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WORKERS FLOW AND ON-TIME COMPLETION OF CONSTRUCTION PROJECTS

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Abstract: The construction sector is one of the most important economic activities since it is responsible for planning, designing, and developing the infrastructure that social development requires, such as roads, schools, and hospitals. Thus, the late completion of construction projects may harm social welfare. Construction companies have problems coping with completion times since they simultaneously manage multiple infrastructure projects that differ in the number of workers they need and the possibility of having projects whose development overlaps. So, companies split their projects into development stages to simplify the management of construction projects, which require an efficient allocation of workers to cope with the stages' activities. This paper analyzes the distribution of workers among development stages to cope with the projects' completion times. Noticing that not all workers should participate in the same development stage of a single project, the previous problem casts similarities with the maximum flow problem. We follow this modeling approach to determine the number of workers participating at each development stage when a company simultaneously manages more than one construction project. Later, we apply the previous model for a company that operates 11 projects and has 24 workers; the maximum workers' flow model sets the number of workers that each development stage needs for the on-time completion of the 11 projects by considering three different scenarios, concerning the overlapping of development stages.

1 Introduction

Due to the high costs associated with construction projects, sponsorship-based tenders are common for increasing the competitiveness and efficiency within the sector in the realization of infrastructure projects [1], in order to avoid a crisis management [2]. Sponsorship-based tenders are competition systems that assign projects to those companies that offer low construction costs at a reasonable completion time. In other words, these assignment mechanisms pretend to reduce projects' costs while parallelly coping with completion times. Although tenders have succeeded in lowering costs [3], the on-time completion of these projects remains a challenge since companies simultaneously manage several projects with different features.

For the on-time completion of each project, construction companies split their projects into development stages, when they manage different projects at the same time. However, the complexity of this strategy increases as stages overlap with other projects' stages because each phase requires a different number of workers. For example, the initial stages tend to be more labor-intensive than the last stages, which implies that the initial stage needs more workers than the last stages. Hence, construction companies characterize by having permanent and eventual workers during the completion of a project [4]. Even more, the empirical evidence points out that late completion times are caused by an inadequate allocation of workers among stages when companies are in charge of several projects [5].

In this paper, we analyze the previous allocation problem for the case of a construction firm that manages 11 projects with different completion times. The company splits them into development stages, and each requires a different quantity of workers. Since projects' stages develop similar activities, workers can 'flow' from one project to another whenever a stage requires them. So, the previous problem casts similarities with the maximum flow problem of Ford and Fulkerson [6]. In other words, our modeling approach considers that workers move on a bipartite network whose nodes represent stages and projects; and arrows go from stages to projects. So, arrows indicate the stages that a project needs for its on-time completion. Moreover, the arrow's weight is the maximum number of required workers at some stage.

Typically, the maximum flow problem determines the maximum amount of some resource from a source node to a destination node, satisfying capacity constraints. For example, Karshenas and Haber propose a piecewise linear objective function to minimize the total project cost through the maximum flow problem [7]. However, Gorham [8] demonstrates that this approach can assign training personnel in the U.S. Air Force at a lower cost. In recent years, Gorham's ideas have been applied to industries like textile [9], automotive [10], aeronautics [11], and manufacturing [12] to optimize human resources.

Our paper is closely related to the previous literature. Specifically, we apply Gorham's ideas for the construction industry, one of the most important sectors within a country since it generates and maintains the infrastructure that other industries use [13]. So, we analyze three different scenarios that consider different starting and ending stages by considering data from a construction enterprise that simultaneously manages several projects. In other words, our assignment procedure is flexible enough to deal with problematic situations that are either beyond control and often lead to delays. In comparison, the traditional approach of planning and controlling projects tends to fail mainly because of too much precise control, which curtails creativity from playing a crucial role in construction [14].

2 Methodology

The allocation of temporary workers among development stages for projects' on-time completion casts similarities with a maximum flow problem. As we mentioned before, a worker may 'flow' from project to project whenever their skills are needed at a particular stage. However, if the construction company is in charge of several projects, it needs to allocate such workers to cope with the completion times of all its projects. We model the workers' flow by considering a network $\boldsymbol{N} = (\boldsymbol{X}, \boldsymbol{A})$, where $\boldsymbol{X}$ is the set of nodes and $\boldsymbol{A}$ is the set of arrows.

We assume that $\boldsymbol{N}$ is a bipartite network, i.e., $\boldsymbol{X}$ is partitioned into two sets, a set of nodes that represent periods, $\boldsymbol{S} = \mathbf{1}, \mathbf{2}, \ldots, \boldsymbol{n}$, and a set of nodes that represent projects, $\boldsymbol{P} = \boldsymbol{p_1}, \boldsymbol{p_2}, \ldots, \boldsymbol{p_m}$. A generic period is denoted by $\boldsymbol{i}$, while a generic project is denoted by $\boldsymbol{p_j}$ or $\boldsymbol{p}$. So, an arrow $\boldsymbol{ip}$ is an arc from some stage $\boldsymbol{i}$ in $\boldsymbol{S}$ to some project $\boldsymbol{p}$ in $\boldsymbol{P}$. Since $\boldsymbol{N}$ is bipartite, there are no arrows from $\boldsymbol{S}$ to $\boldsymbol{S}$, or from $\boldsymbol{P}$ to $\boldsymbol{P}$. We consider that $\boldsymbol{S}$ is a well-ordered set concerning time development, i.e., the company starts construction activities in period 1, and ends its operations during period $\boldsymbol{n}$.

Assumption 1. $\boldsymbol{\Gamma^-(p)} = \{\boldsymbol{i} \in \boldsymbol{S} | \boldsymbol{ip} \in \boldsymbol{A}\}$ is the set of all periods in which the construction company develops activities for completing project $\boldsymbol{p}$.

By Assumption 1, the on-time completion of project p requests $|\boldsymbol{\Gamma^-(p)}|$ periods. Even more, note that we can interpret periods in $\boldsymbol{\Gamma^-(p)}$ as development stages for project $\boldsymbol{p}$. Since $\boldsymbol{S}$ is a well-ordered set, the initial development stage of $\boldsymbol{p}$ is $\mathbf{min}\{\boldsymbol{\Gamma^-(p)}\}$, while the last stage of project $\boldsymbol{p}$ is $\mathbf{max}\{\boldsymbol{\Gamma^+(p)}\}$.

To analyze the allocation of workers among projects as a flow problem, we consider the network $\boldsymbol{N} = (\bar{\boldsymbol{X}}, \bar{\boldsymbol{A}})$ such that:

1. $\bar{\boldsymbol{X}} = \{\boldsymbol{s}, \boldsymbol{t}\}$ where $\boldsymbol{s}$ and $\boldsymbol{t}$ are the source and terminal nodes, respectively.
2. $\bar{\boldsymbol{A}} = \boldsymbol{A} \cup \{\boldsymbol{si} | \boldsymbol{i} \in \boldsymbol{S}\} \cup \{\boldsymbol{pt} | \boldsymbol{p} \in \boldsymbol{P}\}$.

A generic arrow in $\bar{\boldsymbol{A}}$ is denoted by $\boldsymbol{\iota\kappa}$.

Quintana [15] points out that each arrow can be considered as a conduit with a capacity that indicates the maximum number of workers that can flow through it. The capacity of an arrow $\boldsymbol{\iota\kappa}$ is a non-negative constant $\boldsymbol{q(\iota\kappa)}$, while the flow $\boldsymbol{f}\ (\boldsymbol{\iota\kappa})$ is a non-negative function $\boldsymbol{f}$ from $\bar{\boldsymbol{A}}$ to $\boldsymbol{R_+}$. Due to the construction company has constraints for hiring additional workers, the flow does not exceed the capacity, i.e., $\boldsymbol{f}\ (\boldsymbol{\iota\kappa}) \leq \boldsymbol{q(\iota\kappa)}$, for all $\boldsymbol{\iota\kappa} \in \bar{\boldsymbol{A}}$. The source and terminal nodes are artificial nodes that allow us to establish the following features concerning the total number of workers and completion times:

1. All workers can flow from $\boldsymbol{s}$ to any vertex $\boldsymbol{i} \in \boldsymbol{X}$. We assume that the total number of workers in the company is $\boldsymbol{K}$, i.e., $\boldsymbol{q(si)} = \boldsymbol{K}$ for all $\boldsymbol{i} \in \boldsymbol{X}$.
2. Weights $\boldsymbol{q(pt)}$ indicates the number of workers each project needs for on-time completion.

Given the previous constraints, the workers-projects allocation problem is to find the maximum flow of workers that each project's stage needs for on-time completion. Below, we present the mathematical model that summarizes the previous problem.

$$\boldsymbol{Max\,z} = \boldsymbol{x_{ts}} \tag{1}$$

subject to

$$\textstyle\sum_{\kappa:\, \iota\kappa \in \bar{A}} \boldsymbol{f(\iota\kappa)} - \sum_{\kappa:\, \kappa\iota \in \bar{A}} \boldsymbol{f}\ (\boldsymbol{\kappa\iota}) = \begin{cases} \boldsymbol{x_{ts}}, & \textbf{if } \boldsymbol{\iota = s} \\ \mathbf{0}, & \textbf{if } \boldsymbol{\iota = \kappa} \\ -\boldsymbol{x_{ts}}, & \textbf{if } \boldsymbol{\iota = t} \end{cases} \tag{2}$$

$$\mathbf{0} \leq \boldsymbol{f(\iota\kappa)} \leq \boldsymbol{q(\,\iota\kappa)} \tag{3}$$

Expression (1) establishes the objective function of our problem, i.e., to maximize the number of workers that should flow from the source node to the terminal node. Expression (2) illustrates flow constraints related to the total number of workers that flow through the network $\bar{\boldsymbol{N}}$. Specifically, the number of workers that depart from the source node must equal the number of workers that arrive in the terminal node. At the same time, flow's conservation is satisfied in middle nodes, which means a flow equal to zero. In other words, the number of workers that start working in a project's stage is the same that leaves the project. Finally, the worker's flow in an arrow must not exceed the maximum capacity of such an arrow, expression (3) requires.

3 Data description

The construction company that we analyse is in charge of eleven projects, which the company got from participating in public sponsorship-based tenders. All projects have the same completion time, 45 days, and the company splits all projects into three development stages of 15 days. Moreover, the company has a total labour force of 24 workers, and each development stage needs at most 14 workers.

Table 1 Data of the construction company

Workers	Projects	Project completion time (in days)	Stage duration (in days)	Work year (in days)
24	11	45	15	360

Despite the construction company's efforts to cope with the on-time completion of its projects, it struggles to reach this goal. More than 14 workers are assigned to some developmental stages, according to historical data. At the same time, some projects start their development many periods after the company gets it because there are no available workers. In other words, projects' construction does not initiate because the company's assignment mechanism does not allow the ow of workers from projects, where they are not necessary, to new projects. We apply the maximum ow problem explained in the previous section to deal with this problem.

4 Results and discussion

This section solves the maximum flow problem described in Section 2 by considering the company's features summarized in Table 1. Since the maximum flow problem is a linear programming model, we use the LINGO 11 software to compute its solutions. Below, we present and explain the model's code.

MODEL:
SETS:
We first set the variables of the maximum flow model. So, we establish the total number of nodes and arrows describing the network under workers from one development stage to another. The cardinality of the nodes set is n = 37 because we have 11 projects, 24 development phases, and the initial and terminal nodes.

NODES / 1. . . *n* /:
Before specifying the arrows set, it is essential to remember that the maximum ow problem unfolds on a network whose nodes play different roles. Hence, nodes represent development stages and projects, but we also include a source and a sink, nodes one and n, to describe the problem as a linear programming model. Consequently, the arrows' set includes arrows from the source node to all stages, while all projects should be connected with the sink node. It is worth recalling that arrows from stages to projects depend on the period where the company gets the project. So, all projects may start and finish during the same development stages, or the initial stage may overlap with the last stage of particular projects. In the following subsections, we present networks that illustrate the company's current scenario and other possibilities.

ARROWS (NODES, NODES):
ENDSETS:
The objective is to maximize the flow of workers that go from the sink node to the source node.

MAX: FLOW (N,1)
Now, we describe the problem's constraints. First, we set the capacity constraints

@FOR(ARCOS(I,J):FLUJO(I,J)<=CAPACIDAD(I,J)):
Later, we establish the flow conservation constraints

@FOR(NODOS(I):@SUM(ARCOS(J,I):FLUJO(J,I))
=@SUM(ARCOS(I,J):FLUJO(I,J))):
Finally, the data that our model needs summarize arrows capacities.

DATA: *For each arrow, we need to specify its capacity, i.e., the maximum number of workers that can flow through them. Note that arrows with nodes not in $\{s,t\}$ have a maximum capacity of 14, while arrows from the source node to stages have a capacity of 24 workers. Also, arrows from projects to the sink node have a capacity constraint of 14 because it represents the maximum number of workers needed to complete a project in 45 days.*

CAPACITY:
ENDDATA:
END:
In the following subsections, we discuss three possible scenarios. The first one is the construction company's situation at the moment of our study; such a scenario considers that the company needs to plan the year to initialize and terminate a project because it has already gotten the 11 projects. The other two examples show the flexibility of our modeling approach by specifying the stages where projects arrive and should finish. The complete codes for each scenario are shown in the Appendices.

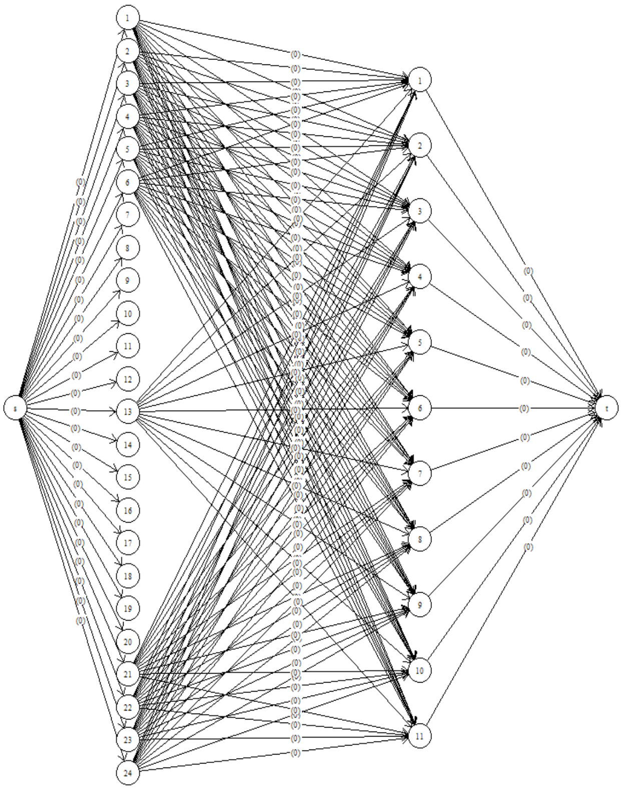
4.1 Scenario 1 (the current situation)

Nowadays, the construction company is in charge of 11 projects whose arrival was characterized by the lack of planning from the company's managers. Since the company needs to complete each task by using its workers for 45 days, we assume that the company can carry out and complete any project at any period. So, in the network where workers ow, the set of arrows whose initial or final nodes are not in $\{s,t\}$ is:

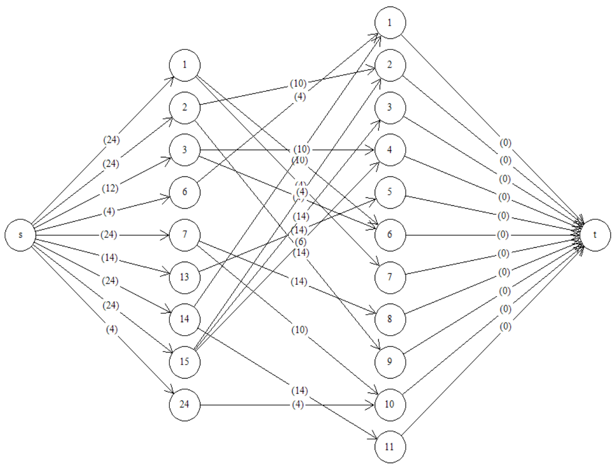
$$A = S \times P \tag{4}$$

that is to say, for all $\iota \in S$ and $p \in P$, there exists an arrow ιp in $\bar{A}$.

In other words, the previous scenario is represented by a complete bipartite network when we only consider nodes in S and P. Figure 1a illustrates the network that serves the case where the company is not sure of the initial and final stages of its eleven projects. We use the LINGO software to solve the maximum ow problem represented in Figure 1a. The results show that the company can complete each project in two stages. Table 2 indicates the initial and final stages and the number of workers that the company needs to cope with completion dates.



(a) Network



(b) Results

Figure 1 Scenario 1: Any project can start and terminate at any period

In other words, the projects' features allow the company to cope with completion times in a year. When the company does not have specific delivery stages, it is possible to allocate the necessary workers to complete a project in only one stage. Figure 1b illustrates this solution.

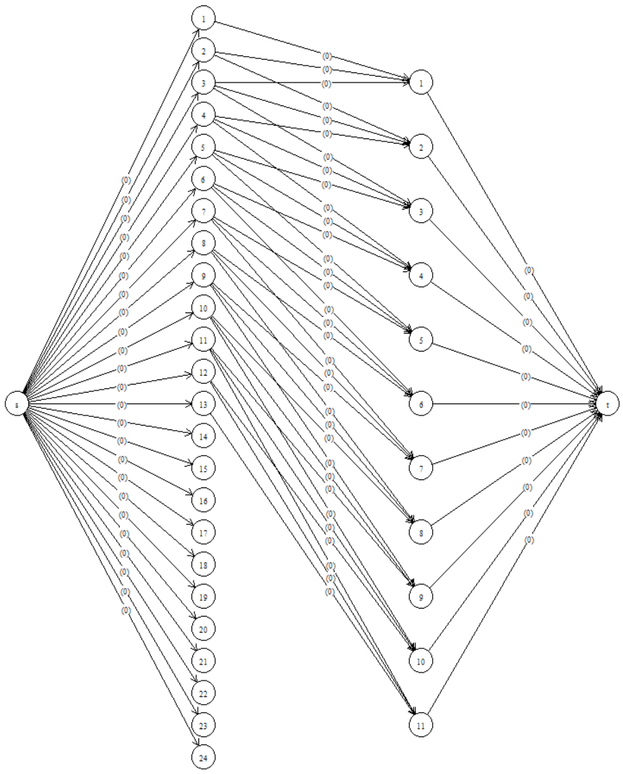
Table 2 Allocation of workers by initial and final stages

Project	Initial Stage	Number of workers	Final Stage	Number of workers
1	6	4	14	10
2	2	10	15	4
3	15	14		
4	3	8	15	6
5	5	14		
6	1	10	3	4
7	1	14		
8	7	14		
9	2	14		
10	7	10	24	4
11	14	14		

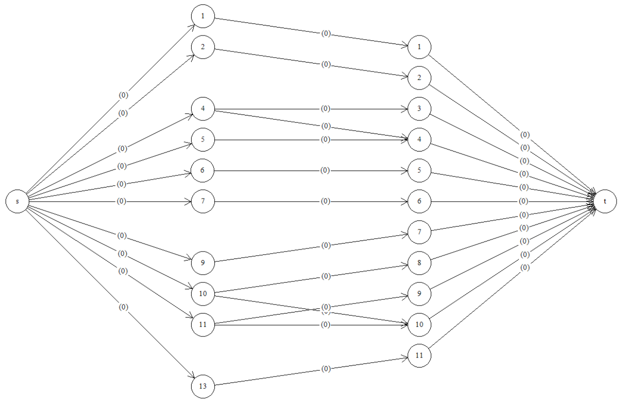
4.2 Scenario 2

Although the previous analysis allows the company to plan the number of active workers at each project during a year, it is common that the initial and final stages of different projects overlap. Our second scenario analysis is based on the previous observation.

Hence, we consider that the construction company carries out a new project halfway through completing a project; that is to say, the company starts a new project in the second development stage of a previous project. Also, we consider the existence of a tight completion time. For example, we have that project 2 starts during period 2, which implies that it should finish at period 4. Figure 2 illustrates this scenario.



(a) Network



(b) Results
Figure 2 Scenario 2: Projects begin in the intermediate stage of a previous project

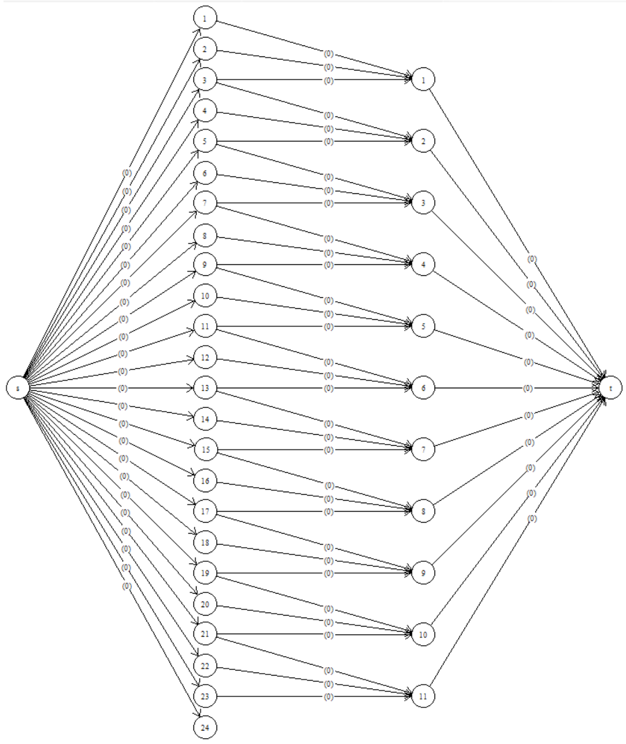
As before, we use LINGO to solve the maximum ow problem by considering the network in Figure 2a. Table 3 summarizes the number of workers that need to work on each project during a particular stage. As before, we observe that no project is completed in three stages; even more, it is possible to complete a project by assigning 14 workers in only one development stage.

Table 3 Allocation of workers by considering the second scenario

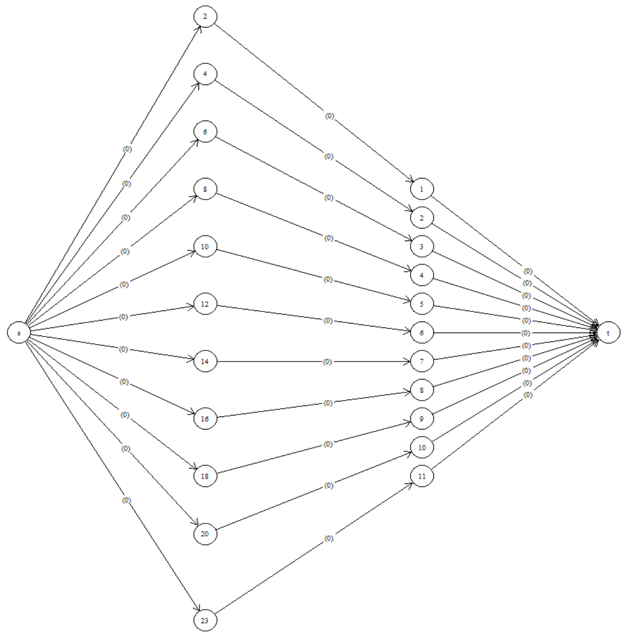
Project	Initial Stage	Number of workers	Final Stage	Number of workers
1	1	14		
2	2	14	15	4
3	4	14		
4	4	4	5	10
5	6	14		
6	7	14	3	4
7	9	14		
8	10	14		
9	11	14		
10	10	4	11	10
11	13	14		

4.3 Scenario 3

In the third scenario, we assume the company does not start a new project in the middle of a previous project. This means that the company accepts a new project in the last development stage of a given project, see Figure 3a.



(a) Network



(b) Results
Figure 3 Scenario 3: Initial and final stages overlap

Using the LINGO software, we observe the company can assign the maximum number of workers in only one stage. Table 4 presents the stage under which each project is completed, while Figure 3 illustrates this result.

Table 4 Allocation of workers by initial and final stages

Project	Initial Stage	Number of workers
1	2	14
2	4	14
3	6	14
4	8	14
5	10	14
6	12	14
7	14	14
8	16	14
9	18	14
10	20	14
11	13	14

5 Conclusions

In this paper, we analyse the number of workers that development stages need for the on-time completion of simultaneous construction projects. Since development stages may overlap, companies need to distribute workers across them. Graphically, we represent the previous problem through a bilateral directed network that links development stages with projects. We assume that stages nodes are ordered; consequently, the arrows that arrive at each project summarize the time the company can spend on a project. So, in this manner, we capture the projects' completion times. Moreover, we weight each arrow by considering the maximum number of workers participating in the stage node where the arrow departs. Consequently, the maximum flow problem determines the number of workers each stage needs to cope with projects' completion times.

To exemplify our model, we consider a company that manages 11 projects and only has 24 workers. We use LINGO to determine the distribution of workers in the development stages of each project. Our results indicate that the company has enough staff to carry out the 11 projects over a year. In addition, we compare different scenarios where the projects differ in their initial and final stages. So, the modelling approach allows us to compare the distribution of workers when overlapping development stages change; that is to say, the maximum flow model is flexible enough to analyse different scenarios, which is useful for planning the acceptance of new projects that may overlap with the previous ones.

The optimal solution provides a workers' allocation that avoids idle times; such a solution demonstrates that the company does not need to hire additional workers to cope with completion times. This result prevails when considering different structures concerning the dates when projects start or finish.

Although our modeling approach is flexible enough to analyze different structures concerning the possibility that development stages may overlap, the maximum flow problem we analyze ignores uncertain phenomena that may impact project development. For example, we implicitly assume that the workforce does not change during a year, which is not always true. So, our model does not consider that the total number of workers at each stage may vary. Also, projects' completion may change by exogenous factors like natural disasters or economic crises. This means that the directed network may suffer random modifications. In future works, we pretend to extend our analysis by considering exogenous factors that introduce uncertainty to the number of workers or the network's structure.

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