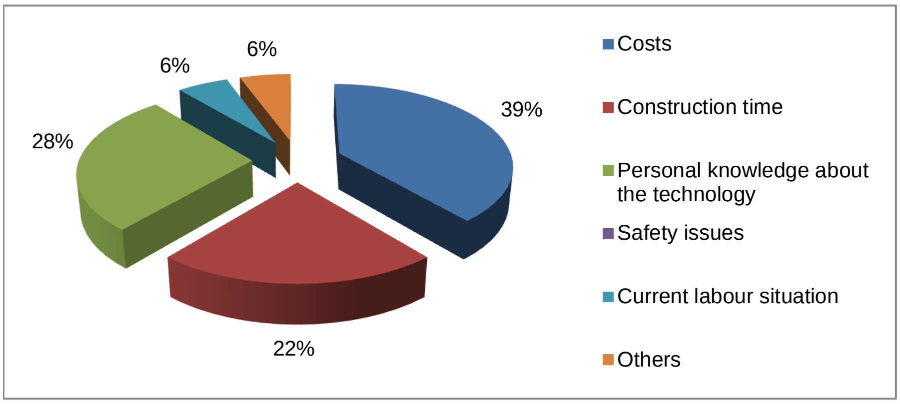

Fig. 9.16 Exclusion criteria for climbing formwork technology

With 39%, the costs are definitely the most decisive exclusion criteria for climbing formwork technology. It is very interesting that 5 of 14 people (28% of all answers) evaluated the personal knowledge about climbing formwork technology as an exclusion criterion. This is even more than the construction time with 22%. The other factors are insignificantly low.

26. *Are there any kinds of projects for which you consider exclusive use of **Slipforming** companies?*

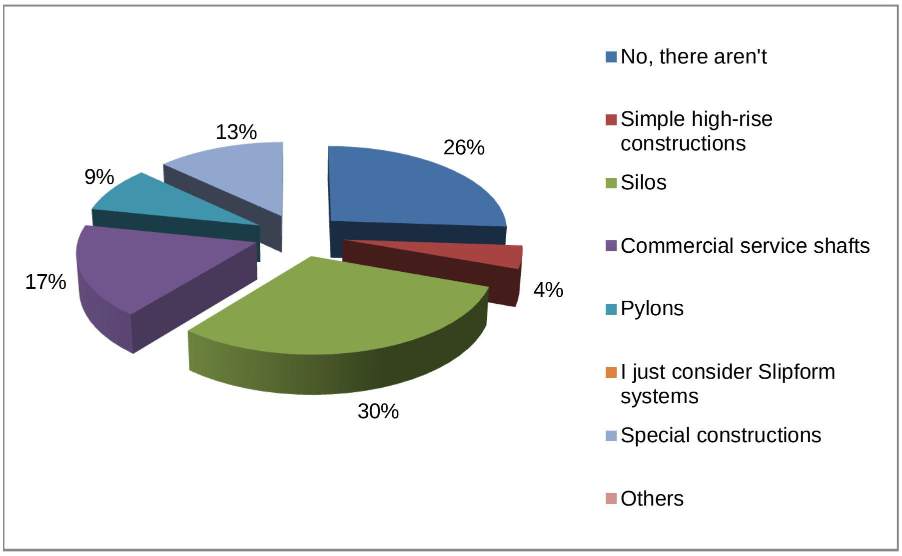

Fig. 9.17 Projects with exclusive use for slipforming technology

In principle, Figure 9.17 is self-explaining. But it must be mentioned that the category “depends on” is not included in the graph. Three participants ticked off this point: One said it depends on a number of factors, the second person said that it depends on the crane availability on site and the third noted that it depends on the results of the analysis which are used for decision making.

27. *Which service do you **expect** to get offered by a formwork company?*

	Persons	In %
Design	0	0%
Design + material supply	0	0%
Design + material supply + advice	12	75%
Design + material supply+ advice+ labour	4	25%

The reason why 75% of the participants prefer to get offered the service without labour is that they have lower labour costs when employing their own workforces. One participant mentioned that he would appreciate a full turnkey solution. Another person ticked off both answers.

28. *What kind of construction would you define as **typical projects** for **Slipforming** Technology?*

- High-rise towers up to 180m
- Silos (9x)
- Curved cores (2x)
- Continuous vertical elements
- High-rise with simple core wall structures I
- Pylons (3x)
- Tanks (3x)
- Not lift cores
- Structures with constant wall thickness or minor variations
- Chimneys (2x)
- High-rise construction with more than 8 floors, more than 100 m of wall and no finish requirements (UK)
- Towers (2x)
- Shaft cores
- Wind wheels of offshore projects

29. *What kind of construction would you define as a **typical project** for **Climbing Formwork** Technology?*
    - Towers with complicated core shape
    - Big building cores
    - High-rise buildings with irregular changes in geometry and dimensions
    - Structural complications (e.g. PT beams, many box-outs, openings)
    - Lift cores
    - Any construction going ahead without the floor slab (e.g. lift and stair shafts, dam wall, large diameter tanks, piers, etc.)
    - High-rise buildings (5x)
    - Pylons (2x)
    - Shafts (2x)
    - Changing shapes (UK)
    - Small cores (UK)
    - Buildings with high specific finish requirements (UK)
    - Towers
    - Dam walls
    - Silos
    - All projects

30. *In which kind of projects is the **competition** between Slipforming Technology and Climbing Formwork Technology **closest**?*
    - High-rise buildings up to 30 floors (100-150m)
    - High-rise buildings (in Dubai not in Australia)
    - High-rise buildings (3x)
    - Shafts
    - Pylons (2x)
    - Silos (2x)
    - High-rise buildings between 10 and 20 floors with about 80 - 100 m of wall and no finish requirements (UK)
    - Towers (2x)
    - Chimneys

31. *What are your **key requirements** concerning the choice of formwork systems?*

- Cost (5x)
- Time (4x)
- Quality (exposed concrete)
- Safety (3x)
- Availability (2x)
- Efficiency
- Cutting-edge technology
- Less labour
- Crane independence
- Service solution
- Quality/time
- Buy back option
- Reliability
- Best time saving
- Technical support
- Costumer requirements
- Logistical aspects
- Depends on the project (2x)
- Knowhow of the formwork contractor
- Manpower delivery

II. Decision-making Factors

*32. Do you use **methods** for **decision-making**?*

Table 9.11 Used methods for decision-making

	yes definitely	yes certainly	yes generally (+)	Yes generally (-)	Yes moderately	Yes but not essentially	No
Cost-utility analysis	7%	7%				21%	64%
Cost benefit analysis	23%	23%	8%	8%	8%	8%	23%
Cost effectiveness analysis	7%	29%			7%		57%
Brainstorming method		38%					62%
Decision matrix	7%	21%		7%			64%
Morphological analysis				14%			86%
SWOT analysis			7%		7%		86%
Potential analysis						8%	92%
Decision tree							100%
Personal experience	31%	15%	23%	8%			23%
Others	8%	8%					85%

Table 9.11 shows in percentages which methods for decision making are used by the participants. In average, the most used method is the **cost benefit analysis**, but still, the **personal experience** is of higher importance for the participants than any method for decision making.

In conclusion, a low number of participants take use of methods for system selection and decision making. Apart from the cost benefit analysis, all other methods are used less than 50%. Half of the methods are used even less than 80%. One participant uses logistic programs, another one uses a company intern method.

33. *System decision*

a. *Who in your organisation has the greatest influence and makes the decision in selection the preferred Formwork system?*

- Technical director + project manager
- Always project manager and construction manager and others
- Project manager (4x)
- Operations manager, Constructions manager, Contracts manager, Formwork manager
- Technical office, Construction manager
- Planner, Contracts manager (UK)
- The whole team
- Construction manager (3x)
- Head of department
- Foreman

b. *Which factors do you compare in selection process?*

- Cost (9x)
- Time (5x)
- Safety (5x)
- Performance of the system
- State of art of the system
- History of the system
- Cost-effectiveness
- Program of works (2x)
- Building geometry
- Availability of cranes
- Availability (2x)
- Costumer conditions
- Company intern equipment
- Employment of staff
- Warranty
- Total costs of ownership

c. *How do you compare*

- Analysis of all systems, after final analysis comparing the systems
- Full technical and cost analysis (cost analysis has priority)
- Program vs. costs
- Full analysis (does the system fulfil the requirements), price is secondary
- Depends on the project
- Cost-benefit analysis
- Weighted price comparison
- Interviewing the contractor
- Evaluating the quality of the quotation

d. *Which companies do you compare (only asked in Dubai)*

- Local companies
- All companies (3x)
- Slipform middle east
- BRM
- DOKA
- PERI
- ALUMA

*e. Which of the factors: **Quality, Costs and Time** would you describe as the **most decisive** for **decision-making**?*

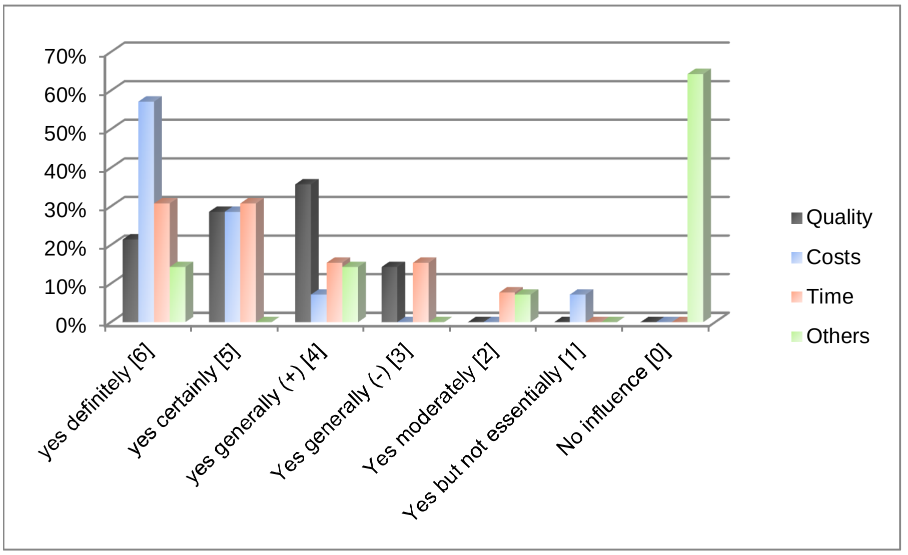

Fig. 9.18 Quality, costs and time as decisive factors

	Quality	Costs	Time	Others
Median:	4.50	6.00	5.00	0.00
Standard Deviation:	1.02	1.37	1.33	2.37

This statistical evaluation makes it obvious that only the three factors costs, time and quality influence the decision-making process, whereas the **costs** emerge as the most decisive factor. With a median of 6.00, they can be evaluated with **Yes definitely**, followed by the factor time.

The result shows that also the factors time and quality play a crucial role in the decision-making process and must not be neglected. All three factors are rated very high with a lowest media of 4.50. Even though the point others came to a media of 0.00, two participants mentioned **safety** as a decisive criterion for the decision-making process.

f. *Which of the factors: **Quality, Costs and Time** would you describe as the **most decisive** for **excluding** a system?*

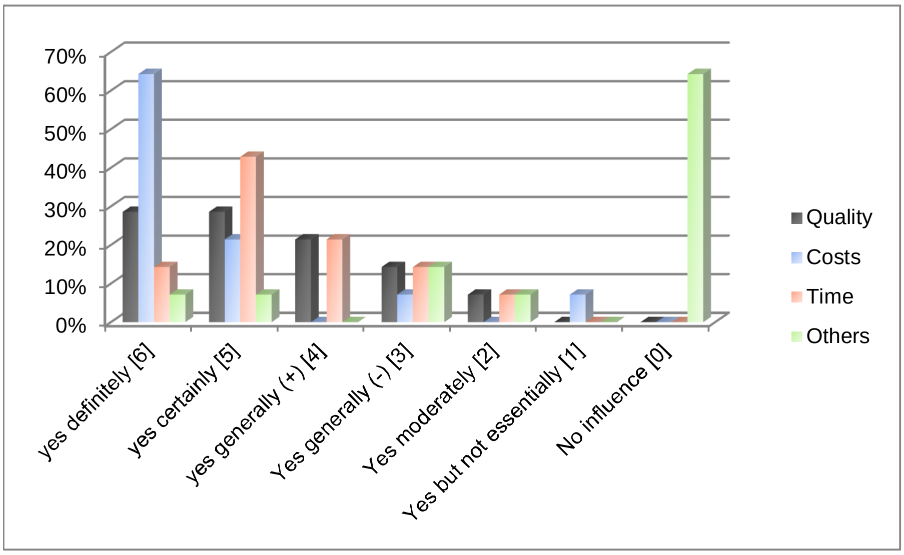

Fig. 9.19 Quality, costs and time as exclusion factors

	Quality	Costs	Time	Others
Median:	5.00	6.00	5.00	0.00
Standard Deviation:	1.28	1.48	1.16	2.10

As expected, the result of this question is very similar to the result of question 33.e). Also here, only the factors costs, time and quality are evaluated regarding to whether a system is excluded or not. Two participants mentioned the factor safety as an exclusion criterion, for another participant the availability of the product is also an exclusion criteria. Again, the costs are the determining factor, closely followed by the factors time and quality.

Many participants did not understand why this question was asked, they did not see a difference to question 33.e). Question 33.e) is about decision criteria, question 33.f) is about exclusion criteria. It was asked in both ways in order to find out if the participants distinguish between decision criteria and exclusion criteria. One further target was to find out if there are other factors that influence the decision-making process.

*34. Influence of **soft facts***

a. Do you personally have a tendency to the Slipforming Technology or to the Climbing Technology?

b. Does your workforce prefer to work with Slipforming systems or Climbing Systems?

c. Which system is easier for your workforces to work with?

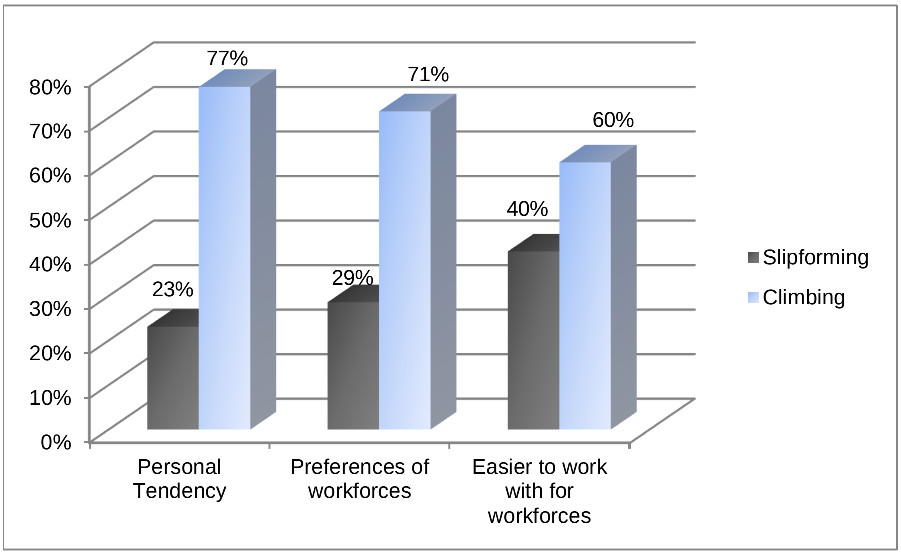

Fig. 9.20 Influence of soft facts a-b-c

Figure 9.20 shows to result of the questions 34 a, b and c. In all three categories climbing formwork technology is performing better than slipforming technology.

d. *Does your workforce have equal skills and knowledge about both systems?*

Yes	8
No	7

e. *Does the current labour situation influence the decision which formwork system you choose?*

Yes	4
No	10

f. *Do you own a Slipforming system in your company?*

Yes	2
No	12

g. *Do you own a Climbing formwork system in your company?*

Yes	7
No	7

h. *Does your relation to Sub-contractors influence your decision for the formwork system?*

Yes	8
No	6

III. Future demands of Slipforming and Climbing Formwork Technology

*35. Do you think there is a **development potential** for **Climbing Formwork** Technology?*

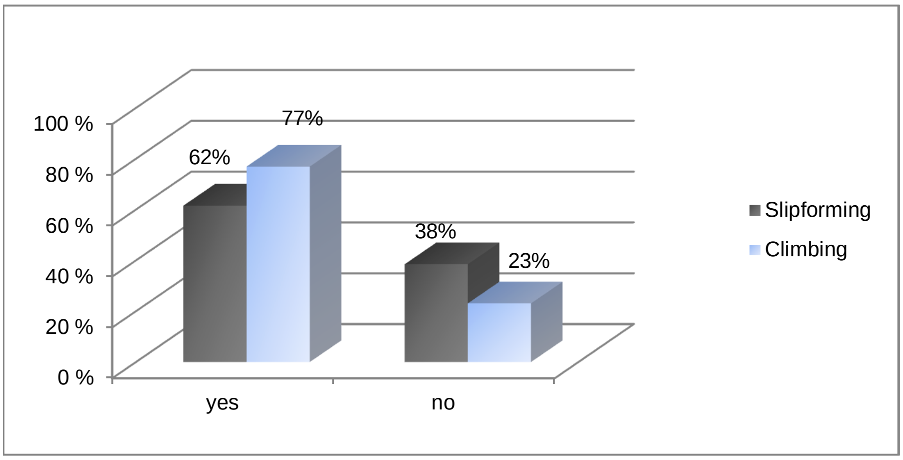

Fig. 9.21 Development potential for slipforming and climbing formwork systems

According to the answers of the participants, there is development potential for both technologies, whereas potential of climbing formwork technology is evaluated slightly higher.

What is missing in climbing formwork technology?

- Self-vibrating walls
- more auto control
- Smarter and more competitive system
- Lost effectiveness, speed, present market condition
- Technical and practical improvements are required for automatic climbing systems
- Safety at work
- System reliability
- Application of sensor technology
- Set-up needs to be quicker
- Lightweight systems
- Higher independence of concrete strength, wind and weather condition

*36. Do you think there is a **development potential** for **Slipforming** Technology?*

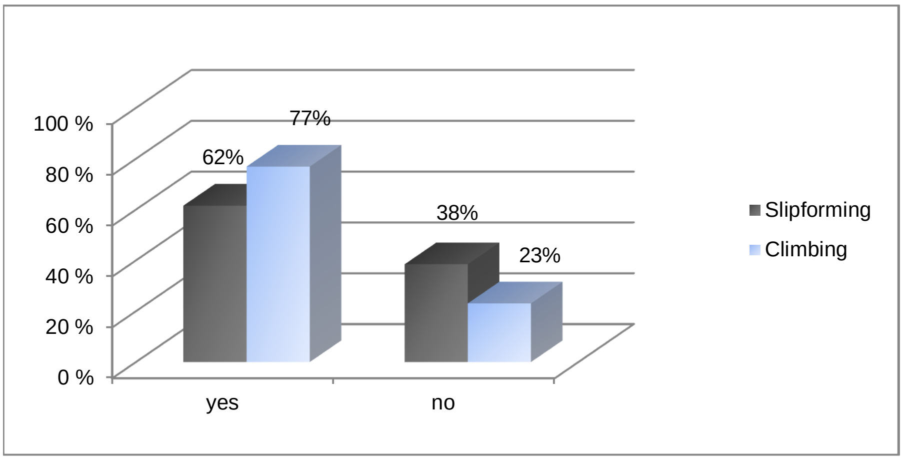

Fig. 9.22 Development potential for slipforming and climbing formwork systems

According to the answers of the participants, there is development potential for both technologies, whereas potential of climbing formwork technology is evaluated slightly higher.

What is missing in slipforming technology?

- Smarter and more competitive system
- Better quality is required
- Solutions how to tackle embedments, box-outs, geometry changes
- Slipforming is an old system, without progression for many years
- Safety at work
- System reliability
- Application of sensor technology
- Formwork sheeting made of stainless steel

*37. How do you see the **demand** of **Slipforming** Technology in **future**?*

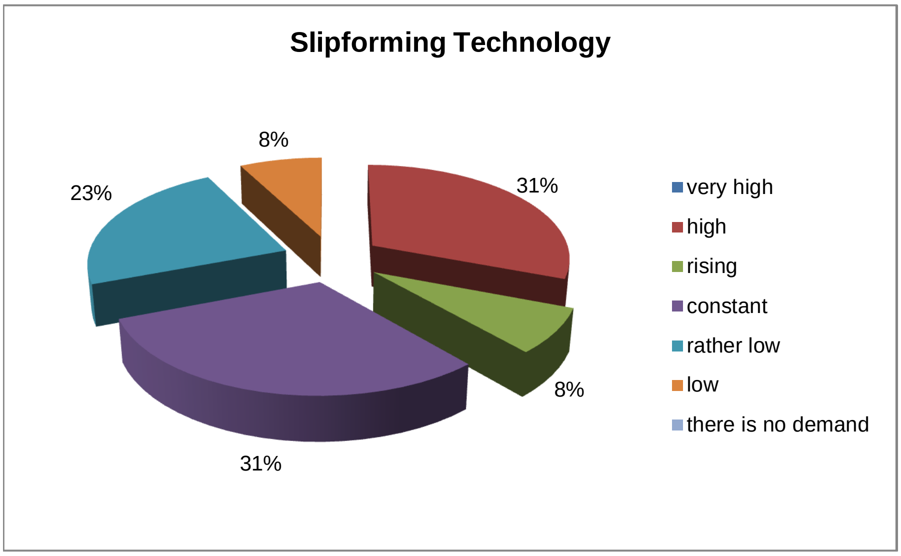

Fig. 9.23 Demand of slipforming technology in future

With a mean value of 3.00, the future demand of slipforming technology can be evaluated as **constant** even though 31% of the answers were rated as high. The standard deviation of the answers is 1.38.

In the interviews all participants agreed that there will be a market for slipforming technology in future, but for providing a quantitative answer, a separate research study needs to be done.

*38. How do you see the **demand** of **High-rise constructions** in **future**?*

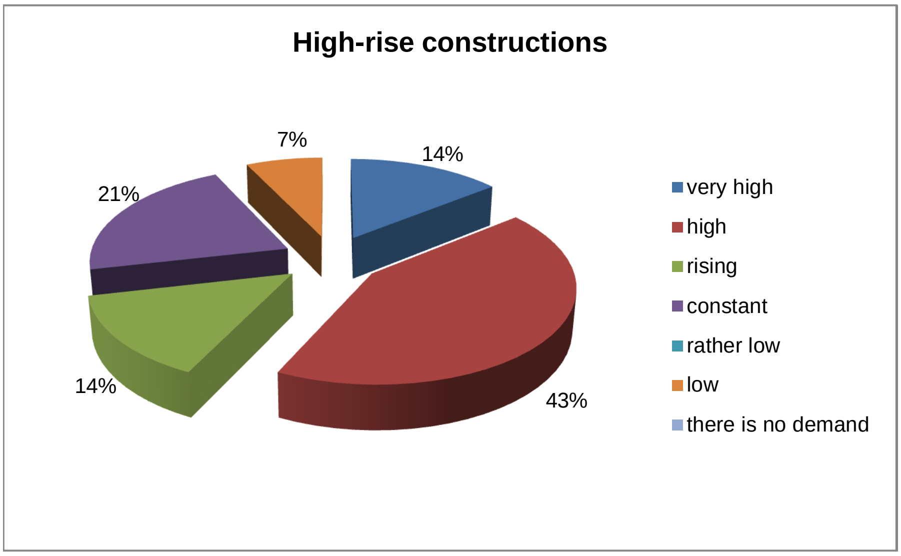

Fig. 9.24 Demand of high-rise constructions in future

According to the statistical evaluation, there will be a higher demand for high-rise construction than for slipforming technology. This makes sense, otherwise the capacity of slipforming would not be used. The median comes to 5.00, thus, the demand for high-rise construction in future can be evaluated as **high**.

At this point, the question came up about which kind of high-rise constructions will be demanded in future. The majority of the participants believe that there will always be a market for residential high-rise buildings, but the future of prestigious high-rise buildings is uncertain.

39. *Would you like to **add** something that you consider as important?*

Below the quotations of the participants who wrote something additionally are stated:

1. *Both systems have their advantages and disadvantages. Technology can be used to improve the systems and to reduce the disadvantages and make it user friendly. Also reduce the manpower requirement.*

2. *Jumpform technology is a problem eliminator because things are easier to be changed.*

3. *There is a market for slipform technology anyway, slipform is perfect.*

4. *Demand for:*
   - *formwork sheeting made of synthetic composite panels*
   - *frame formwork made of composite material in order to avoid thermal bridges for the construction of pylons in winter*
   - *insulated formwork, or formwork that can be heated in order to accelerate the hardening process of the concrete*

5. *There are a lot of regulations in each country and all have their specific requirements, but in the end the risk has to be borne by the building contractor.*

6. *Climbing formwork technology is more like a business development, in the future there will be more demand for labour delivering…*

10 Conclusion

Because of the low number of participants, the statistical evaluation was done in a descriptive way. **Descriptive statistics** are not based on probability theory, therefore, the results are quantitative summaries of the filled in questionnaires with simple graphs wherefrom **tendencies** can be interpreted.

In **technical aspects**, the participants evaluate climbing formwork technology better than slipforming technology. Only in the category "How much effort and resources are required in the main phase and in the end phase", slipforming technology performed slightly better than climbing formwork technology. In safety issues and in the selection process, both technologies are rated equal. In all other technical categories, climbing formwork technology outperformed slipforming technology.

From the technical point of view, as the biggest advantages of slipforming technology the shorter construction time and the fact that no anchors need to be installed into the concrete are rated. Low flexibility and the installation of the reinforcement were evaluated as the biggest disadvantages.

According to the experts, the biggest advantages of climbing formwork technology are the exposed concrete quality, flexibility and the easier installation of the reinforcement. The construction time is rated as the biggest technical disadvantage of climbing formwork technology.

Most of the participants expect *design + material supply + advice* as **service** to get offered by a formwork supplying company. Due to the low labour costs in Middle East, labour does not necessarily need to be included in the offer.

The construction companies' **key requirements** concerning the choice of a formwork system are primarily costs, construction time, quality and safety issues as well as the availability of the products. Also a range of other factors were mentioned.

The project manager and the construction manager have the greatest **influence on the selection process** of a formwork system, but there are also other people involved. Systems are compared by doing a total analysis of each technology. Primarily the costs are compared, but also the factors time, quality, safety issues, availability as well as the whole project specific program. Some participants take use of cost-benefit analysis to compare formwork systems, other decision-making methods are rather unregarded or neglected. Most of the participants compare local formwork supplying companies, some also compare all suppliers around the world.

The **highest competition** between slipforming technology and climbing formwork technology is in high-rise buildings, assumed that there are no special requirements regarding the concrete quality, and the ground plans and geometries of the buildings are rather simply designed.

Most of the participants **prefer to work** with climbing formwork technology, also the workforces rather have a tendency towards climbing formwork technology because it is easier to handle for them.

According to the statements of the participants, there is **development potential** for both technologies, but slightly more for climbing formwork technology.

The consulted experts hold the opinion that there is **future demand** for high-rise buildings as well as for slipforming technology.

In conclusion, both formwork systems are considered as good technologies with their advantages and disadvantages. Whether one of these two systems will be the system of the future could not be answered by the interviewees, but all of them agreed that slipforming technology is strongly competing with climbing formwork technology because of the lower cost expenditures. No interviewee regarded it as negative to invest in slipform equipment, especially when going beyond the high-rise sector.

11 List of literature

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