

# Consideration of Soft Dependencies under Stochastic Uncertainty in Multi-Project Program Implementation

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**Abstract**—This paper addresses the problems of managing a multi-project program under soft dependencies between some program projects. As a rule, the use of soft dependencies saves the time and/or cost of executing the next project, which decreases the time and/or cost of implementing the entire program. An example shows how rarely dealing with soft dependencies can be reduced to simple schemes without losing the problem essence. Consideration of stochastic uncertainty in project implementation is introduced. According to the conclusion, the effect from considering soft dependencies depends on the probability of realizing them.

*Keywords:* program, project, hard dependencies, soft dependencies, stochastic uncertainty in the realization of soft dependencies

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## 1. INTRODUCTION

In a program consisting of interdependent projects (multi-project program), the results of one project can often be used in the execution of others, thereby decreasing the implementation time (duration) and/or cost of the entire program. Such dependencies between projects, without mandatory fulfillment but with a positive effect on program parameters, are called soft dependencies.

Problems with soft dependencies were investigated in [1–4]. Note that rather simple setups were studied in [1, 2], e.g., the effect from considering several soft dependencies was supposed to be additive, and no probabilistic characteristics [6–9] of the effect of soft dependencies, which is certainly present, were taken into account. This practice is not always applicable; see an illustrative example in the next section.

## 2. AN EXAMPLE OF ESTIMATING SOFT DEPENDENCIES IN A PROGRAM

Let a program consist of 5 projects. Their numerical parameters are combined in the table below.

This table has the following notation:  $t_{\min}$  and  $t_{\max}$  are the minimum and maximum project execution times (terms), respectively (in days);  $p$  is the probability of project completion within the corresponding term;  $t_c$  is the time saving of the next project (in days); finally,  $r_c$  is the resource saving of the next project (in million rubles).

The residential complex construction project has a hard deadline of 500 days. In the example, this is the only project that may be executed in the maximum term with a probability below 1. This situation occurs when the project deadline is set “from the outside” (e.g., by the customer),

**Table 1.** Numerical parameters of program projects

Project	Minimum term, $t_{\min}/p$	Maximum term, $t_{\max}/p$	Impact on projects	Saving $t_c/r_c$
1. Start-up of C1 concrete production line	12/0.5	20/1	2, 5	7/20, 5/100
2. Start-up of C15 concrete production line	15/0.6	22/1	5	8/150
3. Start-up of R0 rebar production line	7/0.8	11/1	4, 5	4/15, 6/120
4. Start-up of R15 rebar production line (can be used only with C15 concrete; when used together, $t_c = 2$ and $r_c = 5$ )	9/0.7	12/1	5	7/180
5. Construction of a residential complex	400/0.75	500/0.95	—	—

and everything possible will be done in the calendar plan to complete the work by the specified date.

Now we explain this table. Residential complex construction can be initiated independently of the start-up of production lines. By assumption, the pit has already been dug. Then both concrete and rebar, needed immediately, will have to be purchased from suppliers, requiring additional time (to wait for delivery) and additional money. Currently, all these items are included in the construction project. Obviously, the cost of components purchased “on the side” is higher than in-house production. Therefore, given the plans to organize production lines for concrete and rebar, it makes sense to consider the self-supply of the construction project with these materials. This approach is financially reasonable for the contractor, and it remains to assess its time feasibility: first, the production lines have to be launched.

It is possible to start up a production line for concrete of universal grade C1 or improved (modified) grade C15. For example, the use of C15 eliminates the need for some additives, reduces the curing time of the structure, etc. The production of C15 can be established independently or based on the available line for C1. In the second option, the start-up time of the production line is reduced by 7 days, but it is possible to initiate this work only after launching the C1 line. This line is started in 20 days with probability 1 (surely). That is, with saving both time and resources, the production of C15 is definitely launched in 35 days. Under favorable conditions (everything can be accomplished in the shortest term), this time is reduced to 20 days with a probability of

$$p_{12\min} = p_{1\min} \times p_{2\min} = 0.5 \times 0.6 = 0.3,$$

where  $p_{1\min}$ ,  $p_{2\min}$ , and  $p_{12\min}$  are the probabilities of completing the first, second, or first and second projects, respectively, under soft dependencies within the minimum term.

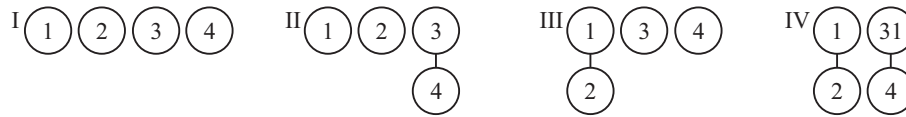
Rebar can be considered similarly. The rebar of grade R15 is stronger, lighter, and more reliable, but can be used only with C15 concrete. Their simultaneous use adds 5 to the resource saving and 2 to the time saving. R0 rebar (universal) can be used with any grade of concrete. Based on the R0 line, the production of R15 can be launched in 12 days with the probability of

$$p_{34\min} = p_{3\min} \times p_{4\min} = 0.8 \times 0.7 = 0.56$$

and in 19 days with probability 1 (surely).

Obviously, in the described situation, all dependencies are soft and their effects cannot be simply summed. First, there are different scenarios for their use:

1. Start all projects independently; then, the time to launch production lines is likely to be reduced since, in a sequential start-up, it is possible to start working with complex lines at best only after 12 and 7 days (in both cases, these figures exceed the time saving due to soft dependencies). Construction can be started at least a week earlier as well. Note that the time saving due to soft dependencies is not considered here.



**Fig. 1.** Interaction options of projects 1–4.

2. Use in-house concrete (plain or improved), waiting 12 to 35 days and saving 100 to 150 million and 5 days. Due to the hard construction deadline, the 5 days also count appreciably.

3. Use in-house rebar, either universal or improved, waiting 7 to 19 days and saving 120 to 180 million and 6 days. Due to the hard construction deadline, the 6 days also count appreciably.

4. Use both in-house concrete and in-house rebar with their compatibility in mind (R15 can be used only with C15). R0 rebar is universal and can be used with any grade of concrete, but does not offer several advantages. In this scenario, the waiting time is taken into account only for concrete: the production of rebar is established earlier. But on the other hand, 11 days can be saved on the term reduction.

In reality, the above 4 scenarios generate a much larger number of particular options. We will deal with them by full enumeration, considering all logical and simultaneously reasonable options to combine the projects. There are not so many of them. Note that the first four projects interact with each other. The fifth one can be combined with any of their combinations. Figure 1 shows the interaction options of projects 1–4.

Figures 2–5 present the interaction options of all five projects for combinations I–IV, respectively. We briefly discuss their features.

I) The soft dependencies between the first four projects are neglected, all projects are executed in parallel and as fast as possible, albeit without resource and time savings. In this combination, there are five logical and reasonable options for including project 5:

1. Project 5 is also included without soft dependencies, in parallel with the others. This case corresponds to the situation without resource deficiency but with a desire or need to complete all projects as fast as possible. For I.1, we have  $t_c = 0$  and  $r_c = 0$ .

2. Project 5 is included after project 3 and uses in-house rebar. When executing after project 3, the corresponding soft dependency (3–5) is used, and  $t_c = 6$  and  $r_c = 120$ . The duration of project 3 does not exceed 11 days (and merely 7 days with a probability of 0.8). Subtracting the time saving, we obtain a shift of 1–5 days and resource saving.

3. Project 5 is included after project 4 and uses improved in-house rebar. The soft dependency (4–5) is considered, and  $t_c = 7$  and  $r_c = 180$ . As a result, project 5 is shifted by 2–5 days, and the resource saving increases markedly to 180. An additional constraint is that R15 rebar can only be used with C15 concrete, so the contractor has to purchase concrete of that grade. Or, when the C15 concrete line is running, the contractor can start using in-house concrete.

4. Project 5 is included after projects 1 and 3, and both soft dependencies (1–5) and (3–5) are considered. Note that the option of executing project 5 after projects 1 and 4 is eliminated as illogical: the use of R15 requires concrete of a higher grade, and it makes no sense to wait for the production of unnecessary concrete. As a result,  $t_c = 5 + 6 = 11$  and  $r_c = 100 + 120 = 220$ . We estimate the shift of project 5 by the largest time of projects 1 and 3, i.e., 12–20 days, or 1–9 days, taking the savings into account.

5. Project 5 is included after projects 2 and 4, and both soft dependencies (2–5) and (4–5) are considered. The option of executing project 5 after projects 2 and 3 makes no sense: during the start-up of the C15 line, the production of R15 has enough time to start, and these materials together give a much higher gain than when using C15 jointly with R0. As a result,  $t_c = 8 + 7 + 2 = 17$  and

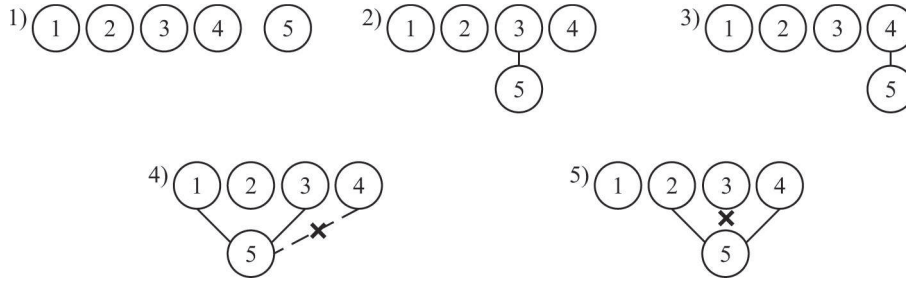


Fig. 2. Inclusion options for Project 5 in combination I.

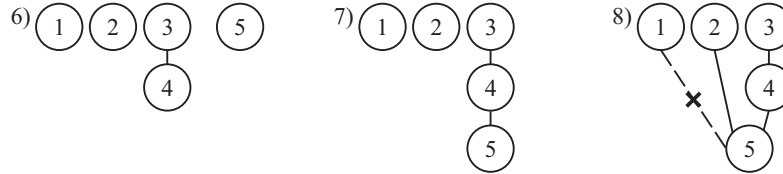


Fig. 3. Inclusion options for Project 5 in combination II.

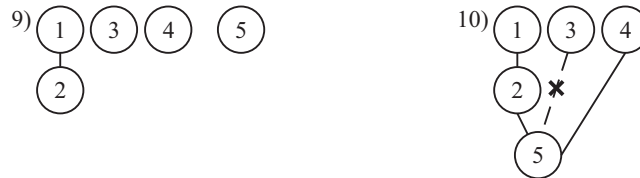


Fig. 4. Inclusion options for Project 5 in combination III.

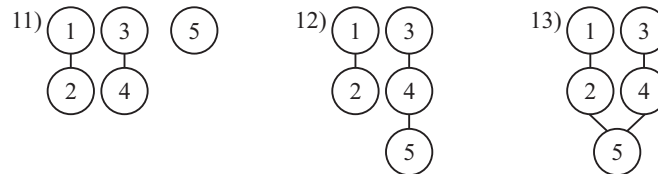


Fig. 5. Inclusion options for Project 5 in combination IV.

$r_c = 150 + 180 + 5 = 335$ . The third term of this sum is the synergistic effect, representing the gain from the joint use of R15 and C15. We estimate the shift of project 5 by the largest time of projects 2 and 4, i.e., 15–22 days, or  $(-2)-5$ , taking the savings into account. The value  $(-2)$  shows that, at best, the execution time of project 5 can be reduced even more compared to the case of neglecting the soft dependencies. In addition, the resource saving is appreciable as well.

II) Among the first four projects, only the dependency (3–4) is considered, giving the savings  $t_c = 4$  and  $r_c = 15$ , and the production of R15 rebar is eventually set up in 12–19 days. In this combination, there are three logical and reasonable options for including project 5:

6. Project 5 is included in parallel without soft dependencies. The features of this situation have been discussed above. The time and resource savings due to the soft dependency between projects 3 and 4 are  $t_c = 4$  and  $r_c = 15$ .

7. Project 5 is included after project 4 (and project 3 as its component) and starts using in-house R15 rebar. With executing this project after project 4, we use the corresponding soft dependency

(4–5), and  $t_c = 7$  and  $r_c = 180$ . As a result, the R15 line is launched in 12–19 days (and will be further used in project 5), the term of project 5 is shifted by 5–12 days, and C15 grade is needed to purchase only for project 5. Note that the longest term for launching the rebar production line does not exceed the shortest term for launching the concrete production line. Therefore, it may be logical for project 5 to use in-house rebar but not in-house concrete; on the other hand, by the time of using in-house concrete, the rebar production line will already be running, and it makes no sense to use in-house concrete without in-house rebar.

8. Project 5 is included after project 4 (and project 3 as its component) and project 2, and uses R15 rebar and in-house C15 concrete. The soft dependencies (2–5), (4–5), and, of course, (3–4) are used. The saving from the joint use of R15 and C15 is also taken into account. Accordingly,  $t_c = 8 + 7 + 4 + 2 = 21$  and  $r_c = 150 + 180 + 15 + 5 = 350$ . The term of project 5 is shifted by (–6)–1 days, i.e., it is very likely to be completed earlier than required. By the above reasoning, it makes no sense to consider project 1 instead of project 2 in such a combination.

III) Among the first four projects, only the dependency (1–2) is taken into account, giving the savings  $t_c = 7$  and  $r_c = 20$ , and the production of C15 concrete is eventually set up in 20–35 days. This combination describes the least probable situation: when considering the dependency (1–2), it makes sense to take the dependency (3–4) into immediate account (see combination IV below) due to no extra costs and a significant gain. Nevertheless, such a situation is theoretically possible under a set of circumstances (e.g., there is enough rebar of the required grade in stock). In this combination, there are two logical and reasonable options for including project 5:

9. Project 5 is included in parallel without soft dependencies. The features of this situation have been discussed above. The time and resource savings due to the soft dependencies between projects 1 and 2 only are  $t_c = 7$  and  $r_c = 20$ .

10. Project 5 is included after project 2 (and project 1 as its component) and project 4, and uses R15 rebar and in-house C15 concrete. The soft dependencies (2–5), (4–5), and, of course, (1–2) are used. The savings from the joint use of R15 and C15 are also taken into account. Accordingly,  $t_c = 8 + 7 + 7 + 2 = 24$  and  $r_c = 150 + 180 + 20 + 5 = 355$ . The term of project 5 is shifted by (–4)–11 days. By the above reasoning, it makes no sense to consider project 1 instead of project 2 in such a combination.

IV) Among the first four projects, both dependencies (1–2) and (3–4) are taken into account, giving the savings  $t_c = 7 + 4 = 11$  and  $r_c = 20 + 15 = 35$ , the productions of C15 concrete and R15 rebar are set up in 20–35 days and 12–19 days, respectively. In this combination, there are three logical and reasonable options for including project 5:

11. Project 5 is included in parallel without considering soft dependencies. The features of this situation have been discussed above. The time and resource savings due to the soft dependencies between projects 1–4 only are  $t_c = 7 + 4 = 11$  and  $r_c = 20 + 15 = 35$ .

12. Project 5 is included after project 4 (and project 3 as its component) and starts using in-house R15 rebar. With executing this project after project 4, we use the corresponding soft dependency (4–5), and  $t_c = 7$  and  $r_c = 180$ . As a result, the R15 line is launched in 12–19 days (and will be further used in project 5), the term of project 5 is shifted by 5–12 days, and C15 grade is needed to purchase only for project 5.

13. Project 5 is included after project 4 (and project 3 as its component) and project 2 (and project 1 as its component) and uses R15 rebar and in-house C15 concrete. Besides the above dependencies (1–2) and (3–4), the soft dependencies (2–5) and (4–5) are fulfilled (actually, all the soft dependencies). The savings from the joint use of R15 and C15 are also considered. Accordingly,  $t_c = 7 + 8 + 7 + 4 + 2 = 28$  and  $r_c = 20 + 150 + 180 + 15 + 5 = 370$ . The term of project 5 is shifted by (–8)–7 days.

We summarize the results in the table below.

**Table 2.** The interaction of program projects: a comparison of options

Combination	Option	$t_c$	$r_c$	The number of soft dependencies	The shift of project 5's term (in days)
I	1	0	0	0	0
	2	6	120	1	7–11
	3	7	180	1	2–5
	4	11	220	2	1–9
	5	17	335	2	(–1)–5
II	6	4	15	1	0
	7	7	120	2	5–12
	8	21	350	3	(–6)–1
III	9	7	20	1	0
	10	24	355	3	(–4)–11
IV	11	11	35	2	0
	12	7	180	3	5–12
	13	28	370	3	(–8)–7

Analysis shows no obvious patterns in Table 2, which is the main conclusion. Moreover, efficiency criteria in this situation can be different, e.g., the saving of resources or the shift of the term of project 5, as the most ambitious part of the program. Despite some correlation between the above criteria (e.g., options 5, 8, 10, and 13 are quite effective in terms of both criteria), we note that in each of the combinations I–IV, the option with the maximum number of dependencies used is most effective. Generally speaking, it is not easy to make an unambiguous choice.

At the beginning of this section, we have emphasized the importance of the probabilistic component, which is neglected in the illustrative example. Also, the term of each project is not two limit points but any point on the interval between them, and each such point has a particular probability (in the simplest case, a linear probability distribution). These facts are not considered in the example as well. In reality, this probability evolves over time in a much more complicated way.

The example is very simple for a real construction program, the more so in the elementary setting: it ignores the stochastic reduction of the project execution time and/or resources according to some temporal distribution. Therefore, dealing with soft dependencies can rarely be reduced to simple schemes without losing the problem essence. This paper takes a step towards considering the probabilistic and uncertain parameters of soft dependencies.

### 3. THE SET OF REALIZABLE SOFT DEPENDENCIES

Consider the problem of reducing the implementation time (duration) of a multi-project program with soft dependencies using the basic definitions provided in [4, 5].

By assumption, there are many options for including soft dependencies into the program. Each option is characterized by the probability of its realization and the corresponding program duration.

We introduce the following notation:

$\tau_i$  is the project execution time when neglecting soft dependencies;

$m$  is the number of projects in the program;

$T = \sum_{i=1}^m \tau_i$  is the program duration when neglecting soft dependencies.

An algorithm for including soft dependencies into a program to reduce its duration was described in [4].

In this paper, we optimally select soft dependencies using the probability of soft dependence realization and the program duration reduction as the optimality criteria.

## 4. THE PROBABILITY OF SOFT DEPENDENCE REALIZATION

Suppose that the program has a set  $S$  of  $n$  soft dependencies. Let  $p_i$ ,  $i = 1, 2, \dots, n$ , be the probability of realizing the  $i$ th soft dependency, and  $t_i$ ,  $i = 1, 2, \dots, n$ , be the program duration reduction under the realization of the  $i$ th soft dependency.

According to [10], if all soft dependencies are realized, the program duration will be  $T - \tilde{T}$ , where

$$\tilde{T} = \sum_{i=1}^n t_i.$$

Since the realization of each soft dependency is treated as an independent event, the probability of realizing all soft dependencies will be

$$P = \prod_{i=1}^n p_i.$$

Following [10], the efficiency of different options to realize a soft dependency will be estimated by the mean program duration reduction. We denote by  $M_S$  the mean program duration reduction under the realization of all soft dependencies. As demonstrated in [10], this value is given by

$$M_S = \sum_{i=1}^n t_i \prod_{i=1}^n p_i.$$

Consider a situation when all soft dependencies provide the same reduction of the project execution times, but the probabilities of realizing these dependencies differ.

In this case, the mean program duration reduction under the realization of all soft dependencies can be written as

$$M_S = nt \prod_{i \in S} p_i.$$

Without loss of generality, we arrange all soft dependencies in ascending order of the probabilities of realization:

$$p_1 \geq p_2 \geq \dots \geq p_n. \quad (1)$$

If all soft dependencies provide the same reduction of the project execution times and inequality (1) holds, for  $k$  successively realized soft dependencies, the mean is given by

$$M_m = kt \prod_{i=m}^{k+m-1} p_i, \quad m = 1, 2, \dots, n - k + 1.$$

In view of condition (1), we have

$$M_1 > M_2 > \dots > M_{n-k+1}.$$

Let

$$p_i = p_1 b^{i-1}. \quad (2)$$

In this case,

$$M_1 = kt p_1 b^{k(k-1)b/2}.$$

We find the optimal number of realizable soft dependencies by minimizing the mean:

$$\frac{\partial M_1}{\partial k} = t p_1 b^{k(k-1)b/2} + k t p_1 \frac{b}{2} (2k-1) \ln b = 0. \quad (3)$$

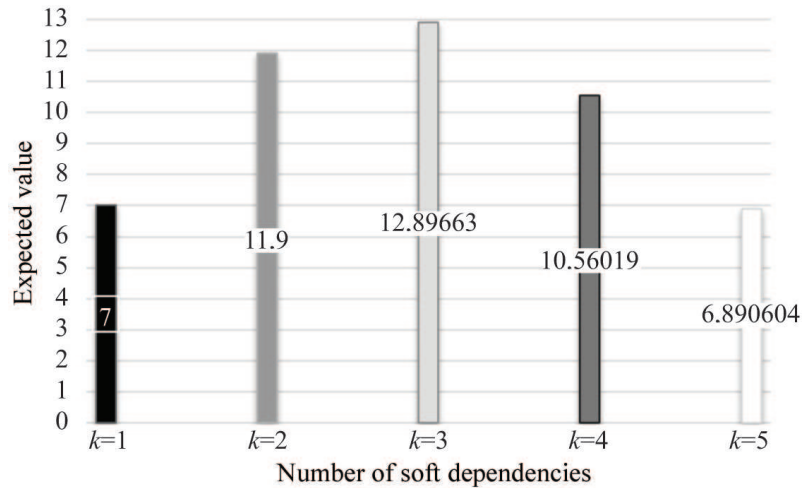


Fig. 6. Change in the expected value versus the probability of soft dependency realization.

From (3) it follows that

$$1 + k \frac{b}{2} (2k - 1) \ln b = 0.$$

The solution of this equation has the form

$$k = \frac{1 \pm \sqrt{1 - \frac{16}{b \ln b}}}{4}. \tag{4}$$

**Example 1.** There are five soft dependencies. The program duration reduction by each soft dependency is  $t = 10$ , and the probability of realizing the first soft dependency is  $p_1 = 0.7$ . The probabilities of realizing soft dependencies form the geometric progression (2); let its ratio be  $b = 0.85$ . Accordingly, the probabilities of realizing the soft dependencies are  $p_1 = 0.7$ ,  $p_2 = 0.6$ ,  $p_3 = 0.51$ ,  $p_4 = 0.43$ , and  $p_5 = 0.37$ . Figure 6 shows the graph of the mean program duration reduction as a function of the number of realized soft dependencies.

In Example 1, it suffices to realize only three soft dependencies to maximize the mean program duration reduction. By the way, this fact follows from the expression (4). For the above value of  $b$ , the calculations yield  $k = 2.95$ . Note that increasing the ratio actually increases the number of realized soft dependencies maximizing the mean program duration reduction; accordingly, decreasing the ratio decreases this number.

Consider now the following situation: when realizing the  $i$ th soft dependency, the project execution time is reduced to the value

$$t_i = t_1 a^{i-1} \tag{5}$$

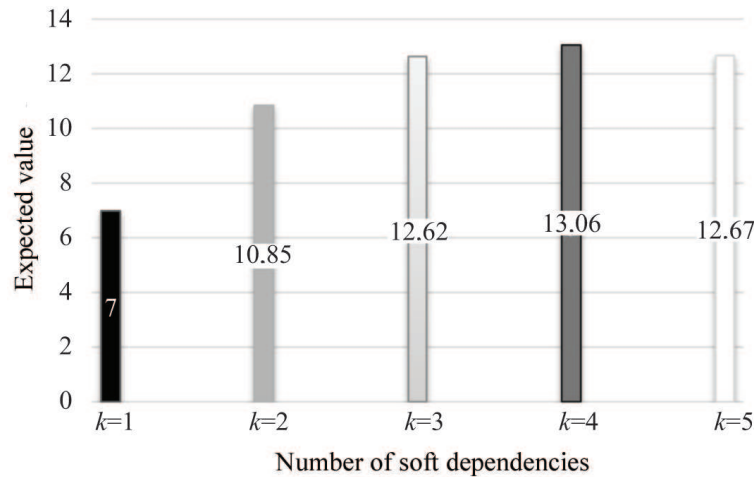
(another geometric progression), and each soft dependency is realized with the same probability.

In this case, the mean program duration reduction under the realization of all soft dependencies can be written as

$$M_S = \frac{t_1(a^n - 1)}{a - 1} p^n. \tag{6}$$

Assuming that only the first  $k$  soft dependencies are realized, the expression (6) becomes

$$M_1 = \frac{t_1(a^k - 1)}{a - 1} p^k.$$



**Fig. 7.** Change in the expected value versus the program execution time reduction.

We find the number of realizable soft dependencies maximizing the mean program duration reduction:

$$\frac{d}{dk} \left( \frac{t_1(a^k - 1)}{a - 1} p^k \right) = t_1 p^k \frac{a^k \ln a}{a - 1} + t_1 \frac{a^k - 1}{a - 1} p^k \ln p = 0. \quad (7)$$

From (7) it follows that

$$k = \frac{\ln \frac{\ln p}{\ln ap}}{\ln a}. \quad (8)$$

Since  $k < n$ , we have

$$p < a^{a^n / 1 - a^n}. \quad (9)$$

**Example 2.** As in Example 1, there are five soft dependencies. For  $a = 1.05$ , formula (9) implies  $p < 1$ , so the probability of realizing each soft dependency can be chosen to be 0.7. The program duration reduction by each soft dependency is described by (5):  $t_1 = 10$ ,  $t_2 = 10.7$ ,  $t_3 = 11.45$ ,  $t_4 = 12.25$ , and  $t_5 = 13.11$ . Figure 7 shows the graph of the mean program duration reduction as a function of the number of realized soft dependencies.

In Example 2, it suffices to realize only four soft dependencies to maximize the mean program duration reduction. By the way, this fact follows from the expression (8). For the above value of  $a$ , the calculations yield  $k = 3.11$ . Note that changing the ratio actually changes the number of realized soft dependencies maximizing the mean program duration reduction.

Thus, we have considered two settings: in the first, all soft dependencies provide the same reduction of the project execution time, but the probabilities of realizing these dependencies are different; in the second, the reduction of the project execution time when realizing soft dependencies differs, but the probabilities of realizing soft dependencies are the same.

## 5. CONCLUSIONS

This paper has analyzed the use of soft dependencies in multi-project program implementation. An example has been provided to demonstrate how rarely dealing with soft dependencies can be reduced to simple schemes without losing the problem essence. The problem of determining the optimal number of realizable soft dependencies maximizing the mean program duration reduction under a stochastic uncertainty in the realization of soft dependencies has been considered. As shown, the maximum value of the mean program duration reduction depends on the number of

realized soft dependencies and, moreover, is largely determined by the probability of realizing each soft dependency. Numerical examples have been given in which the maximum value of the mean program duration reduction is achieved for a smaller number of available soft dependencies.

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