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The impact of the availability function on the structure of unit costs in a construction project: a case study

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ABSTRACT

Neglecting availability during bidding and project execution can lead to inaccurate cost estimates and organizational problems. The significance of availability is essential in evaluating the duration of failures and repairs for both individual system components and the overall system. This assessment directly impacts project timelines and associated costs. This paper examines how the availability function influences construction production costs, particularly in highway construction, where mechanized work is highly represented. The proposed methodology evaluates how operational availability affects overall project availability and the capacities of construction system components, which are critical for accurately calculating unit costs in the bill of quantities. Past experiences indicate that project cost estimates and profit margin calculations—reflecting the difference between actual prices and projected costs—may lack precision. A system for producing and embedding bitumen-bonded materials for road pavements was selected to test this methodology using real-world data. Specifically, the data used to calculate unit costs, including machine downtime costs and durations, were compared with actual conditions during the construction of a key pavement layer in road projects. The results show that actual unit costs, which incorporate the availability factor, are 10.57% higher than those obtained using the traditional approach. This underscores the risk of losing projected profits and suggests that contracted prices may be underestimated, potentially leading to significant financial losses for construction companies.

1. Introduction

The availability of system components, subsystems, and the entire system indicates the likelihood that the system will operate successfully and remain within acceptable deviations of the specified performance criteria at a given time and under specific environmental conditions. As a performance metric, availability is becoming increasingly important. By its nature, it can be seen as a measure of the reliability of repairable systems and of the connection between planned and actual values for real-world performance, unit costs, and system costs [1].

Construction production systems are unique industrial systems defined by their design structure. Each construction project generally has a clear start and finish, marking the achievement of specific goals. No two projects have identical organizational setups; however, every project requires specific key components for smooth operation. These include skilled personnel, a trained workforce, equipment and machinery, and materials such as raw and semi-finished products. The complexity of construction systems, especially in highway engineering, is particularly evident in projects that involve a high degree of mechanization.

This complexity arises from various factors, including the specific environment in which the building is being constructed, often uncertain total costs, operations in open spaces, and the presence of multiple production lines that may be far apart. Additionally, construction projects can vary significantly in duration, ranging from several months to several years, and they often involve specific contractual relationships between investors and contractors [4].

1.1. Availability of construction production systems and components

The availability of components, subsystems, and the system is predicted, estimated, and evaluated at each level of system design (general, preliminary, and main design). The historical database on the system and its components has a crucial impact on determining the projected and operational availability for a specific period. The above data serves as a starting point for assessing the system's availability during project implementation. Possible activities to increase availability and ensure the system's smooth functioning must be coordinated with the project's projected income and expenses to avoid jeopardizing the calculated profit [4].

The measure of projected system availability during implementation is more closely determined by analyzing it after the project's completion. The result of the construction production process is a product that can be quantified in several ways as a desired goal. Therefore, a logical approach to analyzing the availability of a specific production system is to define the final number of states as a function of work results and resource consumption over time. Regarding this production process characteristic, construction systems are viewed as stochastic processes with a discrete state space and continuous time. On the other hand, several authors, after extensive analyses of continuous operating systems with emerging subsystems and components, concluded that it is not necessary to assume any special distribution for the duration of the function state and non-function state of those components, i.e., subsystems, because such systems function in the so-called steady state. Namely, the time interval during which the availability of production processes (systems) is observed is long enough so that the stochastic process is essentially distant from the start time, which is why the probability distributions reach statistical equilibrium, indicating that the process is in steady-state conditions. The data collection period for the system's operation is quite long. From a mathematical perspective, this can be acceptable, as time often approaches infinity. However, it is essential to verify the hypothesis of process stationarity by selecting the distribution function that best approximates the operating times, failures, and repairs (both corrective and preventive) [5, 6].

The results obtained should be compared with previous theoretical and practical experiences. The types of connecting system components are analyzed to precisely determine the analytical expressions for calculating the availability function, enabling the availability analysis. Construction production systems, although complex in structure, are classified as serial-parallel systems. These systems are characterized by dynamism and reconfiguration. The study of availability, performance, costs, and time has significantly impacted projects within construction production systems. The exclusion of other criteria is justified within the context of specifically defined occupational safety and health procedures, environmental protection, and system maintenance at all levels of company management [2, 4]. Figure 1 illustrates the concept of availability and its parameters.

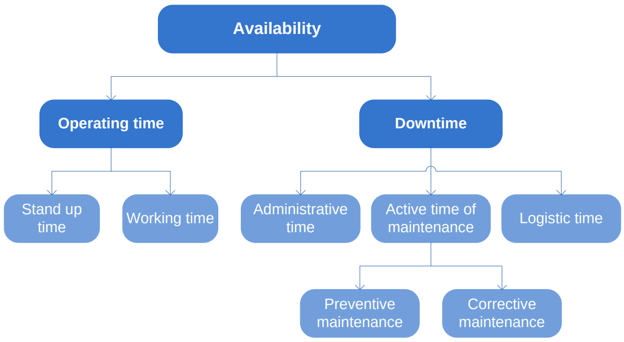

Figure 1. Structure of components and system availability

2. Literature review

System states are divided into available and unavailable times. Available time refers to the period when the system is in use or ready for use, while unavailable time encompasses system downtime, as illustrated in Table 1. Therefore, time can be divided into system state and system usage requirement. While the state of the system can be operational or inoperational, in terms of requirements for using the system, there are two possibilities [7]:

- Use of the system is required
- No use of the system is required

Table 1. System states in the time function

States of the system	
Inoperative	**Operative**
Administrative downtime	Operating time
Logistic downtime	Standby time
Active time of maintenance (corrective/preventive)	Operating time
Administrative downtime	Standby time
Logistic downtime	Operating time

The most important classification of availability is based on time intervals and types of downtime [2].

Availability as a function of time is categorized into instantaneous availability A(t), mean availability A(T), and steady-state availability A(∞). Considering the previously mentioned characteristics of construction production systems, this discussion will focus solely on steady-state availability [8].

2.1. Steady state availability

Steady-state availability, as indicated by Eq. 1, is the limiting value of the instantaneous availability of a function as time (t) approaches infinity.

$$A(\infty) = \lim_{n \to \infty} A(t)^n \quad (1)$$

It has been demonstrated that the current availability approaches steady-state availability after a duration equal to four times the mean time to failure. Therefore, steady state availability is a condition in which the system's availability remains constant over time. In industrial systems, including construction systems (which consist of construction machines and plants for executing specific project tasks), steady-state availability is often applied when the total operating time (t) is sufficiently large. In these scenarios, when we observe mathematically, time approaches infinity; according to Eqs. 2 and 3, the failure rate (λ) and the repair rate (μ) are constant values [2, 5].

$$\lambda(t) = \lambda \quad (2)$$

$$\mu(t) = \mu \quad (3)$$

In this case, the availability can be represented by Eq.4 [2], [5].

$$A(t) = \frac{\mu}{\lambda+\mu} + \frac{\lambda}{\lambda+\mu} \cdot e^{-(\lambda+\mu)\cdot t} \quad (4)$$

For a significant value of time (t), Eq. 4 can be represented by Eq.5.

$$A(\infty) = \frac{\mu}{\lambda+\mu} \quad (5)$$

So, unavailability (U) is determined based on Eq. 6.

$$U(t) = 1 - A(\mathrm{t}) \quad (6)$$

Additionally, when time approaches infinity, unavailability is calculated using Eq. 7.

$$U(\infty) = \frac{\lambda}{\lambda+\mu} \quad (7)$$

Equation 5 for A (∞) can be represented as a function of the mean time to failure (MTTF) and the mean time to repair (MTTR), as shown in Eq. 8. [5, 7, 9, 10]. The authors should have defined the MTTR times as the mean time to restore, because the difference lies in the time required for the system to return to its pre-failure operational state after repair.

$$A(\infty) = \frac{MTTF}{MTTF+MTTR} \quad (8)$$

Analogous to Eq. 7, unavailability is determined by Eq. 9.

$$U(\infty) = \frac{MTTR}{MTTF+MTTR} \quad (9)$$

Availability, as a function of downtime and availability over time, can be categorized into three distinct types: inherent availability, achieved availability, and operational availability. Inherent and achieved availability do not account for administrative and logistical times required for preventive and corrective maintenance, including standby time. Therefore, they are not applicable to construction production systems.

2.2. Operational availability

Operational availability refers to the system's experience, which is based on its current state. The previous availabilities are estimates based on the system model, which is a function of the statistical distribution of time spent in and out of the system's function. Operational availability can be expressed as the ratio between the time in operation and the total time of the system, Eq.10, or according to Eq.11, with the ratio of the mean time between maintenance (MTBM) and the sum of the mean time between maintenance and the mean downtime (MDT) [7, 10].

$$A(o) = \frac{UpTime}{OperatingCycle} \quad (10)$$

$$A(o) = \frac{MTBM}{MTBM+MDT} \quad (11)$$

The operational availability requirement identifies and isolates the effectiveness and efficiency of maintenance operations. It impacts the level of maintenance resources and the organisational effectiveness of the production system. Operational availability is the empirically determined lower limit of performance (as observed in operation) for the given designed performance and other previously mentioned criteria. When the system's availability is high, it is likely to achieve the set goal. The construction technology designer expresses the desired availability, often referred to as project availability [7], [9]. There are two accepted approaches to evaluating operational availability. The first approach, a general one, focuses on the previously mentioned expressions, highlighting the system's total time spent both in and out of operation. Conversely, the second approach assesses the system's operational availability by considering its recovery time.

For both methods, Eq. 12 accounts for the time the system component remains non-operational, including the time required for administrative and logistical actions to restore the component to an operational state after preventive or corrective repairs. Additionally, Eq. 12 is practically significant for calculating operational availability, as it provides crucial time data that enhances the database for each machine [7].

$$A(o) = \frac{OT+ST}{OT+ST+TCM+TPM+ALDT} \quad (12)$$

Where are:

- OT: Operational time
- ST: Standby time
- TCM: Total corrective maintenance
- TPM: Total preventive maintenance
- ALDT: Administrative and logistic downtime

2.3. Unit costs and unit prices

After determining the method statement for the position from the bill of quantities, all necessary inputs are defined, including the expenses for mechanized work, workers, and materials. The classic approach to determining the unit price of all system components (machines) is to adjust the average construction norms to the project's specific requirements. At the same time, possible work failures are not considered. When determining the unit costs of the construction machinery system, Eq. 13 was used [2, 7].

$$U_c = \frac{planC_s}{planQ}, \left[\frac{\$}{t, m^3, m^2, \ldots}\right] \quad (13)$$

Equation 14 shows that the system's unit price (Up) is determined by increasing the unit costs for management and profit (φ) [3, 4, 5].

$$U_p = U_c \times (1+\varphi) \quad (14)$$

This approach emphasizes aligning the capacity of system machines with that of the key machine to prevent downtime of individual components. During project implementation, issues with daily and monthly execution frequently occur, often due to failures of system components and, at times, the entire system. To tackle these challenges, changes to work planning were introduced, including an availability function that considers downtime and repairs. This adjustment was made during the bidding phase to set prices close to current market rates for the contracted construction period and determine the appropriate number of machines needed for each subsystem by adding hot or cold reserves [3, 10]. The proposed methodology highlights discrepancies between planned and actual system performance, offering solutions to mitigate potential delays and reduce the chances of disputes and claims.

3. Methodology

The methodology begins by gathering data on the operational availability of components (machines) to calculate subsystem availability. After obtaining the subsystem availability values for the series-connected replacement components, the system's operational availability (A^*) is calculated. The final part of the proposed methodology involves formulating equations for system costs, unit costs, and capacities, with the total system cost derived from the classical planning approach to more realistic values (actual) by incorporating the availability function.

3.1. Availability of series-parallel systems

The calculation of system availability based on the system structure includes proposed formulas for both serial and parallel component connections. Eq. 15 outlines how to compute the availability of a subsystem or system composed of components connected in series. Equation 16 is used to determine the availability of components arranged in parallel within subsystems or systems.

$$A^*_{ser} = \prod_{i=1}^{n} A_i(t) \quad (15)$$

$$A^*_{paral} = \left[1 - \prod_{i=1}^{n}[1 - A_i(t)]\right] \quad (16)$$

3.2. Actual practical capacity of the system

The actual practical capacity ($_{act}Q$) is determined by Eq. 16, where the planned practical capacity ($_{plan}Q$) is corrected by the design availability value (A^*).

$$actQ = planQ \times A^* \quad (17)$$

3.3. Actual system cost

The actual system cost is the sum of the planned costs ($_{plan}C_s$) reduced by the design availability (A^*), and the system downtime costs (C_{inop}) reduced by the unavailability (U(∞)), as represented by Eq. 18.

$$actC_s = planC_s \times A^* + (1 - A^*) \times C_{sinop} \quad (18)$$

Planning (classical approach) involves the total system cost, including only operable states of the components (n), which is a function of planned costs ($_{plan}C_s$) and operable time (h_{plan}), as shown in Eq. 19.

$$planC_{stot} = planC_s \times h_{plan} \quad (19)$$

The operational condition cost of the component includes the one-time costs (I_c) of putting the machine into operation, divided by the planned hours (h_{plan}) of operation without downtime, the costs of energy (C_{en}), and the costs of the fixed asset (C_{fa}), which also include depreciation costs expressed by Eq.20.

$$planC_s = \sum_{i=1}^{n}\left(\frac{Ic}{h_{plan}} + C_{en} + C_{fa}\right)_i \; i = 1,2,\dots k \dots n \quad (20)$$

The downtime costs of the system components (C_{sinop}) do not include energy costs, unlike Eq. 20, and are presented in Eq. 21.

$$C_{inop} = \sum_{i=1}^{n}\left(\frac{Ic}{hp} + C_{fa}\right)_i \quad i = 1,2,\dots k,\dots n \qquad (21)$$

To estimate the additional costs due to downtime and failure (inoperable time), it is necessary to determine the penalty costs (C_{penal}) and the extra-day costs (C_{ext}) required to complete the project, as shown in Eq. 22 [2,3].

$$C_{sinop} = C_{inop} + C_{penal} + C_{ext} \qquad (22)$$

Penalty costs caused by the delay of works on the project are, as a rule, specified in the contract for each day of delay and are determined mainly as a percentage amount (p) of the price of the contracted values of the works ($_{plan}C_s$), shown by Eq. 23.

$$C_{penal} = ext\ D \times p/100 \times planC_s \qquad (23)$$

Total penalty costs are calculated based on a preliminary estimate of the additional days required to complete the project. These additional days result from failures of components and systems needed to complete the project and are expressed by Eq. 24, which is derived as a function of extra working hours ($_{ext}h$) and planned working hours per day (h_{day}).

$$ext\ D = \frac{ext\ h}{h\ day} \qquad (24)$$

Additional working hours can be represented as a function of actual and planned capacities ($_{plan}Q$), which are adjusted by the ratio of project availability (A*) to unavailability (1-A*), as shown in Eq. 25 [2].

$$ext\ h = plan\ h \times \frac{(planQ - actQ)}{actQ} = planh \times \frac{(1-A^*)}{A^*} \qquad (25)$$

To complete the project on time, it is most effective to use the system's operational availability as input to determine additional days and the necessary system hours. Regular monitoring of work progress can help prevent extra days and reduce penalty costs resulting from delays due to the system's unavailability. Increasing daily working hours is the most economical way to decrease the need for additional workers and machines. A recent practical example highlighted in the paper showed that extending daily operation hours meets the contracted timeline. Consequently, the hours ($_{act}h$) required to finish the project are determined by Eq. 26.

$$acth = planh \times A^* + planh \times (1 - A^*) + planh \times \frac{(1-A^*)}{A^*} \qquad (26)$$

The last cost type is the expense resulting from the system's additional work (C_{ext}) during the period for which the penalty costs were calculated. It is determined based on the system's planned cost ($_{plan}C_s$) and the ratio of additional to planned operating hours, as shown by Eq. 27.

$$C_{ext} = \frac{ext\ h}{plan\ h} \times planC_s \qquad (27)$$

Considering equations 19 to 27, the actual system cost shown by Eq. 18 is depicted by Eq. 28.

$$actC_s = planC_{sop} \times \left(A^* + \frac{(1-A^*)}{A^*} + extD \times \frac{p}{100}\right) + (1 - A^*) \times C_{sinop} \qquad (28)$$

3.4. Actual unit cost of the system

According to Eq.29, the actual unit cost ($_{act}U_c$) is calculated after determining the actual system cost (Eq. 28), which is divided by the smallest value among the exact capacities of all subsystems ($_{act\ min}Q$). In well-designed manufacturing systems, differences in actual subsystem capacities are minor.

$$actUc = actC_s / act\ minQ \qquad (29)$$

4. Methodology testing

Based on data from the company's information system related to managing the machinery fleet, which includes additional details about each plant and machine, as well as data on failures and corrective and preventive repairs, the proposed methodology was tested in the system for producing and embedding bitumen-bonded materials during the 2018 calendar year. The system tested consists of 10 components forming five subsystems. Subsystem availabilities, calculated according to Eq. 15 and Eq. 16, are also shown in Figure 2, along with the system availability (A*) computed using Eq. 15.

The project machinery fleet includes a limited selection of machines, selected through techno-economic optimization, to carry out the roadway reconstruction project for class IB roads. The work was carried out from May 1, 2018, to September 30, 2018. Table 1 carefully outlines the inputs used for the system cost calculation shown in Figure 2. It addresses the performance of embedding 90,000.00 tons of bitumen-bonded materials using the traditional (plan) approach. Additionally, it provides an overview of the actual performance results and costs, using the availability function defined by Eqs. 12-29. Differences between planned and actual system performance and costs after applying the availability function are shown in Table 1.

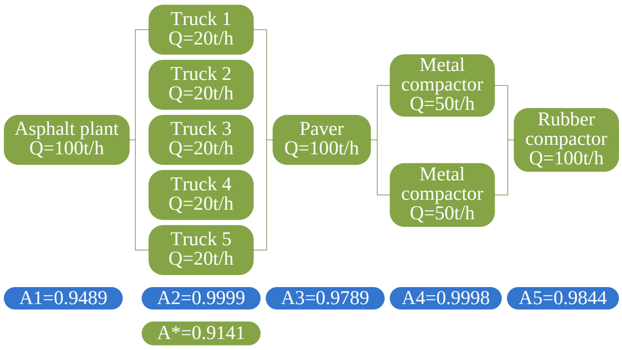

Figure 2. System for production and embedding bitumen-bonded materials

Table 1. Planned(P) and actual(A) performance and costs

Performance	Units	Planned	Actual	A/P (%)
hday	(h)	7.20	7.88	9.40
Days	D	125.00	125.00	0.00
h	(h)	900.00	984.57	9.40
Cs	($/h)	1,280.72	1,343.73	4.92
Cstot	($)	1,152,651.80	1,274,483.09	10.57
Q	(t/h)	100.00	94.89	0.95
Uc	*($/t)*	*12.81*	*14.16*	*10.57*

5. Discussion

The failure and repair rates of system components reduced the planned capacity to 100 tons per hour, thereby increasing the planned unit costs. The measured failure and repair times, along with the structure of time in the system's available and unavailable states (mechanization), were used to analyze the system's availability and its impact on actual capacity, costs, and unit price. Table 1 shows that the system was designed to operate for 125 days, with an average of 7.2 hours per day, and a planned output of 100 tons per hour. Such a dynamic plan is a key part of the contractual documentation. Based on this data, the total planned costs of the project were estimated at $1,152,651.80, resulting in a unit cost of $12.81 for the planned 90,000 tons of material. After the first monthly review of work dynamics, the average daily output was 658.15 tons per hour, instead of 720 tons. Due to agreed penalties for delays—0.3% per day with a maximum of 7% of the contracted value—the contractor decided to extend daily working hours to 9 hours. Throughout the project, daily output varied due to occasional downtime of systems and components, allowing the work to finish in 125 days without penalties. Analyzing the inputs used for calculating the system's unit costs, the actual average capacity was 94.89 tons per hour. Using the availability function for each component, subsystem, and the entire system, Table 1 presents current data on costs and operating hours.

The current unit and total system costs, which are 10.57% above plan, suggest a potential loss of calculated net profits and emphasize the importance of the availability function in cost and price calculations for construction production systems with highly mechanized work. Using the minimum real, practical capacity of all subsystems reduces the risks related to estimates of unit and total system costs. Besides aligning average construction standards for each project during the bidding phase, the construction technology designer can use a database of depreciation rates and component operational availability to develop a unique method to assess component availability for each project. Specifically, based on the machine's age (i.e., the amortization period), it is determined to which time the component belongs [2, 3, 11]. A straightforward statistical analysis can estimate the component's projected availability by accounting for time based on its amortization period and operational availability [2, 12].

6. Conclusion

Production systems are inherently repairable and have a significant role in the development and increasing importance of availability. Beyond its basic definition, availability has evolved into a measure of the reliability of repairable systems. Production systems designed to operate over long periods also include construction production systems, which mainly consist of construction plants and machinery. Given their design for extended durations, it is reasonable to assume that time approaches infinity, enabling high accuracy for the expressions presented in this paper. Failing to consider availability when calculating system prices per unit of the finished product can distort the actual costs. In the study mentioned, the project's working days were not extended, as efforts focused on improving daily output to avoid delays and penalty costs. Special attention should be paid to these expenses, as their frequency was evident in the system analyzed. The company's information system should accurately record failure times and repairs, along with all related costs incurred during and outside of operations. Operational availability and various costs can be assessed based on the system structure. Considering their advantages and disadvantages, it is essential to focus on the subsystem components' hot and cold reserves. The analysis of the indicators in Table 1 shows that availability criteria cannot be overlooked when determining the cost structure for establishing the final selling price. A comparison of nominal total cost differences for identical percentages across different contracted values can be pursued as a further line of research.

Data on planned profits can be especially relevant in scenarios with higher expenses, such as complex, costly projects. In these cases, decision-makers often set a specific profit amount based on the percentage relationship between actual costs and the contracted value. This approach is justified only if potential risks are analyzed and prioritized, with availability being the primary concern. Incorporating availability criteria into the optimal selection of construction machines expands previous research on optimizing the model for choosing the necessary construction equipment for any project.

References

[1] Ivanović, G., Stanivuković, D., and Beker, I. (2010). Pouzdanost tehničkih sistema. Mašinski fakultet, Beograd.

[2] Mirković, M. S. (2016). Optimizacija raspoloživosti sistema za proizvodnju i ugrađivanje bitumenom vezanih materijala (Doctoral dissertation, Univerzitet u Beogradu-Građevinski fakultet).

[3] Mirkovic, M. (2018). The impact of failure types in construction production systems on economic risk assessments in the bidding phase. Complexity, 2018(1), 5041803.18. https://doi.org/10.1155/2018/5041803

[4] Ivković, B. (1988). Optimizacija pouzdanosti proizvodnih sistema u građevinarstvu. (Doctoral dissertation, Univerzitet u Beogradu-Građevinski fakultet).

[5] Trbojević B., and Praščević Ž. (1991). Građevinske mašine. Građevinska knjiga, Beograd.

[6] Praščević, Ž. and Praščević, N. (2015). Pouzdanost, raspoloživost i očekivani radni učinci sistema građevinskih mašina sa rasplinutim (fuzzy) ulaznim parametrima. XL naučno stručni skup "Održavanje mašina i opreme 2015" Beograd-Budva, 18-26. Jun 2015. https://grafar.grf.bg.ac.rs/handle/123456789/2948

[7] Stapelberg, R. F. (2009). Handbook of Availability, Maintainability, and Safety in Engineering Design. Springer, London.

[8] Mirković, M. (2019). Availability classification for applications in construction production systems: A review. Facta Universitatis, Series: Architecture and Civil Engineering, 001-017. https://doiserbia.nb.rs/Article.aspx?id=0354-46051901001M

[9] Vujanović, N. (1990). Teorija pouzdanosti tehničkih sistema. Vojnoizdavački i novinski centar, Beograd.

[10] Lamb, R. G. (1995). Availability engineering and management for manufacturing plant performance. Prentice Hall PTR, New Jersey, USA.

[11] Rigdon S. E., and Basu A. P. (2000). Statistical Methods for the Reliability of Repairable Systems. John Wiley & Sons, Canada.

[12] Mirkovic, M. (2021), "Metadata for availability parameters and life cycle of the researched components", Mendeley Data, V4, https://doi.org 10.17632/5bfjfmfvrb.4.