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CALCULATION OF "NORMAL" CONSTRUCTION TIME FOR BUILDING CONSTRUCTION PROJECTS WHILST CONSIDERING UNCERTAINTIES

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Construction time has a major influence both on the cost-efficient execution of construction works and on the overall project outcome achieved by the client. Clients would do themselves a disservice if they specified short or extremely short construction periods for their projects. The same applies to time made available for project preparation, particularly for the design and tender stages. Any project that is poorly planned, tendered, and executed under time pressure will adversely affect actual construction work but also the building's use and possible reuse. Cost, time and quality targets are at risk due to the resulting disruptions to the construction process. Productivity is adversely affected not only by unduly short but also exceedingly long construction times. Short or very short construction times have a major influence on the efficient and effective utilization of production factors, including elementary (workforce, materials, equipment and machinery) and discretionary factors (project manager, site manager, technicians, etc.). This paper outlines the basic correlation between construction time, labor consumption rates and productivity as well as construction cost. Furthermore, it sets out to determine the influence of construction time on costing and, consequently, on the construction process. A practical example demonstrates how normal construction time can be calculated for reinforced concrete works based on uncertain input parameters. In addition, the benefits of specifying normal construction time for clients and contractors are outlined.

Keywords: Monte Carlo simulation, Construction cost, Construction time, Chance/risk ratio, Histogram.

1 INTRODUCTION

Construction time is a crucial factor that determines whether and to what extent all defined or agreed project targets are achievable. This principle applies to all individuals and organizations involved in the construction project. Whenever particularly high quality standards are specified, such as a sophisticated architectural concrete pattern, the owner or client must allocate a dedicated time period in the project schedule.

Construction time has a major influence not only on the cost-efficient execution of construction works but also on the overall project outcome that the client aims to achieve. Generally speaking, clients would do themselves a disservice if they specified short or extremely short construction periods for their projects. The same applies to time made available for project preparation, particularly for the design and tender stages. Any poor project design, tendering and execution due to time pressure will adversely affect workmanship but also the use and reuse of the building or structure. The resulting disruption to the construction process makes it extremely difficult, if not impossible, to adhere to agreed cost, time and quality targets.

Productivity decreases not only due to short but also exceedingly long construction periods (see Figure 1). Short or extremely short construction times will have a major influence on the efficient and effective utilization of production factors. This applies to both elementary (workers, materials, equipment and machinery) and discretionary (project manager, site manager, technicians, etc.) factors. Clients frequently fail to realize this effect, or even deny it.

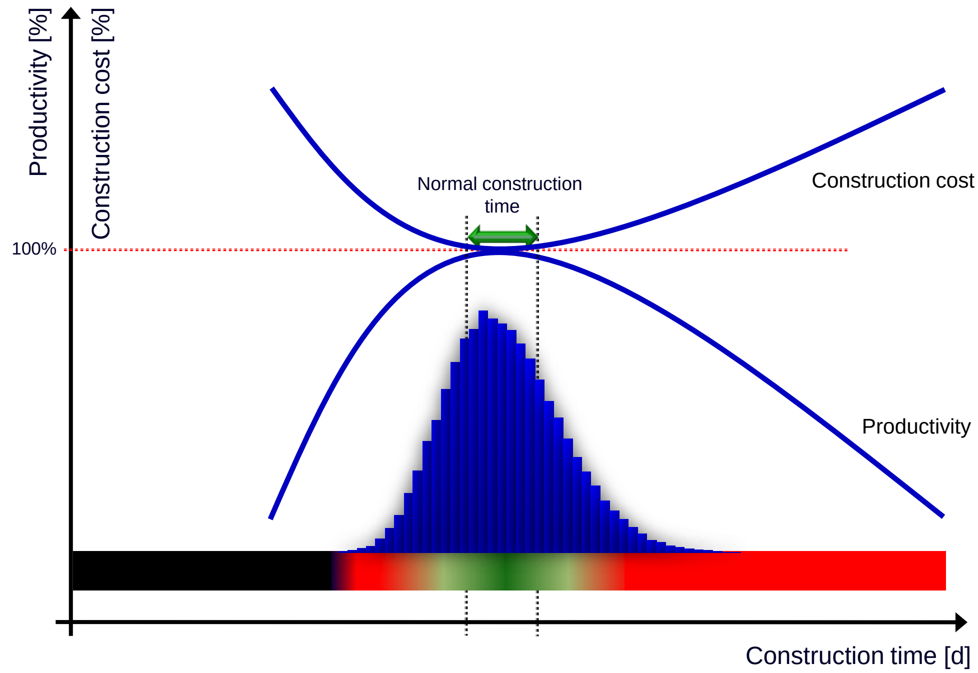

Figure 1. Qualitative correlation between construction time and construction cost (Hofstadler 2014).

Productivity is a key indicator in construction management and economics; it is of fundamental significance for the design, costing and execution of construction works. Productivity provides the basis on which to assess the efficiency of individual work steps or of the entire production or commercial process; it is expressed as the output/input ratio.

Beyond normal construction time, losses of productivity will occur and cause higher costs of production factors. Normal construction time is defined by the productive use of production factors and depends particularly on the type, form and complexity of the building or structure. Deviations from normal construction time give rise to nonlinearities in productivity, and thus losses of productivity (Hofstadler 2014, Kummer 2015, Hofstadler and Kummer 2017).

2 DETERMINING CONSTRUCTION TIME

In this paper, construction time refers to the calculated construction time prior to considering a buffer (assumed by the client). After determining construction time and considering certain conditions related to construction management and economics, clients should additionally include a buffer to be able to compensate for any delays within their control.

Construction times are categorized whilst integrating “bottleneck” equipment. In building construction, cranes form such a category. Differentiation into construction time categories takes place on the basis of the maximum number of workers who can be served by a single crane without incurring losses of productivity.

According to Hofstadler (2014), construction times are usually categorized as follows:

- Extremely short construction time: Construction time is determined such that the number of workers and the number of pieces of equipment to be used productively exceed the relevant maximum values (i.e., thresholds to losses of productivity) by 20%.
- Very short construction time: Construction time is determined such that the number of workers and the number of pieces of equipment to be used productively exceed the relevant maximum values by 10%.
- Short construction time: Construction time is determined such that the number of workers and the number of pieces of equipment to be used productively represent the relevant maximum values. Any disruption to the construction process may lead to immediate losses of productivity if the construction time target is upheld.
- Normal construction time: Construction time is determined such that the number of workers and the number of pieces of equipment to be used productively are 10% lower than the relevant maximum values.
- Long construction time: Construction time is determined such that the number of workers and the number of pieces of equipment to be used productively are 25% lower than the relevant maximum values.

3 DETERMINING NORMAL CONSTRUCTION TIME – WORKED EXAMPLE

In socio-technical systems, the achievable productivity level is determined by optimally coordinating workers with pieces of equipment at the execution stage. A combination of the number of workers with cranes is chosen to illustrate the concept of normal construction time. The crane proportionality factor (which states the maximum number of workers who can be served by a single crane without losses of productivity due to insufficient crane capacity) is used to highlight the interdependency between the number of pieces of equipment and the number of workers (see Table 1 – based on an expert survey conducted in Austria and Germany – see Hofstadler (2014)).

Table 1. Crane proportionality factors – maximum number of workers who can be used per crane without incurring losses of productivity – use of a top-slewing crane.

Concreting method [-]	crane and crane bucket for all structural components	crane only for walls and columns	crane only for columns	without crane
Number of workers per top-slewing crane	13	16	18	20

Figure 3 contrasts the possible number of workers per crane with the defined construction time categories. In this case, the maximum value is assumed for concrete pouring without crane (i.e., 20 workers [W]/crane). This is why the maximum value less 10% (18 W/crane = 20 W/crane * 0.9) is equivalent to the case enabling normal construction time.

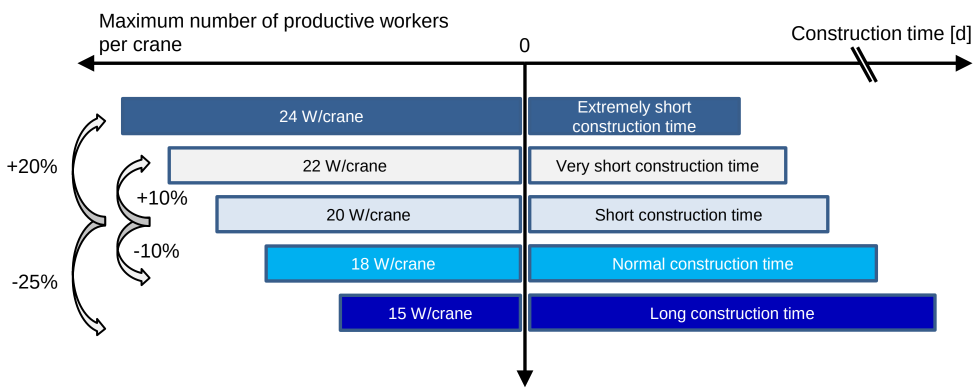

Figure 2. Correlation between crane proportionality factor and construction time (relative to concrete pouring without crane: 20 workers/crane).

The number of cranes that can be installed in the area of the building to ensure appropriate site logistics must be determined to calculate normal construction time from the perspective of the bidder/contractor. The maximum installable number of cranes is very important to determine the achievable productivity level because cranes constitute "bottleneck" equipment and would lead to losses of productivity if their capacity were insufficient.

The number of cranes determined according to the approach described above can then be used to deduce the maximum number of workers $W_{RCW,MAX}$ who can be used during the main construction period. Care must be taken to ensure that the mean value $W_{RCW,MV}$ (which can be significantly lower) is always applied instead of the maximum value for the subsequent calculation of average output. The ratio of the mean and maximum number of workers usually lies between 0.75 and 0.90 and essentially depends on the duration of the ramp-up and final construction phases. The shorter these phases are, the longer the main construction period will be, with a correspondingly greater worker proportional factor [-].

$$W_{RCW,MV} = W_{RCW,MAX} * f_W \tag{1}$$

Besides the labor consumption rate, the mean number of workers determined by introducing a proportional factor forms an essential basis for calculating average output relative to the reference quantity. The latter represents the primary material to be installed. In shell construction works, for example, a cubic meter of reinforced concrete is used as the reference. Labor expressed as paid working hours per cubic meter of reinforced concrete is composed of the shares expended for shuttering, reinforcing and concreting works. Labor is expressed as the total labor consumption rate $TCR_{A,RCW}$ [wh/m³].

The last input parameter required for output calculation is the daily working time WT [h/d]. The number of workers, the total labor consumption rate and daily working time make it possible to calculate the average daily output for reinforced concrete works $O_{RCW,MV}$ [m³/d] (see Eq. (2)).

$$O_{RCW,MV} = \frac{WT * W_{RCW,MV}}{CR_{RCW}} \tag{2}$$

Dividing the total reinforced concrete quantity RC_Q [m³] by the daily output results in the normal construction time (duration) for reinforced concrete works D_{RCW} [d] (without buffer):

$$D_{RCW} = \frac{RC_Q}{O_{RCW,MV}} \tag{3}$$

In a worked example (Opera House project in Linz, Austria), normal construction time is calculated for reinforced concrete works carried out as part of a building construction project. In the first step, the following deterministic values are used as input parameters:

Reinforced concrete quantity RC_Q:	38,275.00 m³
Total labor consumption rate of reinforced concrete works $TCR_{A,RCW}$:	7.00 wh/m³
Number of cranes:	5.00 cranes
Crane proportionality factor:	18.00 W/crane
Worker proportionality factor f_W:	0.80
Daily working time WT:	9.00 h/d

These input parameters make it possible to arrive at a maximum of 90 workers (i.e., 5.00 cranes * 18.00 W/crane) to then derive a mean of 72 workers (i.e., 90.00 W * 0.80). Average daily output is calculated using Eq. (2), resulting in 92.57 m³/d (i.e., 9.00 h/d * 72.00 W / 7.00 wh/m³). Applying these results to Eq. (3) gives a deterministically calculated normal construction time of approximately 413 d (i.e., 38,275.00 m³ / 92.57 m³/d). However, this normal construction time derived from deterministic parameters does not yet permit any conclusion regarding possible ranges or probabilities associated with this period.

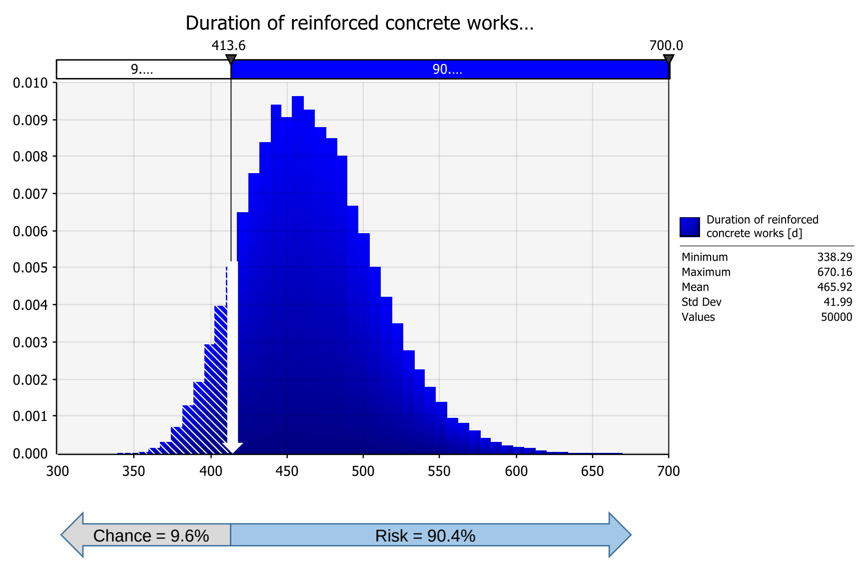

Figure 3. Histogram for the normal construction time of reinforced concrete works – chance/risk ratio.

This is why the next calculation step assigns distribution functions to input parameters (skewed triangular distributions in the case at hand; not shown in this paper) to integrate uncertainties in the calculations of normal construction times. These uncertainties are applied to the above formulae (i.e., Eq. (1) to (3)) to calculate several thousand individual values with random input parameters within the ranges defined for each input parameter. This calculation method is referred to as Monte Carlo simulation and delivers no single number or duration but a histogram, from which corresponding probabilities can be derived relative to a deterministic value. Figure 3 shows the histogram for normal construction time whilst considering existing uncertainties. Furthermore, the deterministically calculated construction time of approximately 413 days is shown as an arrow in the histogram. This visualization reveals that this construction period would result in a risk of about 90.4% for exceeding this duration whereas the chance to adhere to, or underrun, the 413-day period would amount to only about 9.6%.

Spread and skewness of the histogram are essentially determined by the selected input parameter distributions and the calculation model, as well as by possible correlations between input parameters. In the worked example, calculations were performed applying the Latin Hypercube sampling method with 50,000 iterative steps.

The histogram for normal construction time defined by the bidder/contractor can subsequently be compared with the construction time specified by the client or owner. Any specified construction time that is short or extremely short compared to normal construction time involves an increased risk of the bidder/contractor being unable to adhere to this period at the execution stage or incurring high losses of productivity because production factors can no longer be utilized efficiently. This scenario will also lead to cost increases if the bidder/contractor failed to align its costing with the above-mentioned exceedingly short construction time.

3 SUMMARY

"Normal" construction time is assumed if the type, number and combination of production factors enables as-planned, on-site work execution without exceeding or underrunning thresholds to losses of productivity. Any notional shortening of construction time in the quotation phase will occur only if the client deviates from the "normal" construction time calculated by the bidder. Bidders calculate the construction time that they consider to be normal from a construction management point of view, irrespective of the construction time specified by the client. This calculated construction time serves as an internal benchmark to assess the actual productivity level and the tolerable chance/risk ratio. A construction period that enables efficient construction management (i.e., a "normal" period) provides benefits to all parties to the contract. On the one hand, there should only be little disruption to the construction process if the client specifies a "normal" construction time. Conversely, if the client specifies a "normal" construction time, bidders or contractors can be reasonably confident (with a very high probability) that they can utilize their production factors at the planned ("normal") productivity level. Any disruptions that occur nonetheless can be rectified more easily compared to a construction process that is disrupted right from the outset. "Normal" construction time creates a sound basis and is an essential factor that enables both the client and the contractor as well as other parties to the project to achieve their targets in a concerted effort.

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