

## **Construction Sequence Planning – An Interaction Diagram to Determine the Output of Reinforced Concrete Works**

Christian Hofstadler  
*Graz University of Technology, Austria*  
*hofstadler@tugraz.at*

### **Abstract**

To determine the duration of reinforced concrete works, the concrete quantities of the structure or building section are required as well as the output (e.g. cubic meters per day or shift). To date, these calculations have been carried out on the basis of specific project data, arriving at individual durations for each and every section.

The interaction diagram shown in this article provide an option to easily execute these calculations via nomogram, and to obtain graphical results. The diagram enables the calculation of the required output (e.g. for a predetermined completion date), the duration of the works, the total attributable working hours, the maximum (economically) permissible labor productivity expressed as working hours per m<sup>3</sup>, and the number of workers needed for the total reinforced concrete works.

The graphs interlink the results of a number of individual, standardized computations. For each of these computations, parameters are varied within reasonable, practically feasible ranges.

The resulting four diagrams are connected on an interaction diagram that is easy to use in day-to-day practice. Due to the fact that the diagram can be 'operated' from any of the four quadrants, it is especially user-friendly.

During the initial planning phase of a project, the presented diagram may become particularly useful for time scheduling and for the evaluation of construction alternatives.

During tendering and especially for job calculation (once the contract has been awarded), these graphs may become very helpful. It is believed that these diagrams might soon prove indispensable for actual construction scheduling and sensitivity analyses (e.g. when deciding on alternative construction methods).

### **Keywords**

Construction sequence planning, Interaction diagram, Reinforced concrete works, Output, Labor productivity

### **1. Introduction**

For detailed planning, a project is usually 'broken down' to the level of 'processes'. The individual activities are then connected by means of technological and manufacturing interrelationships. The results are shown in bar charts or line diagrams (for example as shown in Halpin and Woodhead, 1998). The

length of a bar in a chart represents the duration of a process (e.g. setting formwork, placing reinforcement, placing concrete, stripping formwork).

The duration of a certain process depends on the specific output. Within an operation, this output is influenced, for example, by labor productivity (expressed as working hours per unit produced), the number of workers, the daily working time, as well as by the degree of familiarity and practice. These activities - particularly if they do form the critical path - are crucial in determining the length of a construction period.

During the initial planning phase, it is sufficient to determine the project period and project costs based on gross estimates of quantities (as per itemized units according to concrete quantity). In the case of reinforced concrete works, both concrete quantity and total labor productivity are most influential on the construction period (duration) and costs.

If the output is computed for a certain number of hours worked [hr], the level of the hourly output is generally expressed as the ratio between number of workers and labor productivity (i.e. working hours per unit produced).

In order to compute the daily output, this value must be multiplied by the number of hours worked on each working day.

This paper presents four basic diagrams which are merged to form an interaction diagram. Examples will be used to demonstrate how to use this interaction diagram.

The benefit of this diagram lies particularly in its immediate application (without further computations), and also in its clear graphical representation of all correlations. For example, it is possible to graphically conclude on the necessary number of workers just by selecting the output required (resulting from predetermined production periods) and the total labor productivity (i.e. working hours per unit produced; estimated in relation to the method of construction).

Another possibility is to determine the maximum permissible total labor productivity (working hours per m<sup>3</sup>) on the basis of a given output and the number of staff.

Apart from the high level of transparency, it is possible to prove the sensitivity of the computed results by varying the parameters accordingly (e.g. by modifying the number of workers, the daily working time or total labor productivity).

If the execution of work is delayed, it will be necessary to implement acceleration steps in order to adhere to the fixed completion date. It is obvious that in such cases appropriate corrective measures include an increase in output. The increase in the output actually required results from the remaining production quantity (e.g. quantity of concrete remaining to be poured) and the production time still available.

The required output can be achieved in different ways. The various options to increase the output can be shown graphically in the interaction diagram presented.

For example, it is possible to achieve a higher output level by simply increasing the number of workers or the daily working time. Another alternative could be to change the construction method in an effort to reduce total labor productivity.

Depending on the specific circumstances, one or more alternatives may be applied simultaneously. Only the detailed planning stage and - at the latest - the execution of construction will show whether and to what extent the assumptions of such an initial (basic) planning (of acceleration steps) will be met.

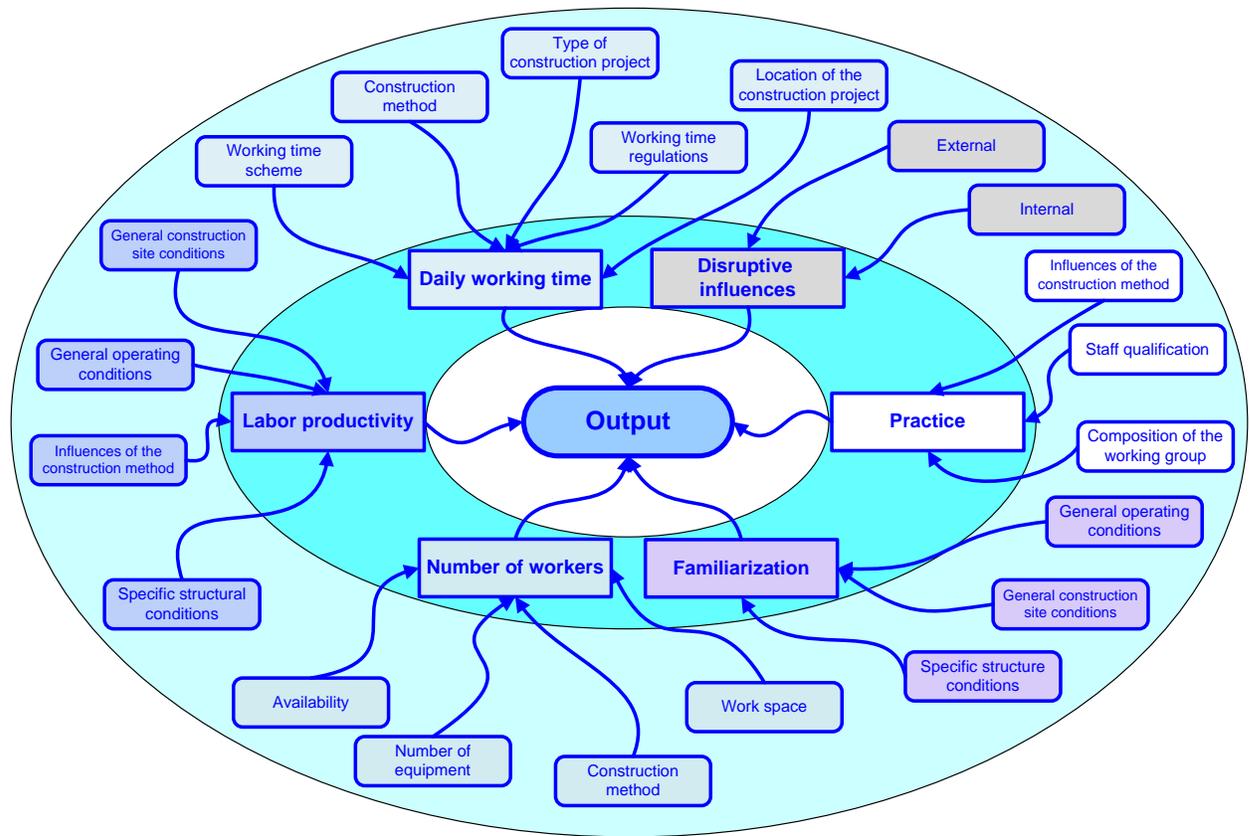
## 2. Fundamentals of Output Computation

Values of the output of an activity indicate which output rates will be achieved when producing (manufacturing) goods in a certain (selected) period of time (e.g. month, week, shift, day, hour).

The daily output  $DO$  [UoQ/UoT] may be computed on the basis of Equation 1 (UoQ = unit of quantity; UoT = unit of time).

$$DO = \frac{W * WT}{LP} \quad (1)$$

The numerator is the product of the number of workers  $W$  [wh/hr] and the corresponding working time  $WT$  [hr/UoT]. The denominator shows the labor productivity (for example as shown in Thomas *et al.*, 1990 and 1992) expressed as total working hours per unit of quantity  $LP$  [wh/UoQ] for the respective activity.



**Figure 1: Influences on the Order of Magnitude of the Required Output (Hofstadler, 2007)**

Depending on the planning phase (initial or detailed planning), a unit of time [UoT] and a unit of quantity [UoQ] must be chosen for which the output has to be computed.

Regarding the detailed planning for formwork-related activities, reinforcement and concrete works, the influences shown in Figure 1 must be adopted to the specifications.

During the initial planning period, only a few influences are usually quantifiable.

### 3. Interaction Diagram for Reinforced Concrete Works

In the interaction diagram shown in Figure 2, the relations between the following parameters are represented:

- Total labor productivity [wh/m<sup>3</sup>]
- Number of workers [wh/hr]
- Hourly output [m<sup>3</sup>/hr]
- Daily working time [hr/d]
- Daily output [m<sup>3</sup>/d]
- Duration of the reinforced concrete works [d]
- Concrete quantity [m<sup>3</sup>]
- Total working hours [wh]

The diagram is used by drawing respective straight lines between the sectors (quadrants).

The diagram in the first quadrant shows total labor productivity on the x axis and the hourly output on the y axis (ranging from 0 to 12 m<sup>3</sup>/hr).

The dimension of total labor productivity must include all works related to the production of reinforced concrete (for example formwork-related activities, insertion of reinforcement and concrete works).

The total labor productivity value can be computed using Equation 2:

$TLP_{RCW} =$	Total labor productivity for reinforced concrete works [wh/m <sup>3</sup> ]
$LP_{A.FW} =$	Average labor productivity for formwork-related activities [wh/m <sup>2</sup> ]
$FR_{A.BD} =$	Average formwork ratio for the entire building [m <sup>2</sup> /m <sup>3</sup> ]
$LP_{A.RW} =$	Average labor productivity for reinforcement works [wh/t]
$RR_{A.BD} =$	Average reinforcement ratio for the entire building [t/m <sup>3</sup> ]
$LP_{A.CW} =$	Average labor productivity for concrete works [wh/m <sup>3</sup> ]

$$TLP_{RCW} = LP_{A.FW} * FR_{A.BD} + LP_{A.RW} * RR_{A.BD} + LP_{A.CW} \quad (2)$$

The accuracy of the values applied in Equation 2 increases with the ‘project depth’ (i.e. the degree of planning detail increasing from the general phase required to obtain building permits to the more in-depth, detailed design planning allows to determine increasingly accurate quantities and assumptions regarding labor productivity values expressed as working hours per unit to be produced).

In the diagram, a range of total labor productivity values from 5 to 8.50 wh/m<sup>3</sup> for reinforced concrete works is shown. The individual curves in the diagram represent a certain number of workers (‘W’), which is marked by the figures stated in the key. The lowest number is 10, the maximum value is 80 (at a 5 workers increment). The curves in the diagram may be changed or amended according to the user’s specific requirements.

By assuming, for example, the order of magnitude of the total labor productivity (at an early planning stage, this may only be a rough estimate due to project data still lacking detail) and the number of workers, the hourly output may be concluded accordingly.

Inversely, for example by entering the daily output and the number of workers, the order of total labor productivity may be determined graphically.

The diagram in the second quadrant includes nine curves, each of which represents a certain daily working time 'DWT'. For every working day, the lowest working time was selected with 8 and the highest with 16 hours. The y axis shows the hourly output [ $m^3/hr$ ], the x axis indicates the daily output (in a range from 0 to 140  $m^3/d$ ).

The specific daily output may, for example, be determined by inserting the required hourly output or adjusting the different daily working times. On the other hand, it is possible to determine the corresponding hourly output for the respective daily working time by entering the respective specific daily output.

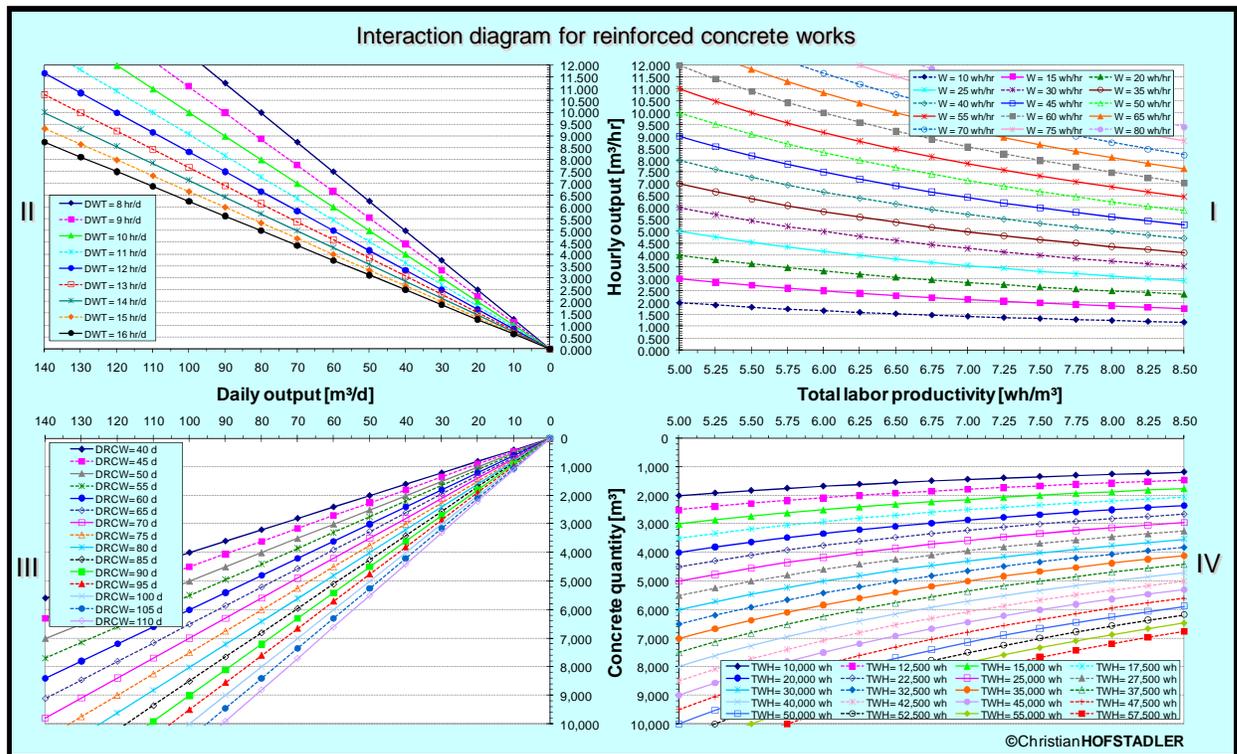


Figure 2: Interaction Diagram for Reinforced Concrete Works

The diagram in the third quadrant shows the correlation between daily output, concrete quantity and the overall duration of reinforced concrete works. Each curve in the diagram represents a unit of time to indicate a certain duration. The curves are labeled 'D<sub>RCW</sub>', and values vary from 40 to 110 working days (at a 5 working day increment).

The daily output is shown on the x axis. The concrete quantity is indicated on the y axis in a range from 0 to 10,000  $m^3$ .

For example, the entire project duration may be graphically determined by using the daily output and the concrete quantity. The minimum daily output for a certain concrete quantity and for the longest available duration of a project can be read from the diagram. Intersections located in-between the straight lines should be interpolated graphically.

This diagram is very well-suited for an initial planning exercise. However, in the detailed project scheduling, it will be necessary to consider the sequence of operations in more detail (e.g. flow production, cyclic production, parallel production), and to account for production sequence relationships (e.g. 'end-start relations' between individual sub-processes; see for example in Bauer, 2007) when computing the duration of the entire reinforcement work.

The curves for the total number of working hours ('TWH') are represented in the fourth-quadrant diagram. The curve with the lowest value stands for 10,000 working hours while the graph for the maximum represents 57,500 hours.

The incremental difference between the individual curves is 2,500 working hours. Total labor productivity is shown on the x axis, concrete quantity on the y axis. Intersections located in-between the curves should be interpolated graphically again.

Using the diagram, the total number of working hours can be determined whilst considering concrete quantity and total labor productivity.

#### **4. Example of Use of the Interaction Diagram**

The following section outlines one example of use of the interaction diagram. The first task is to work out solutions by using the diagram in Figure 2 (considering the respective specifications). The application procedure is plotted and described for the example.

##### **4.1 Specifications Given for the Example**

Total labor productivity value: 5.75 wh/m<sup>3</sup>  
Concrete quantity for the multi-story building: 5,500 m<sup>3</sup>  
Minimum daily working time: 8 hr  
Maximum daily working time: 10 hr  
Number of workers: 45 wh/hr

Parameters to be determined: Daily output and duration on the basis of the specifications given.

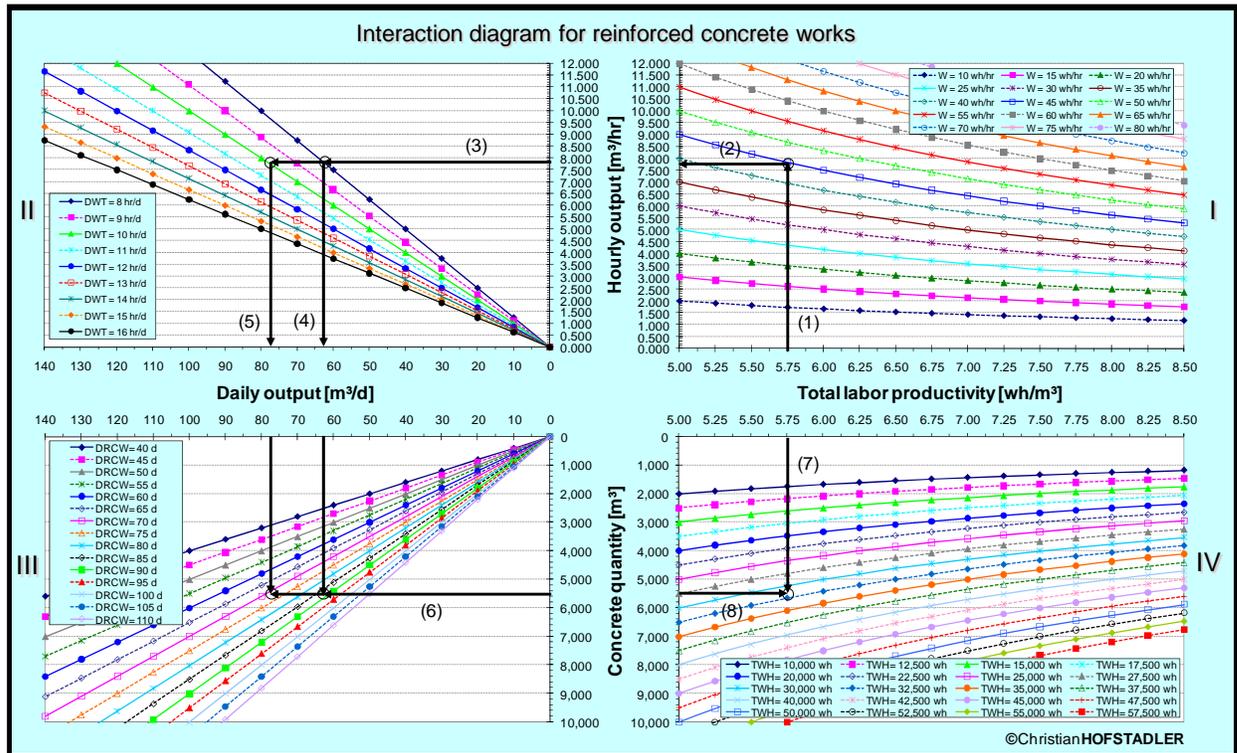
##### **4.2 Solution**

Beginning in the first quadrant, a vertical straight line (1) is drawn upwards from the x axis (at 5.75 wh/m<sup>3</sup>) so as to create an intersection with the curve 'W=45 wh/hr'. Continuing from this point of intersection with the horizontal line (2), the hourly output is determined at 7.75 m<sup>3</sup>/h on the y axis.

The extension of line (3) into the second quadrant results in several intersection points with the set of curves located there (reflecting various daily working times). The first intersection occurs with the curve for a daily working time of 8 hours ('DWT=8 hr/d') and the last one with a daily working time of 10 hours ('DWT=10 hr/d'). From each of these points of intersection, a vertical line is drawn in downward direction, determining two values on the x axis. The lower value for the daily output is 63 m<sup>3</sup>/d, the higher one 77.5 m<sup>3</sup>/d.

In the third quadrant, line (6) is drawn to the left starting from 5,500 m<sup>3</sup>. An intersection occurs with lines (4) and (5). For the lower boundary value (63 m<sup>3</sup>/d), the duration amounts to approx. 87 days while, for the upper value (77.5 m<sup>3</sup>/d), it equals approx. 71 days.

To determine the total number of working hours in the fourth quadrant, a vertical line (7) is drawn downwards at 5.75 wh/m<sup>3</sup>. A horizontal line (8) is also inserted to the right at 5,500 m<sup>3</sup> until a point of intersection with line (7) is reached. This point of intersection results in a total number of working hours of approx. 31,500.



**Figure 3: Interaction Diagram for Reinforced Concrete Works - Example**

Using the given total labor productivity of 5.75 wh/m<sup>3</sup>, the minimum daily output can be determined at approx. 63 m<sup>3</sup> (with a daily working time of 8 hours) while the maximum daily output amounts to approx. 77.5 m<sup>3</sup>. The project duration for the minimum output lies between approx. 87 days and a maximum of approx. 71 days.

## 5. Summary

In the detailed planning for work scheduling, the duration of individual processes is computed by addressing individual output. The duration of an individual section, or the total available period, depends, amongst others, on the following factors:

- Construction contract (with agreed completion dates)
- Technological and manufacturing relationships between the individual activities
- Used or available resources
- Available working space

Both output and duration can be computed by using standardized equations. If input parameters are changed, such as the number of workers or total labor productivity, new computations will be required. Due to the numerical nature of the results, trend forecasting becomes difficult.

For a transparent representation of the correlations, the diagrams presented in this paper have been developed to be used primarily in the initial planning phase. At these first planning stages of a project, the diagrams may become particularly useful for time scheduling and the evaluation of construction alternatives.

By using these diagrams, it is, for example, possible to determine the maximum (economically) permissible total labor productivity, expressed as working hours per m<sup>3</sup>, without having to do intermediate calculations.

For example, the graphical interaction between total labor productivity, number of workers, daily working time and output can be easily demonstrated in these diagrams. The effects resulting from varying input parameters are transparent.

When parameters are varied, the mathematical interconnection ensures that an appropriate modification in the respective quadrant will occur.

The output level depends on the influences represented in Figure 1.

This paper presents one example of use of the diagram. Any change in input parameters makes the sensitivity of the individual parameters transparent.

If changes in total labor productivity are recorded during the execution phase, their effects on output will become legible in the diagrams.

Any corrective measures to be taken to increase the output level can then be checked graphically for their effectiveness before implementation.

## 6. References

- Bauer, H. (2007). *Baubetrieb*, 3. Ausgabe, Springer-Verlag, Berlin Heidelberg.
- Halpin, D. W., and Woodhead, R. W. (1998). *Construction Management*, 2nd Edition, Wiley, New York.
- Hofstadler, C. (2007). *Bauablaufplanung und Logistik im Baubetrieb*, 1. Ausgabe, Springer-Verlag, Berlin, Heidelberg.
- Thomas, H. R., Sanders, S. R. and Bilal, S. (1992). "Comparison of labor productivity". *Journal of Construction Engineering and Management*, ASCE, Vol. 118, No. 4, pp. 635-650.
- Thomas, H.R., Maloney, W.F., Horner, R.M.W., Smith, G.R., Handa, V.K., and Sanders, S.R. (1990). "Modelling construction labor productivity". *Journal of Construction Engineering and Management*, ASCE, Vol. 116, No. 4, pp. 705-726.