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NON-LINEARITIES IN THE CALCULATION OF CONSTRUCTION COSTS

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In construction projects, losses of productivity often incur additional costs and construction time delays, giving rise to disputes and legal proceedings, and the commissioning of expert opinions. In practice, it is usually assumed that labor consumption rates remain constant even if influential parameters change, which means a linear output curve. Only a few approaches to determining and calculating losses of productivity are presented in the literature, largely considering influences only on a certain subset of productivity. However, various disruptions may occur at the same time during the construction period, which is why the individual losses of productivity affect each other, thus aggravating their effects. This paper demonstrates how various losses of productivity – in relation to reinforced-concrete works – can be aggregated. Furthermore, this model subsequently enables both deterministic and probabilistic evaluations whilst considering the non-linear correlations between changes in the influential parameters and the resulting losses of productivity. In the probabilistic approach, the potential risk and/or chance can be captured using distribution functions. Decisions can thus be made on the basis of a defined certainty level. This approach aims to optimize the utilization of productivity factors and determine costs according to their sources, if available resources cannot be used optimally and productivity losses appear likely.

Keywords: Labor consumption rate, Monte Carlo simulation, Productivity, Reinforced concrete works, Productivity losses.

1 INTRODUCTION

In some cases, construction time, construction cost and the number of working hours (WH) required for construction works vary greatly across different projects, despite similar processes and types of work. This is partly due to the unique nature of each construction project, and to the fact that construction processes are subject to constantly changing structural, site, and operating conditions, influenced by internal and external factors and various parties involved. Bidders and contractors are forced to make assumptions with respect to future events at the cost, quotation, and process planning stages. These assumptions are fraught with considerable uncertainties reflected only to an insufficient extent when relying on deterministic parameters in accordance with currently established practices. The use of probabilistic calculation methods (in this case, Monte Carlo simulations) helps to systematically incorporate uncertain input parameters in the calculations to be able to make sound and transparent decisions while selecting a defined risk/chance ratio. Furthermore, calculations of construction costs and times often rely on linear approaches that grossly simplify real-life conditions. This paper critically reviews linear assumptions, and demonstrates how non-linearities can be taken into account in relevant computation models. The related approaches are complemented by considerations on the use of probabilistic calculation methods.

2 BASIC MODELING CONSIDERATIONS

Suboptimal working conditions influence the labor productivity of workers and have an effect on the number of WH required, for instance, to produce one cubic meter of reinforced concrete. This ratio of working hours to units of quantity is referred to as the labor consumption rate *LCR* [wh/m³].

Labor consumption rates and productivity are directly correlated to each other. Productivity decreases if the labor consumption rate increases, and vice versa. The relative change in productivity ΔPL [%] can be determined using Eq. (1). For this purpose, the difference between "baseline productivity" and "actual productivity" is calculated and divided by baseline productivity. Baseline productivity follows from the reciprocal of the target labor consumption rate LCR_{TARGET} [wh/m³]; actual productivity is derived from the reciprocal of the actual labor consumption rate LCR_{ACTUAL} [wh/m³] (Hofstadler 2014).

$$\Delta PL = \left(\frac{\frac{1}{LCR_{TARGET}} - \frac{1}{LCR_{ACTUAL}}}{\frac{1}{LCR_{TARGET}}} \right) \cdot 100\% \tag{1}$$

Appropriate computation models are necessary to consider losses of productivity in the calculation. It is inevitable that the modeling exercise has simplifications and assumptions to be able to capture the real-life situation in the first place. A correlation between the violated limit (i.e., the change in the influential parameter) and the associated type of work or labor consumption rate needs to be established, in order to be able to consider a potential loss of productivity in the computation model. Most calculations use linear correlations (see Figure 1, top left) that assume a linear output curve that corresponds to the increase or decrease in the utilization of production factors. Conversely, this assumption starts from the premise that an identical labor consumption rate can be achieved in each and every case (irrespective of changes in influential parameters; see Figure 1, bottom left). In reality, however, any deviation from ideal values is likely to result in an increase in the labor consumption rate (see Figure 1, bottom right) and in a reduced output (see Figure 1, top right). If these non-linearities are not taken into account in the calculation, this may result in incorrect labor consumption rates, high risks, and, ultimately, financial losses.

3 SOURCES OF NON-LINEARITIES

The magnitude of losses of productivity, or increases in labor consumption rates that result from changes in influential parameters, can be determined either on the basis of estimates given in the literature, or obtained through expert knowledge. Pertinent literature contains various methods to calculate losses of productivity, including Winter (1966), Lang (1988), Lehmann (1962), Schlagbauer (2012), Koehn and Brown (1985), Thomas and Yiakoumis (1987), Oglesby et al. (1989), Schneider and Spiegl (2009), Motzko (1990), and Hager (1991). In each of these references, the related information refers to a specific loss of productivity (such as due to suboptimal external temperatures, prolonged daily working hours, an overrun of the optimal team size, or reduced crane capacity).

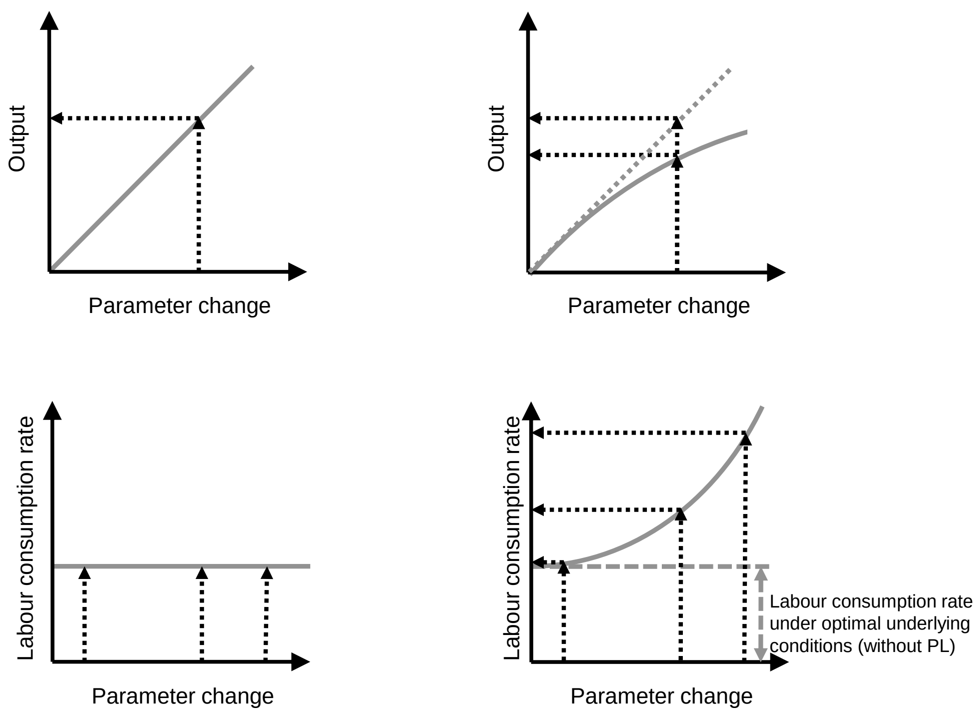

Figure 1. Qualitative curves for outputs and labor consumption rates as a function of changes in input parameters (*left*: assumption frequently applied in current practice; *right*: non-linear curves).

A survey of experts conducted in 2012/2013 at Graz University of Technology made it possible to determine curves for labor consumption rate increases in relation to several individual factors. Labor consumption rate increases were transposed to trend curves applying Huber's M estimator method; third- or higher-order polynomial equations could be defined for these curves. Hence, losses of productivity or increases in labor consumption rates can be determined as a function of the change in the relevant influential parameter (Hofstadler 2014).

Independently of the studies referred to above, the information provided in the literature refers to a specific loss of productivity in each case. This paper also deals with the systematic approach to address mutual dependencies that exist between individual losses of productivity. A simplified process model to consider various productivity losses is presented, and mutual escalation effects are described.

4 MODELING EXERCISE

If the owner or client specifies a total time to project completion, an average daily output is necessary to adhere to this period. The overall labor consumption rate wh/m³ plays a key role in calculating construction costs and times for reinforced concrete works. Multiplying this value by the concrete volume (m³) makes it possible to calculate the total number of paid working hours. Resources such as the number of workers, number of pieces of equipment, or daily working hours, are allocated on the basis of the required daily output. If losses of productivity occur as a result of a triggering event, such as insufficient construction time, an insufficient number of cranes or insufficient working space, this loss results in an increase in the overall labor consumption rate LCR_{INC} (see Figure 2). The information provided in the literature referred to in the third section of this paper, or from our own experiences in completed projects, can be used to quantify this labor consumption rate increase. This leads to a feedback effect that requires adjustments to be made in terms of allocated resources. Once productivity losses have occurred, continued adherence to the required daily output may, for instance, necessitate an increase in the number of workers or extension of daily working hours. These adjustments can then reinforce the originally-expected loss of productivity or cause new losses of productivity. This correlation requires an iterative calculation model that considers the aggregation of these influential factors, which may lead to escalation effects that trigger an increase in construction cost if the specified construction time is adhered to.

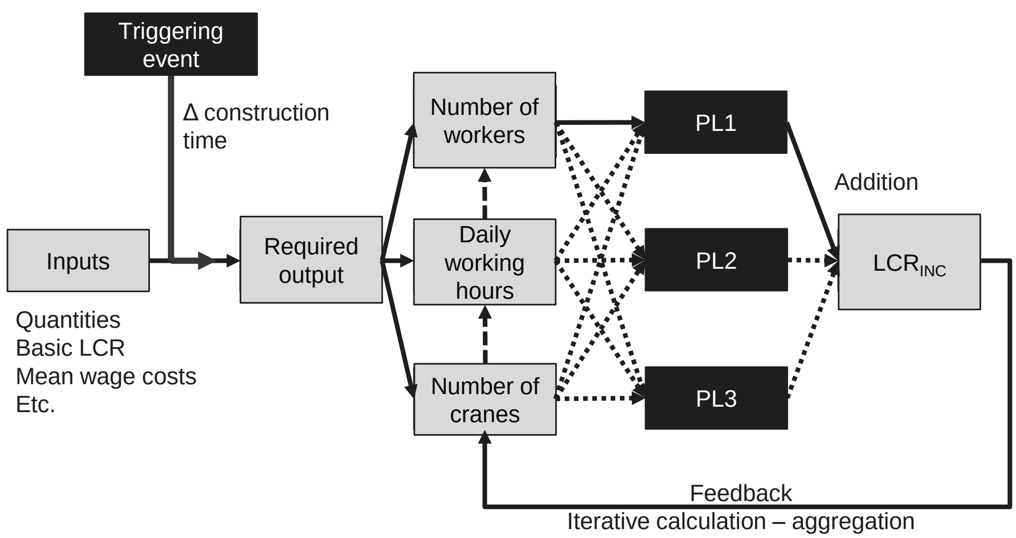

Figure 2. Qualitative process model for the aggregation of several losses of productivity using iterative calculation steps.

The process model shown above can be extended by including distribution functions as probabilistic input parameters, which makes it possible to systematically account for input uncertainties in the calculations whilst analysing the model characteristics with respect to chances and risks. The calculation itself is performed with the aid of Monte Carlo simulations whose results are shown in histograms. When selecting the actual resource allocation, which must ultimately rely on deterministic values, the associated chance or risk can be derived directly using probabilities.

5 CONCLUSIONS

For construction contractors in particular, it is crucial to account for losses of productivity and non-linearities at the cost, quotation and process planning stages, as well as in the construction phase. Clients should also be aware of key construction management correlations in order to define reasonable underlying project conditions and specifications, such as with respect to the construction schedule. Ultimately, both parties to the contract contribute to performing work as cost-efficiently as possible and at the highest possible productivity level.

This paper presented a qualitative model that creates the basis for incorporating non-linearities in costing exercises and construction time calculations. This method essentially relies on repeated iterative steps where calculation results rely upon each other. If a productivity loss occurs, the allocation of resources must be adjusted accordingly – while ensuring continued adherence to the specified construction time and required daily output – to be able to comply with the specified construction period. Any change in the team size, work schedule etc. may lead to new or aggravated losses of productivity. The probabilistic calculation approach provides the option to apply optimization methods to determine the amount of resources that would incur the lowest cost despite the presence of productivity losses (i.e., operation research methods).

In-depth studies are currently being conducted at the Institute of Construction Management and Economics at Graz University of Technology in order to develop a corresponding computation model. This may lead to future research papers.

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