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Non-dominated NSGA-II genetic algorithm for schedule acceleration considering the discrete time-cost compensation problem (DTCTP) in a construction project

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Abstract

Sometimes after scheduling a project, it is necessary to shorten its duration. There are many factors that force to crash the duration. Some reasons may be saving costs, early commissioning or avoiding potential risks. In this case, it is necessary to allocate more resources to activities to shorten their duration while trying to invest as little money as possible. The time–cost tradeoff problem is one important problem in project scheduling. In this study the time–cost tradeoff problem is aborded considering a discrete approach and it is solved using a non-dominated genetic algorithm. The application in a construction project identified a Pareto front that managers could use for decision making. Managers were able to analyze different scenarios to meet delivery date, costs, and scope.

Keywords: Time–cost tradeoff, Crashing, NSGA-II, Multi-objective problem, Scheduling project

Algoritmo genético no dominado NSGA-II para la aceleración de programa considerando el problema de compensación discreta tiempo-costo (DTCTP) en un proyecto de construcción

Resumen

A veces, después de programar un proyecto, es necesario acortar su duración. Son muchos los factores que obligan a acortar la duración. Algunos factores pueden ser ahorro en costos, puesta en operación anticipada o para evitar riesgos. En este caso, es necesario asignar más recursos a las actividades para acortar su duración mientras se intenta invertir la menor cantidad de dinero posible. El problema de la compensación de tiempo y costo es un problema importante en la programación de proyectos. En este estudio se aborda el problema de la compensación tiempo-costo desde un enfoque discreto y se resuelve utilizando un algoritmo genético no dominado. La aplicación en un proyecto de construcción permitió identificar un frente de Pareto que los gerentes podían usar para la toma de decisiones. Los gerentes pudieron analizar diferentes escenarios para cumplir con la fecha de entrega, los costos y el alcance ofrecido.

Palabras clave: Compensación tiempo-costo, Aceleración. NSGA-II, Problema multi objetivo, Programación de proyectos.

1. Introduction

Projects by nature are subject to uncertainty and complexity. As a consequence, there have usually problems that affect its performance. As a result, it is usually expected to have problems with time during the execution phase. And even, the completion time may be expected to exceed the deadline. This is noticeable on construction industry where time delays are common (Adam, Josephson and Lindahl, 2015).

Reducing the time of a project is a recurrent issue when planning or executing a project. This is due to: rush to enter a new product to the market, avoid unfavorable weather seasons, compensation for delays in activities, client imposition, incentive contracts or key resource needs (Gray and Larson, 2009). Reducing project duration is framed in the time-cost tradeoff problem – TCTP.

In this situation, the project management allocates addition resources to shorten completion time. However, he needs to spend the least amount of money possible while achieving an agreed time Shahriari (2016).

The solution of the problem has been evolving on time. The first approach was considering linear this problem. This means that resource costs were considered to be the same over time. So direct and indirect costs were added while reducing task duration (Vanhoucke, 2005).

When practical needs emerged, the research focused on solving the discrete approach of the problem (Vanhoucke, 2005). This approach was abbreviated as the DTCTP, the discrete time-cost trade-off problem.

In this case, the activity duration is a discrete, nonincreasing function of the amount of the single nonrenewable resource assigned. So, each activity can be executed in a limited number of time-cost alternatives, so-called modes, for each activity, according to all possible resource allocations (Wei, Su and Zhang, 2020)an equivalent simplification approach, which is an effective method for solving large-scale complex problems. We first study a way to deal with the anomalies under GPRs, such as the reduce (increase, (Wglarz *et al.*, 2011). It involves the selection among execution modes (the cost-time tuples for each activity) to achieve an objective (Vanhoucke, 2005).

Solution procedures to the DTCTP are classified into exact and heuristic. Exact procedures used are dynamic programming, enumeration algorithms, or project network decomposition (Shahriari, 2016), (Tareghian and Taheri, 2007). But considering the structure of networks, and the number of activities and operation modes, it cannot be solved optimally in a reasonable amount of time (Tareghian and Taheri, 2007). Prabuddha *et al*. (1997) proved that the problem is strongly np-hard for project networks. So a variety of optimal solutions are reached by heuristic procedures González (2013).

According to (Wei, Su and Zhang, 2020) there are three solution orientations in literature. The orientation may be focused on the deadline, budget or efficiency between time-cost solutions over the set of feasible durations.

Exact methods for the DTCTP have been based on dynamic programming algorithm (Robinson, 1975), (Hindelang and Muth, 1979); branch-and-bound-based algorithms (De *et al*., 1995), (Demeulemeester *et al*., 1998), (Vanhoucke, Demeulemeester and Herroelen, 2002), (Değirmenci and Azizoğlu, 2013); column generation method (Akkan, Drexl and Kimms, 2005); and cutting plane algorithm (Hadjiconstantinou and Klerides, 2010).

However, there are two drawbacks for research about DTCTP. There is much research effort in DTCTP but it usually considers few activities (Li, Xu and Wei, 2018). But in practice, most projects have over 25 activities (Liberatore, Pollack-Johnson and Smith, 2001), (Wiest, 1967). The other drawback is the lack of real performance analysis. The test is often in simple examples so adaptability and effectiveness are not proved (Li, Xu and Wei, 2018), (Zheng, Ng and Kumaraswamy, 2005), (Feng, Liu and Burns, 1997).

The use of heuristics and metaheuristics is oriented to apply simulated annealing algorithm (Anagnostopoulos and Kotsikas, 2010); ant colony algorithm (Mokhtari, Baradaran Kazemzadeh and Salmasnia, 2011); tabu search (He *et al*., 2017); variable neighborhood search (He *et al*., 2017); memetic algorithm (Wood, 2017); network analysis algorithm (Bettemir and Talat Birgönül, 2017); particle swarm algorithm (Aminbakhsh and Sonmez, 2016), (Aminbakhsh and Sonmez, 2017); and genetic algorithm (Mokhtari, Baradaran Kazemzadeh and Salmasnia, 2011), (Sonmez and Bettemir, 2012), (Shahriari, 2016), (Agdas *et al*., 2018).

For this study, it was used the non-dominated NSGA-II genetic algorithm. The NSGA-II works with Pareto fronts that yield a variety of optimal solutions. The decision is taken according to the available budget and time. The model includes situations from real projects and it has an efficient consumption of resources and machine time.The final front of the solutions in NSGA-II presents a variety of solutions for decision makers, and they have opportunity to select a proper solution based on the available budget and appropriate time for the project.

2. Methods

The mathematical model includes two objective functions corresponding to cost and time. It also considers schedule compression and time delay. The algorithm was programmed in Java language. The task duration is modeled by a negative exponential distribution. It means that the time-cost function takes values inversely, for example, if time decreases, the cost increases and vice versa. The model finds optimal task duration that minimizes the total cost, defined by the sum of indirect, direct, and incentive costs.

Problem Formulation and Notation

$\mathbf{t_i}$=Happening time of event i

$\mathbf{T_{a(ij)}}$=Minimum allowed time of activity ij (crash time)

$\mathbf{T_{n(ij)}}$=Normal time for activity ij

$\mathbf{T_{m(ij)}}$=Maximun allowed time for activity ij

$\mathbf{d_{ij}}$=Scheduled (actual) time of activity ij (decision variable time optimum)

CI=Project indirect cost

CD=Project direct cost

$\mathbf{C_{a(ij)}}$=Compressing cost of activity ij

$\mathbf{C_{n(ij)}}$=Normal cost of activity ij

$\mathbf{C_{m(ij)}}$=Cost of delaying in activity ij

$\mathbf{C_{ij}}$=Compressing cost rate of activity ij

$\mathbf{C'_{ij}}$=Saving rate of delaying for activity ij

$\mathbf{t_{max}}$=Maximum allowed time for finishing the project

$\mathbf{c_{max}}$=Maximum available budget

$\mathbf{y_{ij}}$={1 If activity ij is compresed / 0 Otherwise}

$\mathbf{y'_{ij}}$={1 If activity ij has delay / 0 Otherwise}

$\mathbf{y''_{ij}}$={1 If activity ij has been done in normal time / 0 Otherwise}

The first objective function seeks to compress time and to minimize cost as follows:

$$\text{Min }(Z_1)=CI\,(t_n-t_1)+CD+\sum_i\sum_j y_{ij}C_{ij}\,\{T_{n(ij)}-d_{ij}\}-\sum_i\sum_j y'_{ij}.\,C'_{ij}\,\{T_{n(ij)}-d_{ij}\} \quad \textbf{(1)}$$

It adds indirect costs, direct costs, and compression costs, and subtracts the money saved of delaying activities.

The cost function is non-linear which means that the time-cost curve follows an exponential behavior. This exponential relationship between compression time and compression cost results in:

$$C(d_{ij})=\alpha.e^{-\beta.dij} \quad \textbf{(2)}$$

$$\beta=Ln(C_n/C_a)/(T_a-T_n) \quad \textbf{(3)}$$

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Then,

$$\alpha=e\{Ln(C_n)+\beta.T_n\} \qquad \textbf{(4)}$$

The saving coefficient behaves in the same way, when the execution time of the activities has been extended from the normal time.

$$C'(d_{ij})=\alpha'.e^{-\beta'.d_{ij}} \qquad \textbf{(5)}$$

$$\beta'=Ln(C_m/C_n) \,/\, (T_n—T_m) \qquad \textbf{(6)}$$

Then,

$$\alpha'=e\{Ln(C_m) + \beta'.T_m\} \qquad \textbf{(7)}$$

By substituting (2) and (5) in (1), and replacing the direct cost CD by the expression $\sum_i\sum_j y''_{ij}.\ C_{n(ij)}$, it is obtained:

$$Min\ (Z_1)=CI(t_n—t_1) + \sum_i\sum_j y_{ij}.\alpha_{ij}.e^{-\beta_{ij}*d_{ij}}) + \sum_i\sum_j y'ij.\alpha'_{ij}.e^{-\beta'_{ij}*d_{ij})} +\sum_i\sum_j y''_{ij}.C_{n(ij)} \qquad \textbf{(8)}$$

The second objective function is considered as the project completion time:

$$Min\ (Z_2)=t_n \qquad \textbf{(9)}$$

It is assumed that , where denotes the event of completion of the activity and t_i the event of beginning of the activity , which means that the variable takes a positive integer value of this difference.

For minimum allowed and maximum allowed time restrictions , that the variable may take, there were created the following expressions (10), (11):

$$y_{ij}.T_{a(ij)} \le y_{ij}.d_{(ij)} \le y_{(ij)}.\ T_{n(ij)}\ ;\ \forall i,j \qquad \textbf{(10)}$$

$$y'_{ij}.T_{n(ij)} \le y'_{ij}.d_{(ij)} \le y'_{(ij)}.T_{m(ij)};\ \forall i,j \qquad \textbf{(11)}$$

If the activity has not been compressed or delayed, it meets a logical restriction of equality between y like this:

$$y''_{ij}.d_{(ij)}=T_{n(ij)}\ .\ y''_{(ij)};\quad \forall i,j \qquad \textbf{(12)}$$

Binary variables must meet the conditions of equation 13 and 14:

$$y_{ij}+y'_{ij}+y''_{ij}=1;\quad \forall i,j \qquad \textbf{(13)}$$

$$T_n \le T_{max} \qquad \textbf{(14)}$$

The total cost cannot be less than the sum of the direct and indirect costs of the activities plus the increase or decrease in case the activity is accelerated or delayed:

$$CI(t_n— t_1\ +\ \sum_i\sum_j y_{ij}.\ \alpha_{ij}\ e^{-B_{ij}.d_{(ij)}} — \sum_i\sum_j {}^{y'}_{ij}\ .\ \alpha_{ij}\ e^{-B_{ij.}d_{(ij)}} + \sum_i\sum_j y'_{ij}\ .C_{n(ij)} \le Cmax \qquad \textbf{(15)}$$

The non-negativity constraint for the events is expressed as .

Solving algorithm

The input parameters are the number of tasks, accelerated, normal, and delayed times and costs. Other inputs are precedence relationships, indirect cost per project period, and a random seed. It takes values from -1 to 9 where the lower the value the number of solutions is repeated to a greater degree. Otherwise, solutions with similar values of time and cost are generated, but not equal. Population size. Number of chromosomes in each iteration of the algorithm potential solutions to generate (npop en el articulo). Probability of mutation. Number of chromosomes mutating in each iteration of algorithm. It takes values from 0.1% to 5% (Pm en el articulo). Number of iterations. Maximum number of iterations the algorithm operates and provide the N quasi optimal solutions (Nit en el articulo). Crossover function. The method selects two parents randomly. Then, produces two offpring through a single-point crossover operator. Selection function. The model takes two parents and selects the one with the highest fitness function. It is a direct comparison trough a tournament selection operator. The procedure is repeated in each iteration. Genome to mutate. Number of genome or activities to mutate in each iteration of algorithm.

The algorithm randomly creates an initial population of chromosomes. Then finds the fitness of each chromosome to select those which continue. Selects two chromosomes and create two new child chromosomes using the crossover function and probability of mutation. Substitute the parents for the children and repeat for a number of iterations completing the population requested.

3. Results and Discussion

The proposed algorithm was applied in a project from the building construction industry. The scope of the project was the construction of the Zarzal campus of the Universidad del Valle at the cost of $6.733.473.346. The project had four work fronts: classrooms, restaurant, swimming pool and outdoor areas. The project had four work fronts: classrooms, restaurant, swimming pool and outdoor areas. The four work fronts were simultaneously scheduled and built in parallel way. The information on activities, times and costs of the project can be seen in table 3

Table 3. Direct costs and completion time per module

Modulo	Tiempo de terminación	Costo directo	Actividades modulo
Aulas	513	$ 3.623.752.600	17
Cafeteria - Restaurantes	281	$ 338.643.801	14
Graderias-Vestier-Piscina	336	$1.231.212.819	14
Zonas Exteriores	299	$ 1.539.864.126	38

Consequently, there were four project network diagrams as can see in figure 13.

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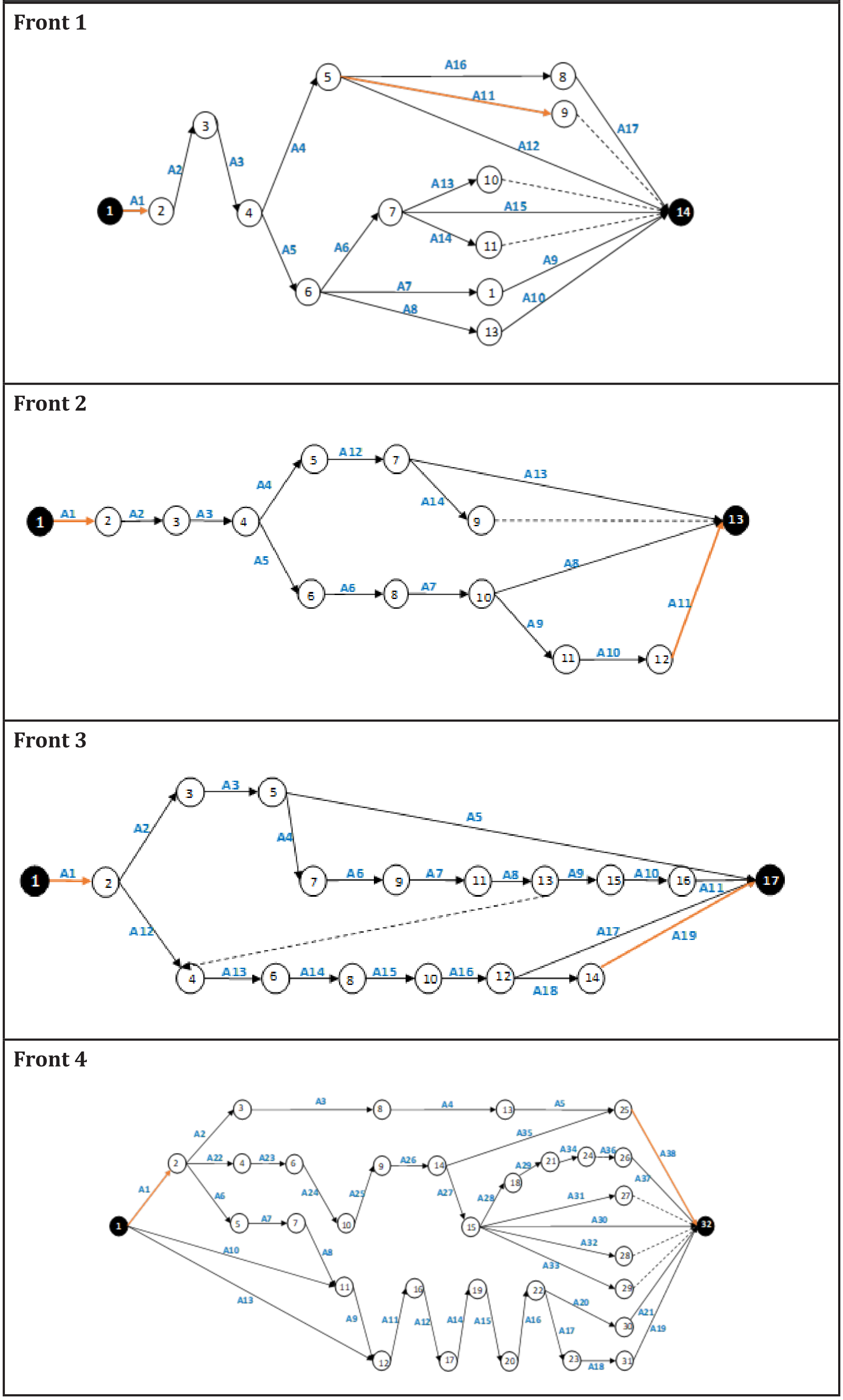

Figura 13. Acitivity on Arrow (AoA) network diagrams.

The consortium in charge of the project provided the design, time and cost of activities. An expert who took part in the project provided accelerated and delayed time and cost of activities. Activities accelerated and delayed time was estimated considering their nature and expected performance. The times changed up to 30% although some tasks, by nature, are not possible to accelerate or delay. The costs were estimated by subtracting or adding the cost per day of the activities. Table 4 shows normal (tn), accelerated (ta) and delayed times (tm), as well as the normal (cn), accelerated (ca) and delayed (cd) costs.

Tabla 4. Input data

	ÍTEM	Ta	Tn	Tm	Ca	Cn	Cm
AULAS	A1	6	8	10	$ 14.717.541	$ 11.774.033	$ 8.830.525
	A2	53	75	98	$ 1.137.649.416	$ 879.625.837	$ 609.873.914
	A3	90	90	90	$ 916.328.259	$ 916.328.259	$ 916.328.259
	A4	32	45	59	$ 241.574.918	$ 187.428.816	$ 129.117.629
	A5	42	60	78	$ 257.844.867	$ 198.342.206	$ 138.839.544
	A6	14	20	26	$ 100.064.851	$ 76.972.963	$ 53.881.074
	A7	21	30	39	$ 371.339.852	$ 285.646.040	$ 199.952.228
	A8	80	80	80	$ 136.668.009	$ 136.668.009	$ 136.668.009
	A9	32	46	60	$ 40.248.839	$ 30.857.444	$ 21.466.048
	A10	32	46	60	$ 21.848.368	$ 16.750.415	$ 11.652.463
	A11	295	295	295	$ 125.212.900	$ 125.212.900	$ 125.212.900
	A12	25	35	46	$ 7.114.036	$ 5.533.139	$ 3.794.153
	A13	19	27	35	$ 19.030.619	$ 14.680.763	$ 10.330.908
	A14	70	100	130	$ 11.531.947	$ 8.870.728	$ 6.209.510
	A15	100	100	100	$ 139.043.946	$ 139.043.946	$ 139.043.946
	A16	168	240	312	$ 760.827.089	$ 585.251.607	$ 409.676.125
	A17	12	12	12	$ 4.765.496	$ 4.765.496	$ 4.765.496
CAFETERIA RESTAURANTE	A1	6	8	10	$ 3.882.631	$ 3.106.105	$ 2.329.578
	A2	42	60	78	$ 116.440.843	$ 89.569.879	$ 62.698.915
	A3	75	75	75	$ 77.363.961	$ 77.363.961	$ 77.363.961
	A4	42	60	78	$ 22.163.192	$ 17.048.609	$ 11.934.026
	A5	42	60	78	$ 47.197.420	$ 36.305.708	$ 25.413.995
	A6	7	10	13	$ 37.094.098	$ 28.533.922	$ 19.973.745
	A7	6	8	10	$ 30.947.501	$ 24.758.001	$ 18.568.501
	A8	45	45	45	$ 34.271.248	$ 34.271.248	$ 34.271.248
	A9	18	25	33	$ 8.331.313	$ 6.508.838	$ 4.426.010
	A10	14	20	26	$ 7.890.075	$ 6.069.288	$ 4.248.502
	A11	11	15	20	$ 2.492.082	$ 1.967.433	$ 1.311.622
	A12	14	20	26	$ 3.220.220	$ 2.477.092	$ 1.733.965
	A13	20	20	20	$ 7.226.661	$ 7.226.661	$ 7.226.661
	A14	15	15	15	$ 3.437.056	$ 3.437.056	$ 3.437.056
GRADERIAS-VESTIER-PISCINA	A1	6	8	10	$ 5.248.105	$ 4.198.484	$ 3.148.863
	A2	42	60	78	$ 432.337.264	$ 332.567.126	$ 232.796.988
	A3	75	75	75	$ 279.302.897	$ 279.302.897	$ 279.302.897
	A4	21	30	39	$ 22.886.521	$ 17.605.016	$ 12.323.511
	A5	32	45	59	$ 90.176.914	$ 69.964.847	$ 48.198.006
	A6	7	10	13	$ 45.667.178	$ 35.128.599	$ 24.590.019
	A7	6	8	10	$ 82.693.201	$ 66.154.561	$ 49.615.921
	A8	25	25	25	$ 31.031.447	$ 31.031.447	$ 31.031.447
	A9	11	15	20	$ 18.391.718	$ 14.519.777	$ 9.679.852
	A10	7	10	13	$ 12.888.042	$ 9.913.878	$ 6.939.715
	A11	3	4	5	$ 3.608.854	$ 2.887.083	$ 2.165.312
	A12	4	5	7	$ 32.238.827	$ 26.865.689	$ 16.119.414
	A13	60	60	60	$ 227.169.431	$ 227.169.431	$ 227.169.431

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	IETEM	Ta	Tn	Tm	Ca	Cn	Cm
	A14	18	25	33	$ 60.393.897	$ 47.182.732	$ 32.084.258
	A15	4	5	7	$ 15.661.017	$ 13.050.847	$ 7.830.508
	A16	7	10	13	$ 5.968.507	$ 4.591.159	$ 3.213.811
	A17	4	4	4	$ 40.751.243	$ 40.751.243	$ 40.751.243
	A18	7	10	13	$ 3.845.989	$ 2.958.453	$ 2.070.917
	A19	10	10	10	$ 5.369.549	$ 5.369.549	$ 5.369.549
ZONAS EXTERIORES	A1	3	4	5	$ 78.398.075	$ 62.718.460	$ 47.038.845
	A2	72	90	117	$ 207.244.319	$ 172.703.599	$ 120.892.519
	A3	70	100	130	$ 97.618.909	$ 75.091.468	$ 52.564.028
	A4	53	75	98	$ 125.544.335	$ 97.070.362	$ 67.302.118
	A5	21	30	39	$ 264.249.923	$ 203.269.172	$ 142.288.420
	A6	1	2	3	$ 877.730	$ 585.153	$ 292.577
	A7	2	2	2	$ 3.824.325	$ 3.824.325	$ 3.824.325
	A8	5	5	5	$ 5.790.935	$ 5.790.935	$ 5.790.935
	A9	2	3	4	$ 2.906.602	$ 2.179.952	$ 1.453.301
	A10	2	3	4	$ 5.659.203	$ 4.244.402	$ 2.829.601
	A11	2	3	4	$ 2.865.908	$ 2.149.431	$ 1.432.954
	A12	1	2	3	$ 1.583.084	$ 1.055.389	$ 527.695
	A13	4	4	4	$ 3.470.205	$ 3.470.205	$ 3.470.205
	A14	1	1	1	$ 1.134.060	$ 1.134.060	$ 1.134.060
	A15	1	2	3	$ 1.591.247	$ 1.060.831	$ 530.416
	A16	2	3	4	$ 91.085.160	$ 68.313.870	$ 45.542.580
	A17	42	60	78	$ 11.502.433	$ 8.848.026	$ 6.193.618
	A18	15	15	15	$ 9.282.203	$ 9.282.203	$ 9.282.203
	A19	15	15	15	$ 304.323.485	$ 304.323.485	$ 304.323.485
	A20	21	30	39	$ 200.124.857	$ 153.942.198	$ 107.759.538
	A21	45	45	45	$ 42.059.384	$ 42.059.384	$ 42.059.384
	A22	15	15	15	$ 13.173.111	$ 13.173.111	$ 13.173.111
	A23	20	20	20	$ 6.484.136	$ 6.484.136	$ 6.484.136
	A24	14	20	26	$ 9.150.255	$ 7.038.657	$ 4.927.060
	A25	11	15	20	$ 2.983.821	$ 2.355.648	$ 1.570.432
	A26	14	20	26	$ 5.121.486	$ 3.939.605	$ 2.757.723
	A27	21	30	39	$ 9.192.075	$ 7.070.827	$ 4.949.579
	A28	45	45	45	$ 41.200.349	$ 41.200.349	$ 41.200.349
	A29	21	30	39	$ 27.094.115	$ 20.841.627	$ 14.589.139
	A30	14	20	26	$ 39.469.813	$ 30.361.395	$ 21.252.976
	A31	11	15	20	$ 3.207.806	$ 2.532.479	$ 1.688.319
	A32	11	15	20	$ 5.451.458	$ 4.303.782	$ 2.869.188
	A33	11	15	20	$ 60.670.337	$ 47.897.635	$ 31.931.757
	A34	7	10	13	$ 94.625.227	$ 72.788.636	$ 50.952.045
	A35	4	5	7	$ 23.018.463	$ 19.182.053	$ 11.509.232
	A36	20	20	20	$ 14.446.090	$ 14.446.090	$ 14.446.090
	A37	10	10	10	$ 13.755.480	$ 13.755.480	$ 13.755.480
	A38	6	8	10	$ 11.719.631	$ 9.375.704	$ 7.031.778

The design of the project allowed the application of the model per work front. To be clear, only work front 1 results are detailed showed. The interpretation of the other modules can be found in the annexes. The work front 1 corresponds to the classrooms module of the project. Module 1 with 17 activities was scheduled with a duration of 513 days and a direct cost of $ 3,623,752,600. The algorithm run with the following parameters: 30 genome to mutate, 1,000 iterations, 50 solutions, probability mutation of 0.1%, crossover function of 0.15%. The indirect cost per period was stablished using the cost of the longest work front.

The model found 50 quasi-optimal solutions. As a result, the module schedule could be reduced to 361 days at a cost of $ 3,923,120,142 as can be seen in table 5. This means that the duration could be reduced by up to 152 periods with an over-cost of $ 299,367,543. At the other extreme is the option to delay to 573 days with a cost of $ 2,945,646,160. This corresponds to an increase of 60 periods for the completion of the module and a saving of $ 678,106,440.

Table 5. Results module 1 of time-cost, compression values , and delay in activities

No	Tiempo	Costo	Periodos Acelerados	Periodos de Retraso	No	Tiempo	Costo	Periodos Acelerados	Periodos de Retraso
1	361	$ 3.923.120.143	109	108	26	437	$ 3.277.000.358	72	147
2	363	$ 3.915.560.592	107	92	27	445	$ 3.261.312.318	54	126
3	364	$ 3.909.378.683	106	108	28	446	$ 3.259.904.474	53	117
4	367	$ 3.846.047.129	103	108	29	450	$ 3.241.402.704	54	131
5	370	$ 3.836.069.525	100	93	30	452	$ 3.235.883.293	53	139
6	375	$ 3.752.950.515	95	93	31	453	$ 3.229.875.284	54	144
7	378	$ 3.718.845.401	92	98	32	454	$ 3.228.293.643	53	142
8	380	$ 3.704.526.052	90	104	33	465	$ 3.216.124.254	32	122
9	382	$ 3.677.132.032	88	92	34	469	$ 3.199.105.045	32	126
10	385	$ 3.638.317.544	87	100	35	470	$ 3.195.125.942	32	127
11	386	$ 3.637.808.935	86	101	36	478	$ 3.177.311.208	30	128
12	392	$ 3.549.263.909	87	112	37	495	$ 3.132.984.677	11	121
13	399	$ 3.467.258.173	87	124	38	496	$ 3.127.865.775	11	135
14	400	$ 3.464.572.335	86	120	39	505	$ 3.109.395.735	2	131
15	402	$ 3.437.718.402	87	103	40	508	$ 3.106.566.387	0	135
16	406	$ 3.395.344.655	87	131	41	526	$ 3.059.257.715	2	137
17	406	$ 3.395.344.655	87	131	42	530	$ 3.046.669.157	0	141
18	414	$ 3.360.415.706	79	131	43	539	$ 3.034.658.749	2	157
19	419	$ 3.341.775.978	74	127	44	540	$ 3.029.760.902	2	161
20	421	$ 3.331.480.950	74	133	45	541	$ 3.026.545.900	2	162
21	422	$ 3.328.587.971	74	118	46	546	$ 3.007.153.891	2	162
22	426	$ 3.309.334.407	74	138	47	547	$ 3.001.867.692	2	168
23	428	$ 3.308.071.228	74	138	48	549	$ 2.994.807.278	2	170
24	432	$ 3.286.796.152	74	141	49	564	$ 2.972.782.121	2	187
25	433	$ 3.282.887.375	74	145	50	573	$ 2.945.646.160	0	189

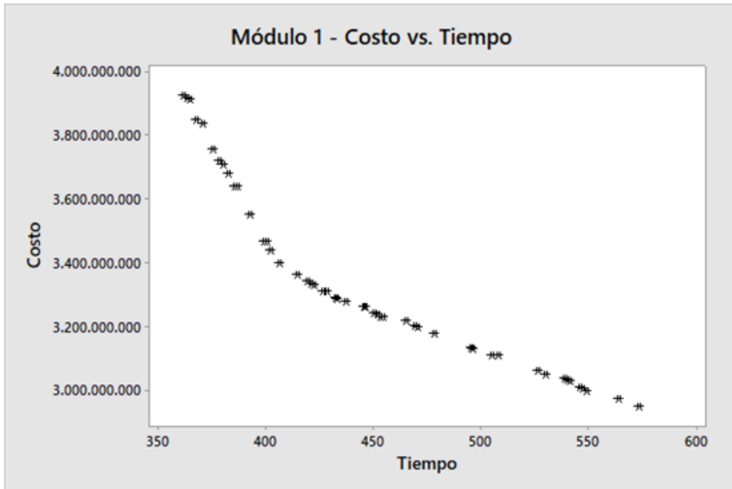
For each solution, the model accelerates activities with an impact on the duration and delays those without it. As a consequence, every solution includes over-costs or cost savings. In all cases within the range stipulated for times and costs. For instance, solution 1 accelerated some activities (A1, A2, A4, A9, A10, and A16). In the same way, it delayed others (A5, A6, A7, A12, A13, and A14). And other, following the initial considerations, were kept the same (A3, A8, A11, A15, and A17). Table 6 shows the final data for solution 1 with the final time and cost (accelerated or delayed). In all cases, the decision considers initial duration ranges. It may be seen that activity A12, having a possible range of durations between 25 and 46 days, is delayed up to 45 days. This results in a cost of $ 125,212,896.

Tabla 6. Tiempo-costo solución factible módulo 1.

Actividad	Tiempo	Costo	Actividad	Tiempo	Costo
A1	6	$ 14.717.542	A10	60	$ 11.652.463
A2	53	$ 1.137.649.408	A11	295	$ 125.212.896
A3	90	$ 916.328.256	A12	45	$ 3.926.548
A4	32	$ 241.574.912	A13	35	$ 10.330.908
A5	78	$ 138.839.552	A14	129	$ 6.283.777
A6	26	$ 53.881.072	A15	100	$ 139.043.952
A7	39	$ 199.952.224	A16	168	$ 760.827.072
A8	80	$ 136.668.016	A17	12	$ 4.765.497
A9	60	$ 21.466.048			

The results show the nature of the time-cost trade-off problem. Searching for better solutions decreases completion time but also increases the cost. It may also find repeated solutions. For instance, figure 15 shows 49 unique solutions because solution 16 was found twice. It is also seen that in the solutions range there is a change in the time-cost rate. From duration 573 to 414, the activities were accelerated at a lower cost. But from 414 to 361 accelerating a period has an exponential increase in cost.

Figura 15. Frente de Pareto módulo 1.



The model was run for the other three modules obtaining their Pareto front and quasi-optimal solutions. The solutions for modules 2, 3, and 4 may be seen in figures 16, 17, and 18 respectively.

Figura 16. Frente de Pareto modulo 2.

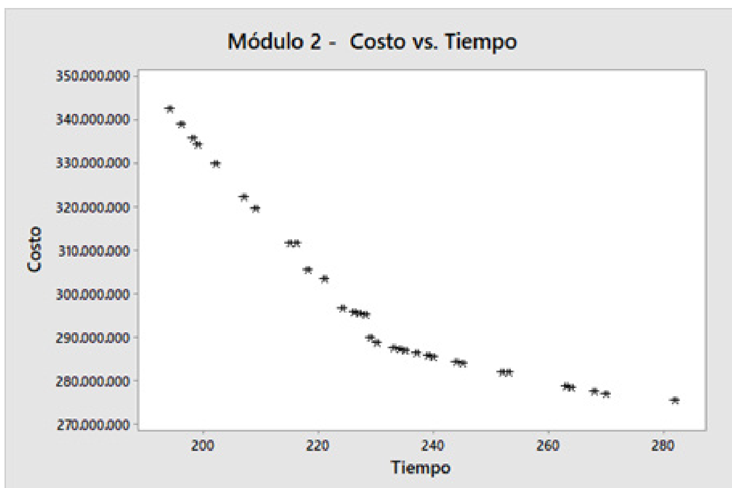


Figura 17. Frente de Pareto modulo 3.

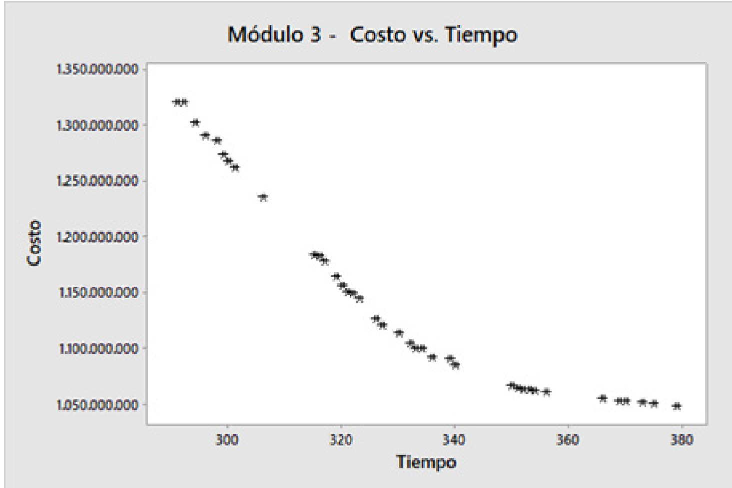
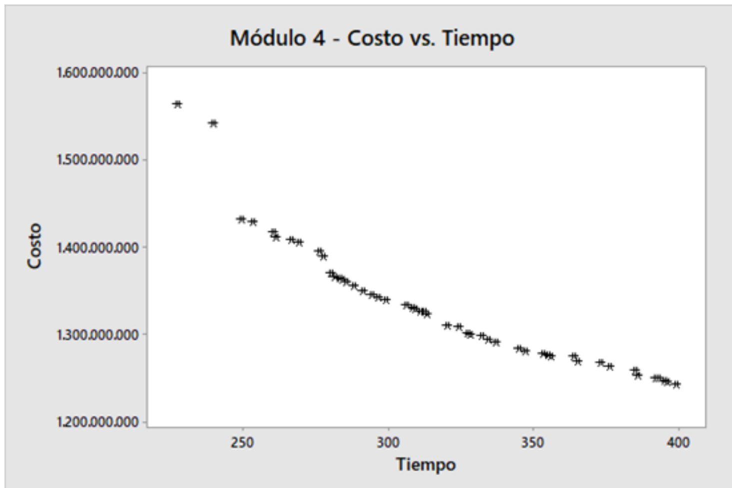


Figura 18. Frente de Pareto modulo 4



The analysis of results allows rezoned decision-making. Project managers may determine more clear commitments and strategies. As an example, the authors selected 4 solutions for the development of the project. The comparison of the original project with the proposal is shown in table 8. For the Classroom module, it was used the solution with the best accelerated time with a value of 361. This accelerated 152 periods. For the other modules, the solutions chosen were the closest to the completion time of module 1. These modules were delayed in obtaining savings. The indirect cost was reduced, due to time reduction from 513 to 361 days, going from $ 2,351,075,409 to $ 1,654,460,470. In the end, the new plan for the project lasts 361 days at a total cost of $ 8,197,611,623. This means that the project may end 152 days earlier and there will be a saving of $ 896,937,132.

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Tabla 8. Comparativo

MÓDULO	PROPUESTA SOLUCIÓN TIEMPO DE TERMINACIÓN	PROPUESTA SOLUCIÓN COSTO DIRECTO	PROGRAMACIÓN INICIAL TIEMPO DE TERMINACIÓN	PROGRAMACIÓN INICIAL COSTO DIRECTO
AULAS	361	$ 3.923.120.143	513	$ 3.623.752.600
CAFETERIA-RESTAURANTE	282	$ 275.446.399	281	$ 338.643.801
GRADERIAS-VESTIER-PISCINA	356	$ 1.060.172.050	336	$ 1.231.212.819
ZONAS EXTERIORES	356	$ 1.274.412.559	299	$ 1.539.864.126
Costo Indirecto		$ 1.654.460.473		$ 2.351.075.409
Total Costo directo		$ 6.533.151.150		$ 6.733.473.346
Total Costo		**$ 8.187.611.623**		**$ 9.084.548.755**
Total Tiempo terminación		**361**		**513**

VARIACIÓN

MÓDULO	Tiempo	Costo
AULAS	152	$ 299.367.542
CAFETERIA-RESTAURANTE	-1	$ 63.197.402
GRADERIAS-VESTIER-PISCINA	-20	$ 171.040.769
ZONAS EXTERIORES	-57	$ 265.451.568

4. Conclusions

The model requires that the network diagram must be correctly prepared. Otherwise the Pareto front will not be built with real solutions. The algorithm uses the dependencies to build the critical path of the project.

The solution of the DTCTP problem by the NSGA-II genetic algorithm does not find an optimal. But rather Pareto fronts with quasi-optimal solutions. However, the selection of a solution from the Pareto front depends on the Project Manager. Decisions should consider pareto front, environment knowledge and risk analysis.

The project was designed in parallel work fronts. This allowed the application of the model as if they were four independent projects. But accelerated scenarios in this context should include an important consideration. It is necessary to speed up the module with the least compression flexibility. A work front cannot be accelerated below the duration of other work front. Any resource added below this limit is an unnecessary cost.

The model considers data that draw the problem nearer to real-world situations. Including direct and indirect costs and the possibility to delay activities provides potential real solutions.

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