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Dynamic Cost Optimization Method of Concrete Mix Design

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Abstract

As in the most practical problems, decisions have to be made sequentially at different points in time, place, and levels, dynamic programming as a mathematical technique is well suited for the optimization of these problems. Concrete mix design includes various parameters choosing each will have many direct effects on the others. Therefore, performing dynamic optimization in design process is essential to achieve the desired conditions. Cost optimization, is one of the most important aspects in the optimization problems especially in engineering ones. Cost optimization via dynamic programming is performed in the present study due to the effects of various parameters such as cement strength grade, water-cement ratio, maximum size of aggregate, amount of cement, concrete workability and other factors as decision variables. In this regard, a nonlinear dynamic model is used to study the behavior of variables; the model is validated using data presented in literature of this study. Since, the dynamic optimization method works as a decomposition technique, it requires the separability and monotonicity of the objective function. So, the objective function has been represented as the composition of the individual stage returns. The procedure then found the optimal profile modification that reduces the cost over a wide range of operating conditions. Dynamic optimization shows a good performance for the computational efficiency as well as the reliability of results. Finally, an application to air-entrained concrete curb is presented and an extremely good performance is obtained by optimization procedures and concrete properties.

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Keywords: Cost optimization, concrete curb, dynamic optimization, mix design ;

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1. Introduction

Optimization is the process of attaining the optimum result under the existing conditions. Engineers have to make some managerial and technological decisions in several stages during the construction, repairing and maintenance of a structure or engineering systems. Minimizing the required efforts or maximizing the intended interests are the

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ultimate purpose of those decisions. Generally, there is more than one acceptable solution or design, so optimization purposes achieved in comparing different designs and selecting one of them as the optimum one [1] . The dynamic optimization problem is solved for any possible transition to determine the operational conditions, which provide the recipe data for the scheduling problem. These recipe data are treated as fixed parameters when the production schedule is optimized. However, it has been recently demonstrated that a collaborative optimization approach which solves the integrated scheduling and dynamic optimization problem simultaneously can significantly improve the overall performance of the entire process system because the operational conditions can be optimized along with the production sequence and assignments [2-4].

The mix design of concrete depends on different parameters that all play critical role in the level of performance [5, 6] and also the cost of concrete. In this regard, dynamic optimization can be a suitable solution. An appropriate method for timely solution of large-scale practical problems is the dynamic optimization [7, 8]. One of the characteristics of this method is that the procedures and negative and positive items are mutually dependent [9]. Moreover, this method has been used in various cases, such as optimization of energy consumption; optimal selection of routes and material transportation, products, and also it is consumables in industries [10, 11]. The objective functions for optimization should be based on decision variables, limitations of decision, and resources (concrete constituent materials) [12, 13].

This study tries to show the application of dynamic optimization on concrete mix design with high durability and minimum cost for the first time. To this, all variables such as air entraining, maximum size of aggregate, slump, cement type, water to cement ratio, and also the costs of them are formulated to obtained a better mix design with minimum cost and in very hard environmental conditions, which needs air entraining into the concrete around 4 and 7 percent.

2. Dynamic Optimization and Proposed Model

Dynamic optimization can be efficient in multi-functional issues which need step-by-step decision making, when each step effects on the next one. A decision making process can be described with specific input parameters, S (or data), specific decision variables (X), and specific output parameters (T) showing the output obtained as a result of making a decision. The input parameters are called input state variables, and the output parameters are called output state variables. Then, a return function or an objective function R measures the effect of the decisions and the output that is the result of these decisions. Fig. 1 shows an example of a single-stage process.

The output (efficiency) is associated with the input through the single-stage conversion function shown in

$T=t(X, S) \qquad (1)$

As the input state of the system affects the decisions, the return function can be presented as follows:

$R = r(X, S) \qquad (2)$

A sequence of a multistage process can be presented briefly as shown in Fig. 2.

Therefore, the parameters of the decision such as strength of cement, water-cement ratio, the contents of cement, maximum aggregate's size, workability, and etc. are high and the results will have an impact on the other parameters, to achieve minimum costs of optimization. The dynamic method can also be very effective. The aim of this study is to provide an optimal mix design to precast the concrete under the extreme environmental conditions, with minimum cost. The flowchart of dynamic optimization method for concrete mix design is shown in Fig. 3. The cost of aggregates,

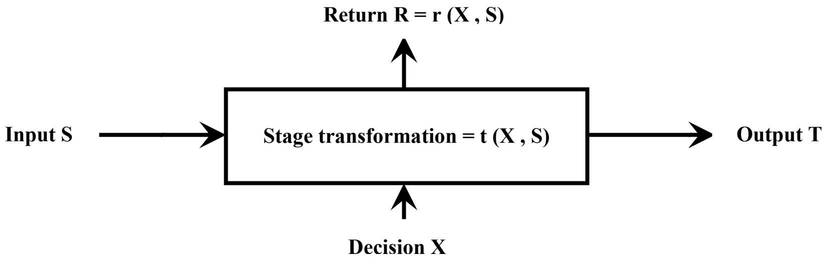

Fig. 1: Processing of dynamic optimization for one step.

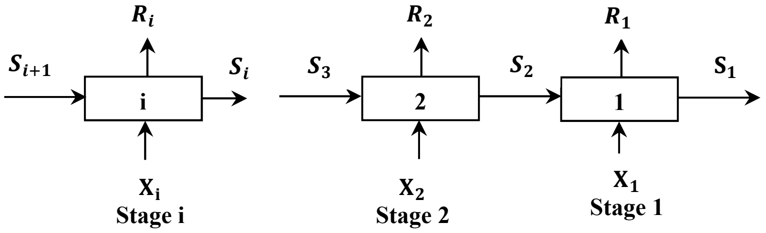

Fig. 2: Processing of dynamic optimization for multiple Steps.

Cement, water, and S are the weight of a cubic meter of concrete materials. The following parameters should be defined for any other optimization method.

2.1. Objective function

The objective function of optimization should be optimal. In this problem, the objective function is very costly and should be minimized as any stage can define local objective function so any part may be minimized to obtain global optimal. It should be noted that, the effect of cement cost is higher in compare with other parameters. Therefore, the cement content is high sensitive to cost's optimization. In addition, all parameters are so effective in the cement. Also, the influence of each parameter on the cement content may require, which can be a basis for comparison and estimate costs. Thus, optimizing the mix design should lead to the mix design that concrete compressive strength of 24 MPa, air entraining is 7% and also includes slump 60-180mm. It is noted that BS standard used for mix design.

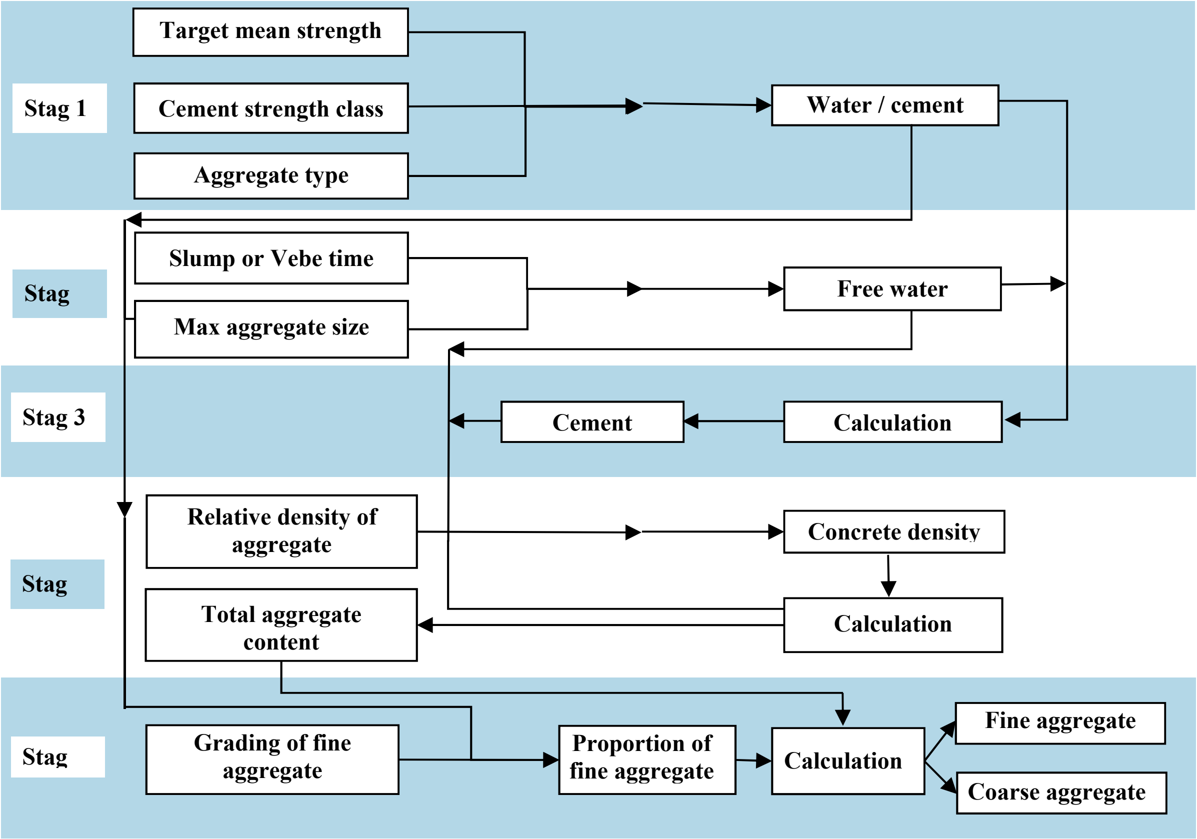

Fig. 3: The optimization process of mix design

2.2. Decision Parameters

Concrete is a cement-based composite material that is made by cement, water, fine and coarse aggregate and other additive material. Properties of concrete are related to many parameters and situations like components, curing and testing. Effecting of some parameters like the amount of water and cement is primary, in the other hand some parameters include the properties of concrete and its component such as slum and size of aggregates are secondary. The effective parameter's decision of concrete which has selected to study is divided into two parameters, the main parameters and sub parameters. The main parameters are water content, the amount of cement and amount of coarse aggregate and fine aggregate. Slump, maximum sizes of aggregate, cement type, percentage passing of fine aggregate a 600 µm sieve, crushed or uncrushed coarse aggregate and water-cement ratio are sub parameters.

Type of aggregate can be completely crushed (fine and coarse both crushed), half-crushed (only coarse crushed) and uncrushed (fine and coarse both uncrushed). There are different types of slump range 0-10, 10-30, 30-60, and 60-180 that for this problem slump, 60-180 are considered. Here, three types of cement strength classes of 325, 425 and 525 are considered that each one has different strength. In the following decision making about each parameter is discussed.

2.2.1. Selection of target water/cement ratio (Stage 1)

As it is mentioned before, the water-cement ratio, is considered as sub parameter according to the figures of water to cement against compressive strength, can be obtained. In Fig. 4 can be obtained the water-cement ratio from the equations for the cement strength classes (325, 425, and 525) with different type of aggregate. The water-cement ratio and compressive strength are considered "y" and "x" respectively.

Table 1: various water-cement ratios

Cement type	Type of aggregate	Water-cement ratio	Cost of aggregate size(1000Kg)($)	Cost of cement($)
325	uncrushed	0.28	4	0.048
325	crushed	0.30	5	0.048
425	uncrushed	0.38	4	0.049
425	crushed	0.40	5	0.049
525	uncrushed	0.48	4	0.050
525	crushed	0.50	5	0.050

In Table 1, according to the desired strength, water-cement ratio based on the obtained equations for different cement, and aggregate type is specified. Also, the cost of cement has been determined. As it can be seen, the cost difference of cements together is insignificant. At this stage, assuming constant water content, by increasing the water-

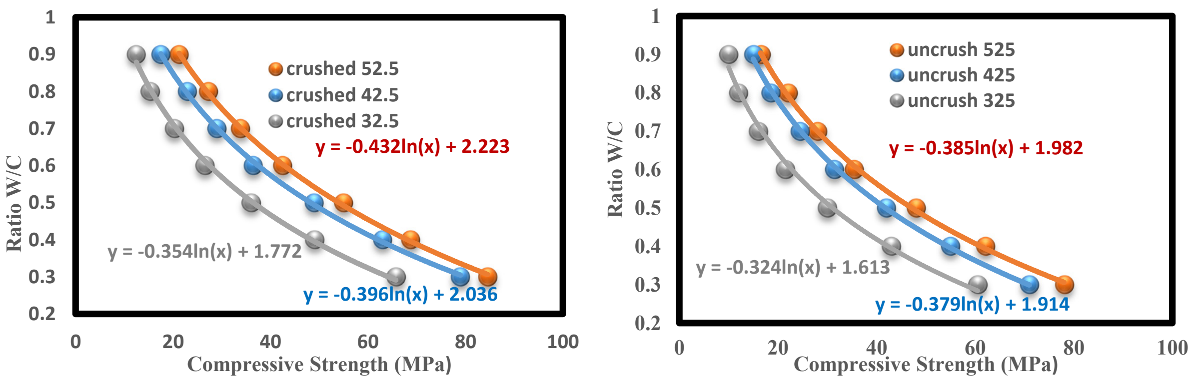

Fig 4: Determine the water-cement ratio according to compressive strength for crushed and uncrushed aggregate.

cement ratio of cement consumed is reduced. So, the optimum choice is more water-cement ratios of cement strength class 525.

For crushed aggregate:

$$y_{325} = -0.354\ln(x) + 1.772$$

$$y_{425} = -0.396\ln(x) + 2.036$$

$$y_{525} = -0.432\ln(x) + 2.223$$

For uncrushed aggregate:

$$y_{325} = -0.324\text{Ln}(x) + 1.613$$

$$y_{425} = -0.379\text{Ln}(x) + 1.914$$

$$y_{525} = -0.385\text{Ln}(x) + 1.982$$

2.2.2. Selection of free-water content (Stage 2)

In this problem, slump 60-180 mm has been selected. According to BS standard, in table 2 the approximate content of water consistent with the maximum size of aggregate and aggregate type can be determined and also using equations obtained in fig 5 the content water can be determined too.

Given that the content of water in a constant water-cement ratio whatever the content water was increased, the amount of cement increases respectively. So that the amount of less water is chosen as the optimal value. Here, the amount of less water is related to the maximum size aggregate and uncrushed aggregate. At this stage, the maximum sizes of aggregates and type of aggregate that had the sub-parameters are optimized.

If the input to this stage s1 is specified, then according to the principle of optimality, water content (x_w), type of aggregate (x_1) and maximum size of aggregate (x_2) must be selected to optimize R_w.

$$f_1^*(s_1) = \text{opt}[R_w(x_1, x_2, x_w, s_1)] \qquad [1]$$

Table 2: Approximate free-water contents (kg/m3)

slump	Type of aggregate	Size of aggregate (mm)	Cost of aggregate size(1000Kg)(R_3)	water content (s_1)
60-180 mm	uncrushed	10	4$	225
	crushed	10	5$	250
	uncrushed	20	4$	195
	crushed	20	5$	225
	uncrushed	40	4$	175
	crushed	40	5$	205

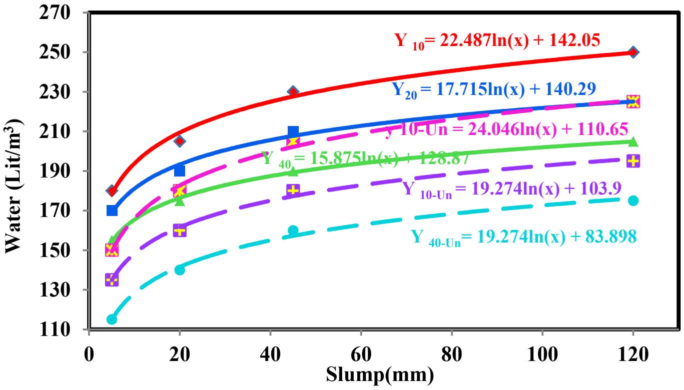

Fig 5: Determine the content of water required to achieve desired slump for crush and uncrushed aggregate in different maximum size aggregate.

2.2.3. Determination of cement content (Stage 3)

Consider the second sub problem by grouping the first two stages together. If $f_2{}^*$denotes the optimum objective value of the first sub problem for a specified value of the input s_2. X_C represents amount of cement.

Table 3: Approximate free-water contents (kg/m3)

Type of aggregate	Size of aggregate(mm)	Cost of aggregate size(1000Kg)($)	Water-cement ratio	water weight (x1)	Amount of cement(Kg) (xc)	Cost of cement + water cost $f_2{}^*(s_2)$
uncrushed	10	4	0.28	225	803	38.5
crushed	10	5	0.33	250	757	36.3
uncrushed	20	4	0.38	195	513	25.1
crushed	20	5	0.43	225	523	25.6
uncrushed	40	4	0.48	175	364	18.2
crushed	40	5	0.53	205	386	19.3

If s_1 is the content of water needed is obtained from the previous stage and $f_2{}^*(s_2)$ the minimum cost of cement is used so have:

$$f_2{}^*(s_3) = \mathrm{opt}[R_c(x_c, s_2) + f_1{}^*(s_1)] \qquad [1]$$

Results in Table 3 are achieved according to information obtained in previous stage. Since the cost of water is low, in calculating the total cost in this part of the cost of water cannot be calculated.

Determination of total aggregate content (Stage 4)

Since, for two input variables are presented in Table 4 can be obtained the value of $f_3{}^*$ for each of these two quantities. Consider the third sub problem by grouping the first three stages together. If $f_3{}^*$ denotes the optimum objective value of the third sub problem for a specified value of the input s_3.

$$f_3{}^*(s_3) = \mathrm{opt}[R_{agg}(x_{agg}, s_3) + f_2{}^*(s_2)] \qquad [1]$$

Table 4: Approximate free-water contents (kg/m3)

Type of aggregate	Size of aggregate (mm)	Cost of aggregate size (1000Kg) ($)	Density of wet concrete (D)	water weight (xw)	Amount of cement(Kg) (C)	Amount of aggregate (D-W-C)	Cost of cement + aggregate cost
uncrushed	40	4	2380	175	364	1841	18.2+7.36=25.56
crushed	40	5	2400	205	386	1809	19.3+9.04=28.34

2.2.4. Selection of fine and coarse aggregate contents (Stage 5)

From the tabulated results of previous stage of $f_3{}^*(s_3)$ the optimum values of $f_4{}^*(s_4)$ corresponding to s_4 can readily be obtained.

Regarding to percentage passing fine aggregate a 600 µm sieve, water-cement ratio, maximum size of aggregate, and slump can be calculated percentage of course and fine aggregate that these calculations are shown in Table 5. Since, the uncrushed optimal use of the uncrushed is that its price is less than the fine aggregate, so apparently the use of coarse aggregate is more economical according to table 5, using the aggregate of the maximum amount it has passed through a 600 µm sieve is cheaper than aggregates, the lowest it has passed through a 600 µm sieve. So, to get the optimum have:

$$f_4{}^*(s_4) = \mathrm{opt}[R_{agg}(x_{fine-agg}, x_{coarse-agg}, s_3) + f_3{}^*(s_3)] \qquad [1]$$

Table 5: Approximate free-water contents (kg/m3)

Type of aggregate	Size of aggregate(mm)	Cost of aggregate size (1000Kg)($)	Amount of aggregate (D-W-C)	percentage passing a 600 μm sieve	Cost of fine aggregate (1000Kg)($)	Proportion of fine aggregate (%)	Proportion of coarse aggregate (%)	cost of fine aggregate + cost of coarse aggregate ($)	Cost of cement + cost of fine aggregate + cost of coarse aggregate ($)
uncrushed	40	4	1841	100	5	22	78	4*1.841*.78+.22*1.841*5=7.76902	18.2+7.76902=25.96
uncrushed	40	4	1841	80	4.8	26	74	7.746928	25.94
uncrushed	40	4	1841	60	4.6	31	69	7.706426	25.906
uncrushed	40	4	1841	40	4.3	38	62	7.573874	25.77
uncrushed	40	4	1841	15	4	48	52	7.364	25.564
crushed	40	5	1809	100	5	24	76	9.045	28.345
crushed	40	5	1809	80	4.8	28	72	8.943696	27.1436
crushed	40	5	1809	60	4.6	34	66	8.798976	26.998
crushed	40	5	1809	40	4.3	41	59	8.525817	26.7258
crushed	40	5	1809	15	4	53	47	8.08623	26.28623

As it can be seen in this stage, for the optimal use of the fine aggregate by 15 percentage passing fine aggregate a 600 μm sieve. So, the optimal mix of price as follows: uncrushed aggregate with maximum size of aggregate 40 mm cement strength class 525 and water-cement ratio 0.48. The weight of cement, water and aggregate, respectively 364 Kg/m^3, 175 Kg/m^3 and 1841 Kg/m^3 and mix design cost equal to 25.564$ per cubic meter.

3. Experimental Result and Discussion

An optimization method was used to find out the mix design of concrete and optimize its cost. The results of dynamic optimization proposed a different mix design and different amounts of cement mixed with water for compressive strength of 20, 27 and 31 MPa and slump of 60-180.

Table 6 shows the mix proportions by weight of the mixtures. Cement strength classes 425 and 525 are from Bojnoord Cement Factory and cement strength class 325 is from Sabzevar Cement Factory. Also, fine aggregate used is uncrushed with special weight 2.6 ton/m^3 (SSD) and coarse aggregate used is crushed with specific weight 2.7 ton/m^3.

Table 6: Details of concrete mix designs.

Mix	Strength Class	W/C	Cement (Kg/m^3)	FA (Kg/m^3)	CA (Kg/m^3)	Water (Kg/m^3)
Z_{1-325}	325	0.48	345	873	714	166
Z_{2-325}	325	0.4	453	875	716	181
Z_{3-325}	325	0.32	578	790	646	185
Z_{1-425}	425	0.59	307	994	813	181
Z_{2-425}	425	0.5	355	906	741	178
Z_{3-425}	425	0.41	449	857	701	184
Z_{1-525}	525	0.65	265	958	784	172
Z_{2-525}	525	0.55	314	899	736	173
Z_{3-525}	525	0.45	414	888	727	186

Table 7: Results of tests conducted on samples taken

Mix	F_c plan (MPa)	F_c actual (MPa)	A (%)	Cost of Cement ($)	Cost of FA($)	Cost of CA($)	Cost of Mix($)
$Z_{1\text{-}325}$	27	19.7	10.0	16.6	3.5	3.6	23.6
$Z_{2\text{-}325}$	20	24.5	7.5	21.7	3.5	3.6	28.8
$Z_{3\text{-}325}$	31	35.0	9.0	27.7	3.2	3.2	34.1
$Z_{1\text{-}425}$	27	28.5	1.9	15.0	4.0	4.1	23.1
$Z_{2\text{-}425}$	20	20.0	10.0	17.4	3.6	3.7	24.7
$Z_{3\text{-}425}$	31	31.0	9.5	22.0	3.4	3.5	28.9
$Z_{1\text{-}525}$	27	28.0	2.6	13.3	3.8	3.9	21.0
$Z_{2\text{-}525}$	20	22.0	8.5	15.7	3.6	3.7	23.0
$Z_{3\text{-}525}$	31	30.0	9.5	20.7	3.6	3.6	27.9

Table 7 shows compressive strength from experimental test and strength of standard. In the other hand cost of each mix proposed. Table 7 show that different amount of actual strength and plan strength is a bit, consequently dynamic programming is a good and fast tool to design concrete mix instead of time consuming and complex method. Additionally, table 7 show the cost of each mix design that optimized by cost optimization via dynamic program. The results show that by increasing in cement strength class amount of cost decreases. Finally, it can be concluded that the use of cement concrete with high strength is be more economical than cement with less strength.

4. Conclusion

The present study considers the dynamic optimization used for cost optimization of concrete mix design by focusing on the effects of cement strength class, type of coarse aggregate, maximum size of aggregate and type of fine aggregate. The following results are obtained:

- The optimization results show the dynamic optimization method is highly efficient in problem solving so that the discrete decision parameters are provided so complex problem that needs many decision variables could be easily concluded. While other methods are not optimizing performance in these cases. The use of dynamic optimization methods can be very effective in reducing costs and decision-making.
- It should be noted that the effect of cement cost is higher to compare other parameters of mix design. Therefore, the cement content is high sensitive to cost's optimization.
- Generally, the result of experimental and dynamic optimization show that cement strength class is effective on mix design optimization.

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