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01-039 – Anomalies of the RRH and RID resource distribution metrics – Anomalías de las métricas de distribución de recursos RRH y RID

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Resource leveling aims to reduce the fluctuations of the resource distribution and peak resource demand during the construction. Obtaining the optimum solution is not a problem as the optimization tools can be accessed easily and large problems can be solved by ordinary desktop computers. However, the most important part of the problem is the selection of the proper metric, because all of the resource distribution metrics do not reduce the fluctuations or peak resource demand. In this study, drawbacks of resource idle day, release and rehire, and minimum moment metrics are discussed on case study problems in which the examined metrics cannot provide proper resource distributions. Resource idle day, and release and rehire metrics cannot penalize peak resource demand properly while they may excessively penalize unimportant fluctuations. Minimum moment metric cannot penalize resource fluctuations efficiently and systematically. Project managers may face with even worse resource distribution if the aforementioned metrics are utilized without any prior knowledge.

Keywords: *Resource leveling; Scheduling; Resource distribution*

La nivelación de recursos tiene como objetivo reducir las fluctuaciones de la distribución de recursos y la demanda máxima de recursos durante la construcción. Obtener la solución óptima no es un problema ya que se puede acceder fácilmente a las herramientas de optimización y los grandes problemas se pueden resolver con computadoras de escritorio comunes. Sin embargo, la parte más importante del problema es la selección de la métrica adecuada, porque todas las métricas de distribución de recursos no reducen las fluctuaciones o la demanda máxima de recursos. En este estudio, se analizan los inconvenientes de las métricas de día de inactividad de recursos, liberación y recontratación y momento mínimo en problemas de estudio de casos en los que las métricas examinadas no pueden proporcionar distribuciones de recursos adecuadas. Las métricas de día de inactividad de recursos y liberación y recontratación no pueden penalizar la demanda máxima de recursos de manera adecuada, mientras que pueden penalizar excesivamente las fluctuaciones sin importancia. La métrica de momento mínimo no puede penalizar las fluctuaciones de recursos de manera eficiente y sistemática. Se puede obtener una peor distribución de recursos si se utilizan las métricas mencionadas sin ningún conocimiento previo.

Palabras claves: *Nivelación de recursos; Programación; Distribución de recursos*

1. Introduction

Solution of resource levelling process aims to reduce the resource fluctuations, the duration of resources being idle, and the peak resource demand. Properly levelled resource distribution throughout the construction period provides steady employment pattern and assists to identify and retain top-quality construction workers (Harris, 1978). Moreover, continuously working personnel would have a better learning curve (Stevens, 1990). Also, reduces the amount of unnecessarily paid idle workers (Jun and El-Rayes, 2011), improves the productivity of the workers and reduces the unnecessary worker density on construction site (Ponz-Tienda et al., 2017). Finally, properly levelled resource distribution reduces the overhead costs and endeavour of the management of the resource allocation throughout the construction period (Waligóra, 2022).The listed items demonstrates the importance of the achieving a proper resource distribution.

The definition or the solution of the resource levelling problem varies according to the priorities of the project manager. In the literature different approaches exist among the delay of activities as such some researches allow splitting of the activities (Hariga and El-Sayegh, 2011; Son and Mattila, 2004) but usually the problem is solved without allowing activity split. Working habits of the construction sector is not always appropriate for activity splitting so that once an activity starts it continues until it finishes. Consequently, in this study resource levelling with no allowance for the activity splitting is preferred. Project completion deadline is not violated during the solution procedure of the resource levelling problem. Therefore only the noncritical activities are delayed.

Delay of noncritical activities creates significant number of schedule combinations and makes the resource levelling problem NP-Hard (Rieck et al., 2012; Neumann et al., 2012). This necessitates implementation of advanced solution techniques to obtain satisfactory results. Koulinas and Anagnostopoulos (2011) proposed a hyper-heuristic algorithm for the solution of RLP. Ballestin et al. (2007) implemented heuristic network analysis algorithms. Apart from heuristic algorithms mixed-integer programming algorithm is implemented by Rieck et al. (2012), Kreter et al. (2014), Rieck and Zimmermann (2015) and Bianco et al. (2016). Rieck et al. (2012; 2015) obtained exact solutions up to 50-Activity projects. Neumann and Zimmermann (2000) and Gather et al. (2011) proposed a branch-and-bound algorithm. Bandelloni et al. (1994) presented a non-serial dynamic programming model. Neumann and Zimmermann (1999) introduced branch-and-bound and truncated branch-and-bound procedures for the solution of RLP. Meta-heuristic algorithms are implemented by Son and Skibniewski (1999), Leu et al. (2000), El-Rayes and Jun (2009), Christodolou et al. (2009), Ponz-Tienda et al. (2013), Geng et al. (2011), Xu et al. (2020), and Iranagh et al. (2023). Erzurum and Bettemir (2021) solved RLP by complete enumeration.

The cited studies reduced the value of the objective function significantly when compared with the value of the objective function of the initial resource distribution. The capabilities of the solution algorithms and the computational power of the computers have increased significantly and obtaining optimum or near-optimum solution of the resource levelling problem cannot be considered as a demanding issue for medium sized construction projects. However, in the literature numerous resource levelling metrics exist and each metric presents different resource distributions from each other (Bettemir, 2025). Therefore, selection of the resource distribution metric which is suitable for the desired resource distribution has paramount importance. In the literature the possible output of the resource levelling metrics are superficially examined. Bettemir and Erzurum (2022; 2019) compared four resource distribution metrics by considering the peak resource demand quantitatively and resource fluctuations qualitatively. Damci et al. (2016) and Damci and Polat (2014) compared the outputs of nine resource distribution metrics but no analytical inference made on the output of the resource distribution metrics. The positive and negative aspects of the existing resource distribution metrics has not been discussed meticulously in the literature. Therefore, this study aims to address the aforementioned literature gap and examines the Release and Re-Hire (RRH) as well as Resource Idle Day (RID) metrics to reveal the strengths and weaknesses of these metrics.

2. Methodology

Methodology of this research includes the examination of the analytical formulations of the RRH and RID metrics. The expected outcome of this examination will reveal the resource distribution pattern that the implemented metric will most likely provide. Then, expected responses of the metrics to the resource fluctuations and higher resource peak demands are examined by scenario analyses. Any anomalies in the responses of the metrics will be searched for and discussed by examining extreme cases. Finally, the detected anomalies are aimed to be eliminated by proposing modifications on the metrics. A case study problem is solved and the outputs of the original and the modified RRH and RID metrics are compared in terms of peak resource demand and resource fluctuations.

Release and Re-Hire (RRH) enumerates the total amount of resources which has to be released during low demand periods and rehired during the high demand periods (El-Rayes and Jun, 2009). Objective function of RRH is given in Eq. 1.

$$RRH = \frac{1}{2} \times \left[r_1 + \sum_{t=1}^{S-1} \left| r_t - r_{t+1} \right| + r_S \right] - MRD \tag{1}$$

In Eq. 1, MRD is the maximum daily resource demand, S is the duration of the construction project, and r_i represents the daily resource demand at the i^{th} day of the construction. Resource Idle Day (RID) measures the total number of idle and non-productive resource days caused by resource fluctuations. Objective function of RID is given in Eq. 2 (El-Rayes and Jun, 2009).

$$RID = \sum_{t=1}^{S} \left[Min\{Max(r_1, r_2, \ldots, r_t), Max(r_t, r_{t+1}, \ldots, r_S)\} - r_t \right] \tag{2}$$

Both resource distribution metrics have complex objective functions which are difficult to intuitively estimate the possible resultant resource diagram. Therefore both metrics should be utilized with a priori knowledge on the responses of the given objective functions. In this respect this study aims to detect the responses of the RRH and RID resource distribution metrics to resource fluctuations and peak resource demand.

2.1 Analytical Inspection of RRH and RID

Eq. 1 has two components; the former is the sum of the absolute values of the differences between the consecutive daily resource demands throughout the construction period. This component is sensitive to the resource fluctuations which can occur as increase or decrease in the resource demand. The absolute value operator outputs zero when the resource distribution does not change and outputs the difference of the resource demands between the consecutive days. If the resource demand of the project starts with value r_1 at the first day and steadily increases to MRD value without any decrease, the sum of the outputs becomes MRD – r_1. In Eq. 1 the first term is r_1 and when it is added to MRD – r_1 the sum becomes MRD. The same logic can be implemented for the time period between the t_p and t_s which represents the time when the peak resource demand occurred and the last day of the construction project respectively. If the resource demand decreases monolithically from MRD to r_s then the sum of the absolute value of the differences of the consecutive daily resource demands between the time period t_p and t_s become MRD – r_s. The last term of HR which is r_s cancels out the $-r_s$ and only MRD remains. Aforementioned inclining and declining paths provides MRD amount of penalty and as represented in Eq. 1. When the obtained value is divided by 2, MRD value is obtained and the last term of the Eq. 1 which is – MRD cancels out the MRD and the value of the objective function becomes zero.

Figure 1: Hypothetic resource histogram to illustrate behaviour of RRH and RID.

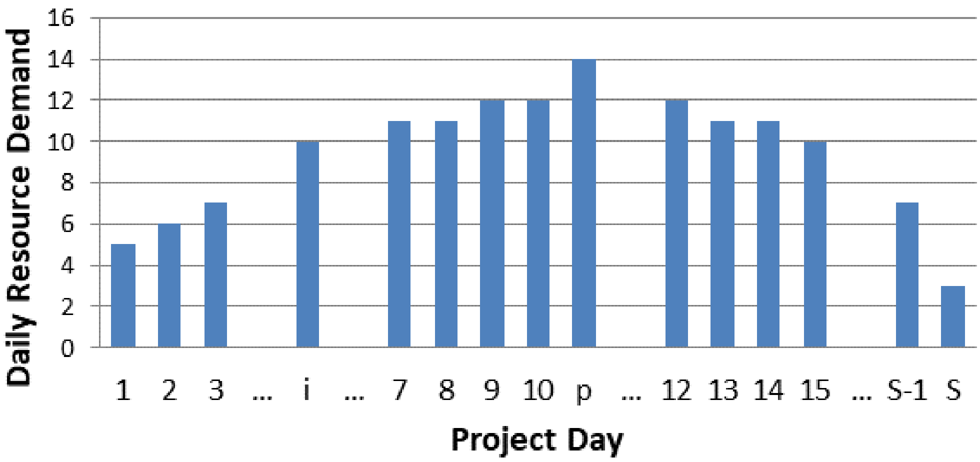


Figure 1 is an illustrative hypothetic resource distribution diagram prepared with a purpose to demonstrate the response of the RRH metric on the monotonic non-decreasing and then monotonic non-increasing resource distribution. When Eq. 1 is implemented to evaluate the resource histogram it is seen that the values of the parameters of r_1, r_S, and MRD becomes 5, 3 and 14 respectively. The daily resource demand values only increases or stays constant between the 1st and the pth days. The summation of the absolute values of the differences between the 1st and the pth day gives 14 – 5 = 9 in the hypothetical example. Then between the pth and S-1st days the daily resource demand decreases or stays constant so that the summation of the absolute values of the differences between the pth and S-1st days gives 14 – 3 = 11. The sum of the absolute values becomes 9 + 11 = 20. The objective function is calculated as (5 + 20 + 3)/2 – 14 = 0.

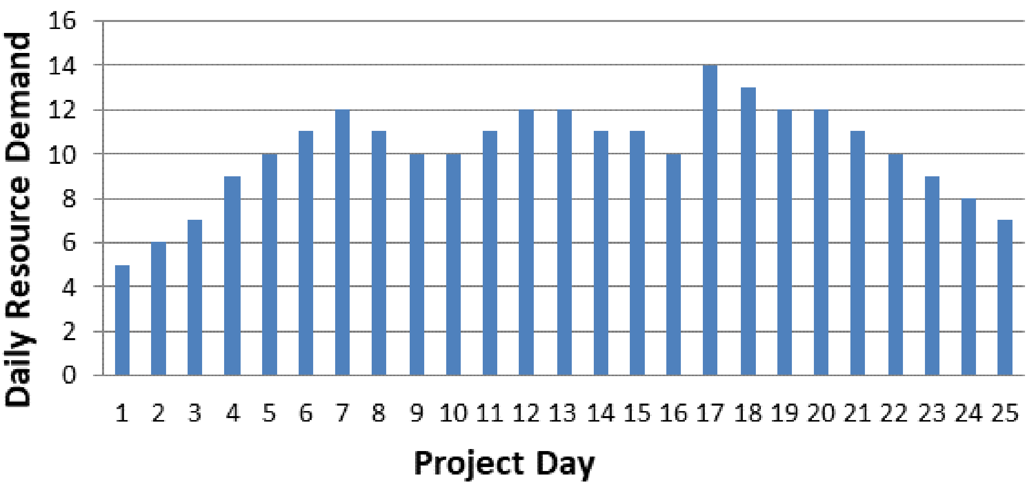
Objective function of the RID metric scans each day of the project and retrieves the maximums of the resource demands of the two periods where the one is from the first day of the project to the current day and the other is from the current day to the last day of the project. Among the two examined time periods it is for sure that one period would return the maximum resource demand which is represented as MRD. The remaining period may also return MRD or it can return a smaller value but which cannot be smaller than the value of the resource demand of the examined day. The min operator returns the smaller value among the compared values. Then the resource demand value of the current day is subtracted. These computations are repeated for each project day to compute the value of the objective function.

The behaviour of the objective function of the RID metric is analysed by examining the outputs of the two periods separately. At first, it is assumed that MRD occurred at the second period and the peak of the first period is smaller than MRD. If this assumption is connected with the resource histogram given in Figure 1 it can be said that the analysed period is earlier than the pth day. The max function of the second period outputs MRD while the max function of the first period outputs the resource demand value of the examined day. Throughout the first period the daily resource demand does not decrease it always increases or keeps constant. The first max operator compares the present day's resource demand with the resource demands of the previous days and consequently the maximum value becomes the resource demand of the present day. Consequently the min operator outputs the resource demand of the present day and it is also subtracted from the output value and 0 is obtained for the aforementioned situation. This situation is valid until the p^{th} project day where MRD occurs. At the p^{th} day both max functions of the first and second period output MRD value and the min function returns MRD which is cancelled out by subtracting r_p. At the later days the peak resource demand occurs at the first period and at the second period the examined day becomes the peak resource of the corresponding day since the forthcoming days have equal or smaller resource demands than the examined day. Consequently, the min function outputs the resource demand of the examined day and it will be cancelled out by subtracting r_p. Therefore the RID metric does not penalize the resource histogram given in Figure 1. The initial examination reveals that both metrics do not penalize monotonically non-decreasing then monotonically non-increasing resource demand histograms.

2.2 Inspection of RRH and RID for fluctuating resource histograms

In order to measure the responses of RRH and RID metrics on the fluctuations of the daily resource demand, the hypothetical resource distribution histogram given in Figure 2 is formed.

Figure 2: Hypothetic resource histogram with fluctuations.



The analysis of the RRH and RID metrics are conducted by dividing the resource histogram into six regions where the resource demand only monolithically increases or decreases. The regions are defined as [1-7], [8-10], [11-13], [14-16], 17, and [18-25]. The first analysis is done for the RRH metric. The sum of the absolute values of the differences of the resource demands are calculated as 7, 2, 2, 2, 4, and 7 respectively. The objective function becomes (5+7+2+2+2+4+7+7)/2 – 14 = 4 which is a penalty assigned because of the fluctuations of the resources.

The analysis for the RID metric is also performed by considering the six regions. In the first region MRD happens at the second period, therefore the second max function always outputs MRD value while the first max function outputs the value of the resource demand of the present day. Consequently, the min function outputs the resource demand of the present day and this value is cancelled out by the negative term of the objective function. The objective function does not apply a penalty for the first region. The second region has a decreasing pattern and therefore the maximum of the first period cannot be equal to the resource demand of the present day. Throughout the first period of the second region the max function always output 12 and the max function of the second period always output MRD which is 14. Consequently, the min function outputs 12 for each day and this value is reduced by the corresponding daily resource demand. For the second region the penalty values are computed as 1, 2, and 2 which are summed as 5. Third region is an increasing region whose maximum peak resource is not larger than the previous peak and the max function of the two periods behaves similarly where min function outputs the value returned by the first max function. The daily resource demand is reduced from the returned value and 1, 0, and 0 values are obtained for the third region. In the fourth region the resource demand has a decreasing demand and MRD is still at the later region and the min function returns the value obtained from the first max function which is 12. The value of the present resource demand is reduced and the outputs of the objective function become 1, 1, and 2 for the fourth region. The fifth region covers only a one day of the project which is the peak resource demand and the both max functions output MRD. Consequently the min value output the same value and this is cancelled out by the $-r_t$ term which will be equal to –MRD. The sixth region is monotonically non-increasing and the peak resource demand occurs at the period of the first max function. Therefore, the first max function outputs MRD and the second max function returns the value of resource demand of the present day. Consequently, the min function outputs the value of the resource demand of the present day which is cancelled out by the $-r_t$ term. The value of the objective function is computed by summing the values of the six regions which is 0 + 5 + 1 + 4 + 0 + 0 = 10.

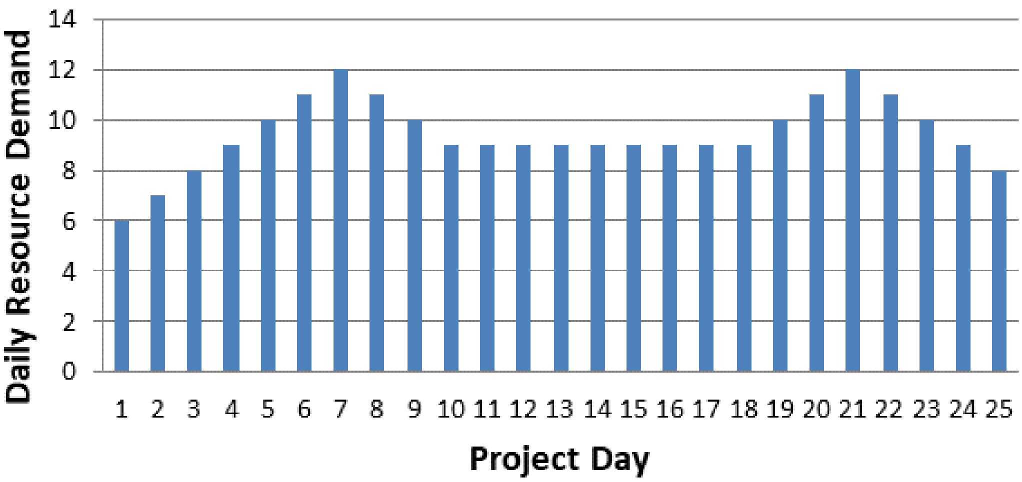
This comparative analysis represents that RRH metric penalises the fluctuations by considering only the magnitude of the fluctuation. On the other hand, RID metric considers both the magnitude of the fluctuation and the duration of the fluctuation.

2.3 Inspection of RRH and RID for long term fluctuating resource histograms

The responses of the RRH and RID metrics to the long term fluctuations are examined on the hypothetical resource distribution histogram given in Figure 3. The resource distribution has two local peak resource demands; the former is at the beginning of the project, and the latter is at the final phase of the project. In the middle of the two peaks a smooth resource demand period exists. This problem is prepared to particularly to determine any improper penalty value assigned by the examined metrics.

RRH metric does not penalize the rise of the resource demand from the initial value to the peak resource demand and then fall of the resource demand from the peak value to the resource demand of the last day. The fluctuations other than the aforementioned rise and fall are penalized by the RRH metric. As a result of this, the fall between the period 7th and 10th days, and the rise between the 18th and 21st days are penalized. This ends up with 3 + 3 = 6 objective function value.

Figure 3: Hypothetic resource histogram with long-term fluctuations.



RID metric penalizes the resource distribution when the present resource demand is lower than the both peaks of the previous and the succeeding periods as discussed in the second hypothetical example. The aforementioned case occurs between the 7th and the 21st days of the project. During the mentioned period the max functions for the previous and succeeding periods will output 12 and the r_t term will be equal to the resource demand of the corresponding day. The daily penalty value will be 12 – r_t for each day. The penalty value of the objective function is computed as 1 + 2 + 3 +3 +3 +3 +3 +3 +3 +3 +3 +2 +1 = 33. When the penalty values of RRH and RID metrics are compared it is seen that RID applies significantly high penalty for this hypothetical example. The high penalty is caused by the long-time interval between the two local peaks of the resource distribution diagram. In real life applications such a resource demand is not inconvenient since the resource may be hired at the beginning of the construction and then it can be released at the end of the 7th time unit and then it can be re-hired at the 21st time unit. The release and re-hire task does not increase the construction cost as tremendously as the objective function implies.

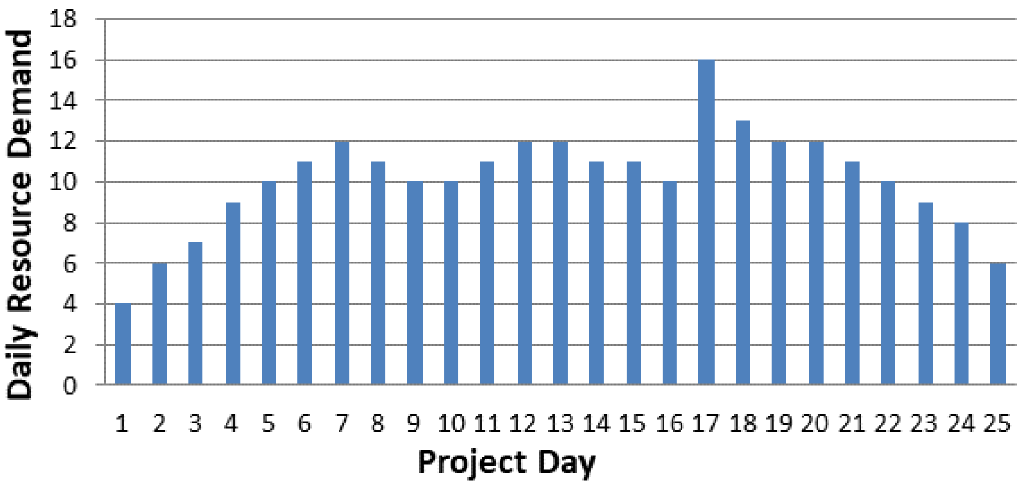
2.4 Inspection of RRH and RID for peak resource demand

The responses of RRH and RID metrics are measured by modifying the resource distribution histogram given in Figure 2. The modified resource distribution where the resource demands of the first and the last day are reduced by one and the peak resource demand which is at the 17th day is increased by two is shown in Figure 4. Evaluation of the resource distribution metrics are similar to the test problem given in section 2.2. Therefore, the solution procedure is not explained in as much detail as before.

RRH metric penalizes the period between the 7th and 12th days as well as the period between the 13th and 17th days. The summation of the absolute values of the falls and rises at the aforementioned period provides 6 which is the same with the value of the objective function of the second case study problem.

RID metric also penalizes the periods between the 7th and 12th days as well as between the 13th and 17th days. The values of the peaks that surround the both valleys are 12 and 12 for the first valley while it is 12 and 17 for the second valley. The penalty function considers the smaller boundary value and as a result the value 12 is taken into account for both cases. The summation of 12- r_t values for the both valleys ends up with 10 for the RID metric which is also the same with the value of the objective function of the second case study problem.

Figure 4: Hypothetic resource histogram with long-term fluctuations.



The fourth case study problem is designed intentionally to reveal that the RRH and RID metrics can be unresponsive to the increase in the peak resource demand which is an undesirable situation. The prepared case study problems demonstrate that RRH and RID metrics have important deficiencies and they should be used in limited applications with their present form.

3. Modifications on the RRH and RID

The deficiencies and the anomalies illustrated in the previous part are aimed to be eliminated by making modifications on the RRH and RID metrics.

3.1 Modification on the RRH

The basic deficiency of the RRH metric is detected as its unresponsive behaviour on the peak resource demand. The metric is designed to output no penalty for monotonically non-decreasing resource pattern at the initial stage of the construction and monotonically non-increasing resource pattern at the later stages of the construction. This preference made RRH metric irresponsive to the peak resource demand. Moreover, the modified RRH has r_1 and r_s terms which tend to reduce the resource demands at the first and last days of the construction. In order to enforce RRH metric to penalize peak resource demand the last term is removed and the modified metric is given in Eq. 3.

$$RRH_M = \frac{1}{2} \times \left[\sum_{t=1}^{S-1} \left| r_t - r_{t+1} \right| \right] \tag{3}$$

The modified metric has important similarities with the Absolute Difference (AD) metric which sums the absolute value of the differences of the resource demands between the consecutive days.

3.2 Modification on the RID

RID metric also does not consider the peak resource demand and it over-penalizes the period between two local peak resource demands. In order to eliminate the detected anomalies it is proposed that the resource can be returned or be allocated at another job if the duration between the two peak demands is long enough. Therefore, the project manager can assign a time period for a feasible freeing and then re-allocating a certain resource type. It can be assumed that the resource would be freed if the idle time would be longer than the threshold duration. If the duration is shorter, keeping the resource idle for the corresponding duration would be preferred. The mentioned duration will be assigned by the project manager and the object function will examine the probable idle resources within the specified time window. The modified RID is given in Eq. 4.

$$RID_M = \sum_{t=1}^{S}\left[Min\{Max(r_i,\ldots r_{t-1},r_t),Max(r_t,r_{t+1},\ldots,r_j)\}-r_t\right]+MRD \quad (4)$$

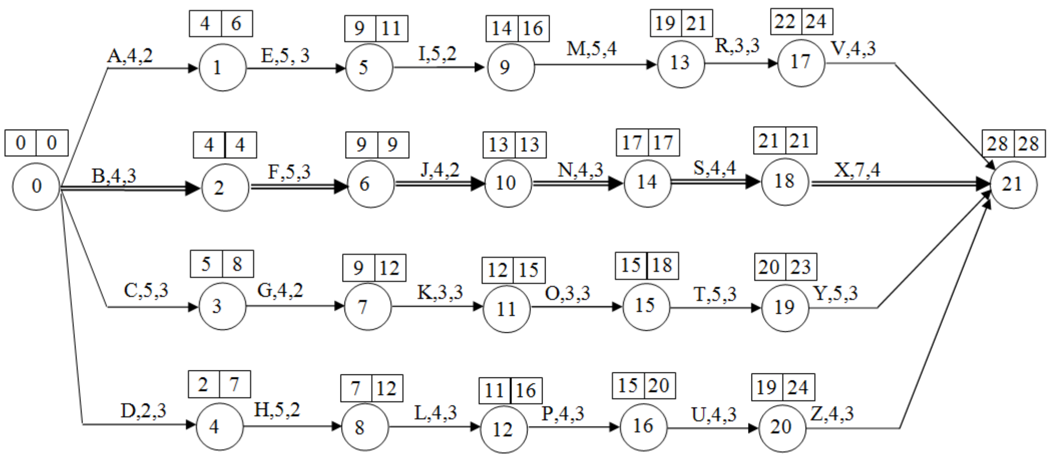
Where i = max(1;t-a) and j = min(S; t+a). Parameter, a, is a predefined duration assigned by the project manager that longer idle times than *a* day will not be allowed. In order to eliminate the insensitiveness on the peak resource demand, MRD term is added to the metric. The output of the metric is dependent on the assigned *a* value which requires expert knowledge to decide the feasibility of the releasing and rehiring of the construction machines and workers.

The time window approach does not penalize the long-period between the high local peak resource demands given in Figure 3. If the parameter *a* is less than 10, and the peak resource demand would be penalized. This modification can prevent wrong assessment of the resource histograms. Moreover, the modified metric penalizes the resource diagram given in Figure 4 higher than the diagram given in Figure 2. This demonstrates that the unresponsiveness of RID metric on the peak resource demand is eliminated.

3.3 Comparative case study

The network diagram given in Figure 5 is used to analyse the effects of the proposed modifications on the RRH and RID metrics. The aforementioned project has 24 activities and 4 parallel paths among which one is critical path. The float durations of the noncritical paths are 2, 3, and 5 days.

Figure 5: Hypothetic 24-Activity resource levelling problem .



The problem is solved by complete enumeration to ensure obtaining the global optimum. The optimization process is completed after the execution of 1.086.624 schedules. The computation duration was less than 1 seconds for RRH and approximately 2.5 seconds for RRH. The resource distribution diagrams of the original and the modified algorithms are given in Figures 6-9.

Figure 6: Optimized resource distribution obtained by original RRH metric .

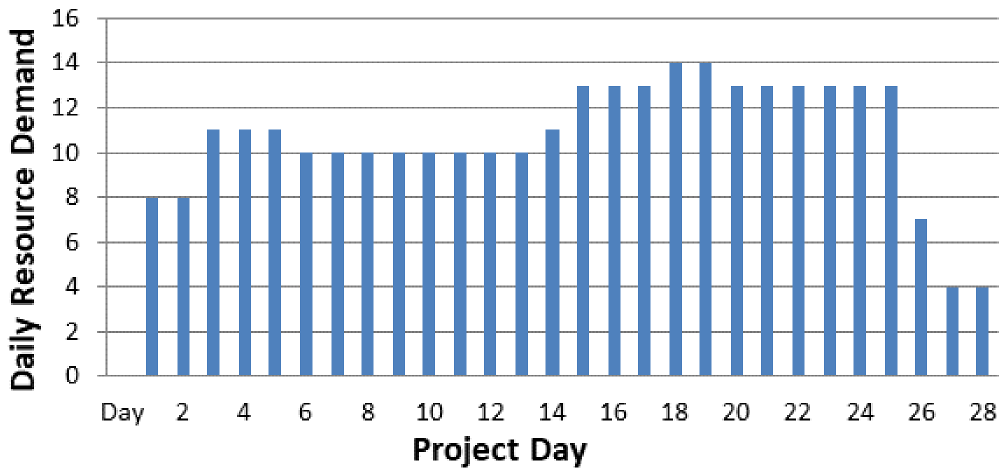
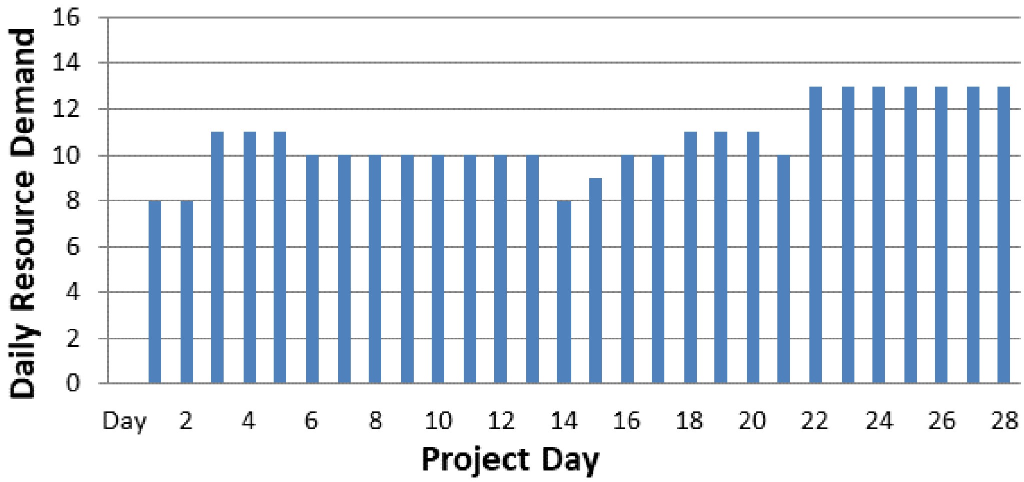


Figure 7: Optimized resource distribution obtained by modified RRH metric.



Original RRH provides a smoother resource distribution histogram at the mid-phase of the project but the resource distribution fluctuates especially at the later phases. Peak resource demand is 14 which continues for 2 time units as illustrated in Figure 6. The modified RRH metric has slightly higher resource fluctuations in the middle phase of the construction while the final phase is smooth as represented in Figure 7. The most important improvement is that the peak resource demand is reduced by one and it is realized as 13.

Figure 8: Optimized resource distribution obtained by original RID metric.

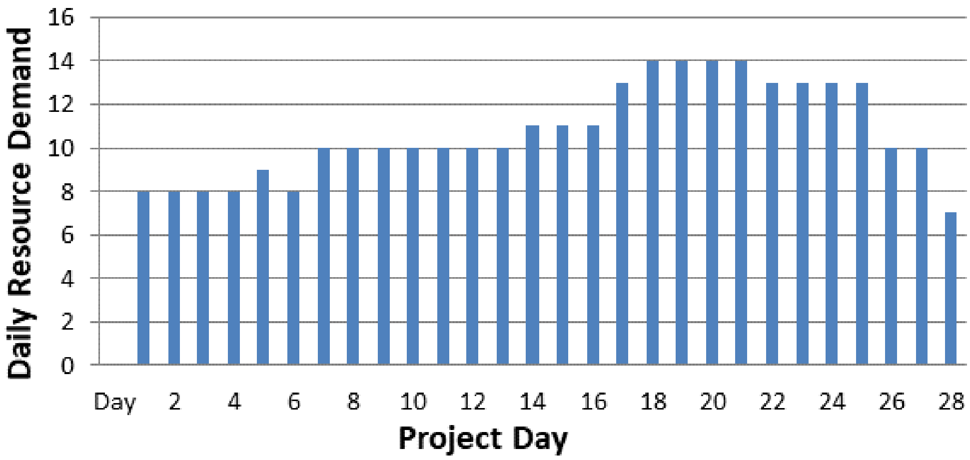
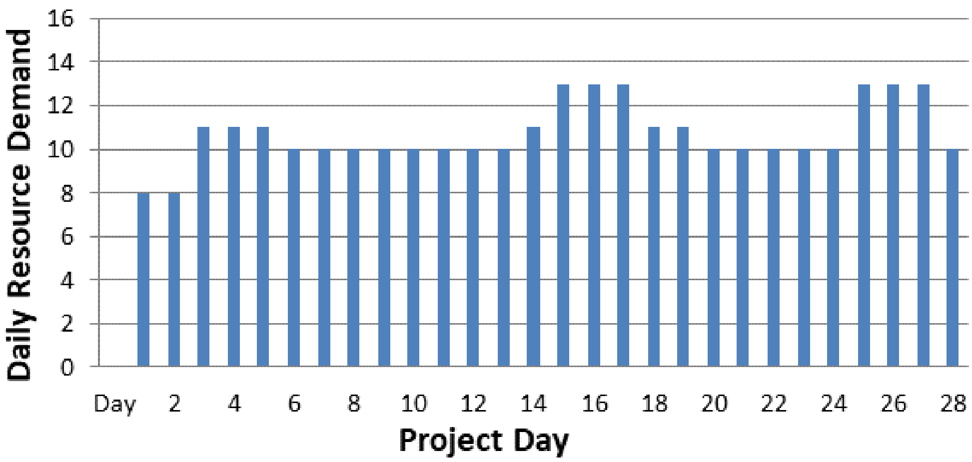


Figure 9: Optimized resource distribution obtained by modified RID metric.



Original RID provides almost a perfect monotonically non-decreasing resource usage pattern at the initial phase of the construction then a monotonically non-increasing resource pattern at the final phase of the construction. However, the resource pattern does not prevent resources being idle as given in Figure 8. To illustrate at day 5 and 17 frequently hiring and releasing of the resources are required. Moreover, the maximum resource demand is 14. The modified RID with 3 units of time window, a = 3, provided the resource histogram given in Figure 9. The resultant histogram is not monotonic anymore but the peak resource demand is reduced by 1 and peak demand is realized as 13.

4. Conclusion

This study aimed to demonstrate some of the inefficiencies of the RRH and RID resource levelling metrics. Within this scope four situations related with resource distribution is examined in order to analyse the responses of the aforementioned metrics. Responses of the metrics on the resource fluctuations, peak resource demand, and time difference between the fluctuations are examined. The most important result was the unresponsiveness output of the analysed metrics to peak resource demand. Moreover, it is detected that RID metric over-penalizes the resource utilization which is between two local peaks.

Two analysed metrics are modified in order to eliminate their unresponsiveness on the peak resource demand. In the modification, value of the peak resource demand is added to the objective function. In the case study problems it is seen that the modification ends up with reduced peak resource demand for both RRH and RID. Furthermore, second modification on RID is conducted by narrowing the examined time window. The modification prevented the application of an over penalty to the long term lower resource utilization between two local peak resource demands. However, this modification required an application of specific parameter for the RID resource distribution metric. The required parameter is the duration for which frequent hiring and releasing of resources is not applicable.

The contribution of this study can be briefly stated as the analytical examination of the RRH and RID resource distribution metrics which reveals the punitive tendencies of the aforementioned metrics. This would assist the project managers to decide on the selection of proper resource distribution metric which suits their project scopes best. In addition to this, some of the deficiencies of the resource distribution metrics are detected and appropriate modifications are done to eliminate the detected deficiencies. Other existing resource distribution metrics can be examined and modified to improve their objective functions as a future study.

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Use of Generative Artificial Intelligence

The author declares that "No generative artificial intelligence was used in preparing this communication".

Communication aligned with the Sustainable Development Goals