Optimizing the Owner's Scenarios for Budget Allocation in a Portfolio of Projects Using Agent-Based Simulation

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Abstract: Budget deficits or owners' cash-flow problems are often blamed for construction delays and construction cost increases that may be caused by these delays. Although many studies have focused on resource allocation, cash-flow management, and budget allocation in a portfolio of construction projects from the contractors' perspective, few studies have been conducted to investigate the allocation of budget, as the main resource of construction projects, from the owner's perspective. This paper presents an agent-based simulation model used to simulate budget allocation and its effects on projects' progress in an owner's portfolio of construction projects. In addition to simulating budget-allocation scenarios and predicting the future state of the projects in the portfolio, the model can reveal efficient ways to manage a limited budget based on defined preferences. The model considers increased costs during the construction period and income growth after completion. It uses the earned schedule (ES) concept to simulate the progress of projects and takes into account the probability of increased progress if there is a budget surplus. The proposed simulation model contributes to the portfolio management body of knowledge by helping organizations optimize budget-allocation scenarios and find an efficient scenario that could lead to earlier commissioned projects, reduced construction costs, and fewer construction delays. The model is validated using historical data from a portfolio of transportation projects, and four optimization scenarios are examined to find an efficient budget-allocation scenario. The results show the model can identify feasible optimized solutions for managing projects with limited budgets. **DOI:** 10.1061/(ASCE)CO.1943-7862.0001315. *© 2017 American Society of Civil Engineers.*

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Introduction

Project delays affect construction projects all over the world, and they often result in cost overruns. There are many reasons for project delays, cost overruns, and quality problems, but owner-related factors are most often identified as the cause of the problems, especially in publicly-financed projects (Larsen et al. 2015). Kazaz et al. (2012) found that owner-based factors were the most frequently reported cause for project delays in 16 countries, and the results of many studies (e.g., Aibinu and Odeyinka 2006; Al-Kharashi and Skitmore 2009; Assaf and Al-Hejji 2006; Abd El-Razek et al. 2008; Frimpong et al. 2003; Kazaz et al. 2012; Le-Hoai et al. 2008; Mahamid et al. 2012; Marzouk and El-Rasas 2014; Sambasivan and Soon 2007; Shehu et al. 2014) suggest that an owner's financial difficulties are one of the most important reasons for delays and cost overruns in many countries. The International Energy Agency (2009), for example, reported that approximately 60 upstream and downstream oil projects were postponed or delayed by at least 18 months in more than 25 countries, including the United States, Canada, the United Kingdom, Norway, Russia, and China, as a result of the 2008–2009 financial crisis. After the recent dramatic drop in oil prices, many construction projects have been postponed (CBC News 2015; Wood Mackenzie 2016). As these studies show, owners may cancel some projects in their portfolio, postpone some projects, or slow down some other in order to reduce expenses as a result of budget limitations.

Researchers have examined the process of selecting projects for a portfolio for more than 40 years (Iamratanakul et al. 2008) and there is an extensive body of literature on project portfolio selection (e.g., Gabriel et al. 2006; Liu and Wang 2011; Shakhsi-Niaei et al. 2015; Tavana et al. 2015). Many studies (e.g., Lee et al. 2003; Kao et al. 2006; Araúzo et al. 2009; Taghaddos et al. 2012, 2014; Besikci et al. 2015) have been conducted to examine how to properly manage limited equipment or human resources in a project or in a portfolio of projects, and some studies (e.g., Navon 1996; Liu and Wang 2010; Kishore et al. 2011; Gajpal and Elazouni 2015) have focused on identifying how a contractor should manage its cash flow in a project or portfolio of projects in order to reduce the number and impact of cash-flow problems. Not enough research, however, has been conducted to examine how owners, as investing organizations, should manage limited budgets for several in-progress projects. This research is needed because owners with many in-progress projects face a difficult situation if they encounter financial problems, which can be the result of cost overruns, optimistic cost estimates, changes during projects, macroeconomic changes, inflation, incorrect prediction of economic conditions, and so forth. If financial problems arise, owners must deal with binding contracts, consultants and contractors who wish to be paid and continue working, and stakeholders who look forward to the

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completion of the projects. In addition, owners may be reluctant to reveal financial problems in order to protect their reputation.

Study Objectives

Improper budget allocation can lead to project delays, including loss of income from completed projects and increased projects costs. In order to help owners make informed budget-allocation decisions, help reduce portfolio managers' concerns about project schedules, and identify the most cost-efficient budget-allocation scenario, the research discussed in this paper was designed to simulate various budget-allocation scenarios including canceling, suspending, or slowing down projects in a portfolio, using an agent-based simulation model (ABSM). This agent-based model mimics the behavior of each project and considers each project as an agent. The model is designed to help organizations efficiently allocate budget to projects in a portfolio that are already in progress in order to meet strategic objectives of the owner.

In this model, different budget-allocation scenarios can be examined to evaluate the behavior of projects, their start and finish dates, and their progress. To identify the budget and cash flow needed for the portfolio and its projects to meet their plans, the model simulates physical progress scenarios. In addition, various budget-allocation solutions can be examined using optimization scenarios in order to identify the most effective way to allocate the limited budget for various projects. This model can help organizations reduce concerns about their portfolio, generate income from their projects as soon as possible, and see the results of their strategies concerning budget limitations earlier in projects.

Literature Review

Two main areas of research are related to the present study:

- Multi-project resource allocation: Some researchers have focused on multiproject resource allocation. Lee et al. (2003) proposed a multiagent resource-scheduling model for allocating resources to multiple projects using a market mechanism. Kao et al. (2006) suggested an event-driven reactive approach to project scheduling that uses a time-cost tradeoff analysis. Araúzo et al. (2009) developed a multiagent model for allocating resources to multiple projects' activities. In this model, projects and resources are considered agents that participate in an auction. Each project agent is a bidder, and each resource is a seller. Later, Arauzo et al. (2010) added another agent to their model, called the MAC agent, to play the role of auctioneer and centralized decision maker. Taghaddos et al. (2012, 2014) presented a simulation-based auction protocol integrated with multiagent resource allocation to solve resource-scheduling problems in large-scale or multiproject environments. Besikci et al. (2015) employed two genetic-algorithm-based methods with a resource dedication policy for solving the multiproject resource allocation problem. Research on multiproject resource allocation is mostly focused on allocating human and equipment resources to activities. Not enough research, however, has been conducted to study how to allocate a limited budget to in-progress projects in a portfolio.
- Portfolio management and cash flow: A few studies have been conducted to examine the financial aspects of project portfolios. Navon (1996), for example, developed a company-level cash-flow model based on the cash flow of a company's individual projects. The outputs of the model include company-level and project-level cash flows for various forecasting horizons. Liu and Wang (2010) proposed a model to optimize the cash flow of a portfolio. Their model could reduce financial pressure by shifting activity schedules without delaying completion time. Kishore et al. (2011) used a method that considered a portfolio's cash-flow risk to predict the cash flow of the portfolio of projects for a contractor. Elazouni (2009), Elazouni and Abido (2011), and Gajpal and Elazouni (2015) employed heuristic methods for the finance-based scheduling of construction projects. The scheduling problem is approached from the contractor's perspective and solved by dealing with each activity in each project. These researchers solved some hypothetical problems to show the ability of these methods to schedule activities in the projects of a portfolio. Touran (2010) presented a mathematical model for calculating a portfolio's budget at different confidence levels using actual budget reports from similar projects in the past. Mostafavi et al. (2014) proposed a hybrid agent-based/system dynamics model to simulate the dynamics of infrastructure financing for policy analysis purposes. A number of policy scenarios were identified, simulated, and examined to determine how they might affect a transportation infrastructure system. The hybrid agent-based/system dynamics model used by Mostafavi et al. (2014, 2016) is a good example of a holistic view of the problem that does not involve every detail of each process or activity. They have created a model to simulate the landscape of financing policies related to highway transportation infrastructure in the United States. Most of the aforementioned studies are focused on cash flow of portfolios and some are related to finance-based scheduling of activities in projects of a contractor organization. Not enough research, however, has been conducted on limited budget allocation.

While many studies have been conducted to examine multiproject resource allocation, cash flow, and finance-based scheduling of projects in a portfolio from the contractors' perspective, few studies have examined these areas from the owners' perspective. Most of the research conducted in multiproject environments scheduled the projects' activities based on resource or finance limits. Owners, however, are not interested in solving problems at this level of detail. Owners mostly deal with the main financial factors of the projects and the portfolio, which have not been studied in previous research.

Research Method

The agent-based method has been used in some areas of the construction industry. Although there is no consensus about the definition of an agent, autonomy is a universally recognized trait (Taghaddos et al. 2012). van Dam et al. (2012) suggested three conditions that make a system suitable for agent-based models:

1. The problem has a distributed character, and each actor is to some extent autonomous;
2. The subsystems (agents) operate in a highly dynamic environment; and
3. Subsystem interaction is characterized by flexibility.

Agent-based models are built from the bottom up, starting with individual agents, defining their characteristics and behavior, and letting them interact in an environment. The function of the system as a whole is a natural result of its agents' spontaneous conduct (Salamon 2011).

Each project in an owner's portfolio has its own contract (with its own terms and conditions), different consultants and contractors, individual project managers, diverse stakeholders and markets, and many other characteristics, and as a result, each project responds in different ways to budget allocations and other financial situations. They have different cost-inflation rates and behave differently when faced with a budget deficit or surplus. Taking into account all these

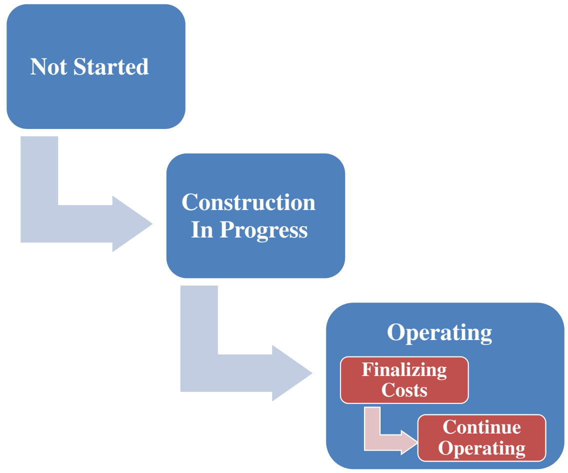


Fig. 1. Agents' states

aspects, projects are somehow autonomous and can be modeled as agents in an agent-based model. Therefore, a multiagent model provides a powerful tool for solving complex resource scheduling problems (Taghaddos et al. 2012) and identifying the best solution for allocating budgets. In addition, this type of model can be used in future studies in which projects can interact with each other in order to identify precedence relationships.

The proposed model simulates projects as agents that progress based on a simulated scenario. It can identify the best solution for managing a portfolio and allocating limited budgets to projects in the portfolio. The model uses the earned schedule (ES) concept (Lipke 2013) to simulate the projects' schedules.

Simulation Model Development

As discussed earlier, projects are considered agents in the proposed simulation model. Each agent can be in the states illustrated in Fig. 1 (i.e., Not Started, Construction in Progress, or Operating).

Projects act based on the simulation scenario and their defined behavioral rules. As illustrated in Fig. 1, each project may be in any of the three main states and two substates (i.e., Finalizing Costs and Continue Operating). The definition and conditions of each state are provided in Table 1. The agents will get into states successively, starting from the Not Started state.

If a budget is not allocated for starting a project or there are no progress targets for it, the project will stay in the Not Started state. Any time the project receives a budget or progress targets are identified in the simulation scenario, it enters the Construction in Progress state. The project stays in this state until its progress reaches 100%. After completion of the project, it enters the Operating state, Finalizing Costs substate. The project can enter the Continue Operating substate when all costs are paid (e.g., retainage and debt). Outcomes of a project (i.e., income or products) can be achieved any time the project enters the Operating state.

For each project in the portfolio, the following data should be collected as input variables:

- Cumulative planned physical progress percentage based on the project plan;
- Cumulative planned cash-outflow based on the project plan (cost flow);
- Predictions of cost inflation rates based on the project's contractual terms, market conditions, and predictions about prices;
- Project outcome (e.g., cash-in, revenue, and derivatives) after completion (can be cumulative or noncumulative);
- Predictions about a project's outcome escalation rate, defined separately because of the differences in the essence of costs and incomes and their market; and
- Increased efficiency factor (IEF), which is newly introduced for each project and defined to consider a project's behavior in case of a budget surplus. The IEF indicates the maximum rate at which a project with a budget surplus can progress compared to its original schedule.

The first four items should be provided in a time-distributed format (e.g., year, month, week, etc.) for the intended simulating period. The last two items are constant parameters of the simulation. The project outcome escalation rate is the anticipated growth rate for project outcomes after project completion. The effects of increased costs and anticipated growth rate for project outcomes are calculated using the net present value (NPV), presented as follows in Eq. (1):

$$\text{NPV}(i,N) = \sum_{t=0}^{N} \frac{R_t}{(1+i)^t} \quad (1)$$

where i = discount rate; N = total number of periods; t = time of cash inflow/outflow; and R_t = net cash inflow/outflow at time t.

The IEF can be provided by experts or by scheduling projects based on an optimistic calculation of the length of time it takes to perform the project's activities. Fig. 2 shows the inputs and outputs of the agent-based model.

The user then provides the scenario for the model to assess. There are three ways to construct a scenario:

- Budget allocation scenario: In this type of scenario, the allocated budget for each project should be provided. The result will show the behavior of the projects and portfolio in relation to the allocation.
- Physical progress scenario: In this type of scenario, the user provides the physical progress target percentage for each project. The simulation results consist of the budget needed for each project to achieve its target progress, and the model takes into account the project's schedule and effect of increased costs.
- Optimization scenario: In this type of scenario, the time-distributed maximum available budget is specified at the portfolio level, and the model allocates financial resources to the projects based on defined preferences. At each time step, the model prioritizes projects based on the specified criteria and allocates the limited budget to projects, starting with the top-ranked one. It is possible that projects at the bottom of

Table 1. Definition of Agents' States

Number	State/substate	Definition
1.	Not started	The project has not started according to the simulating scenario.
2.	Construction in progress	The project is in progress based on the scenario. Physical progress is between 0 and 100%.
3.	Operating	The project's progress is finished, and it is operating (physical progress = 100%).
3.1.	Finalizing costs	The project is finished, but there are still some costs to finalize.
3.2.	Continue operating	The project's physical progress is 100%, and all costs are paid.

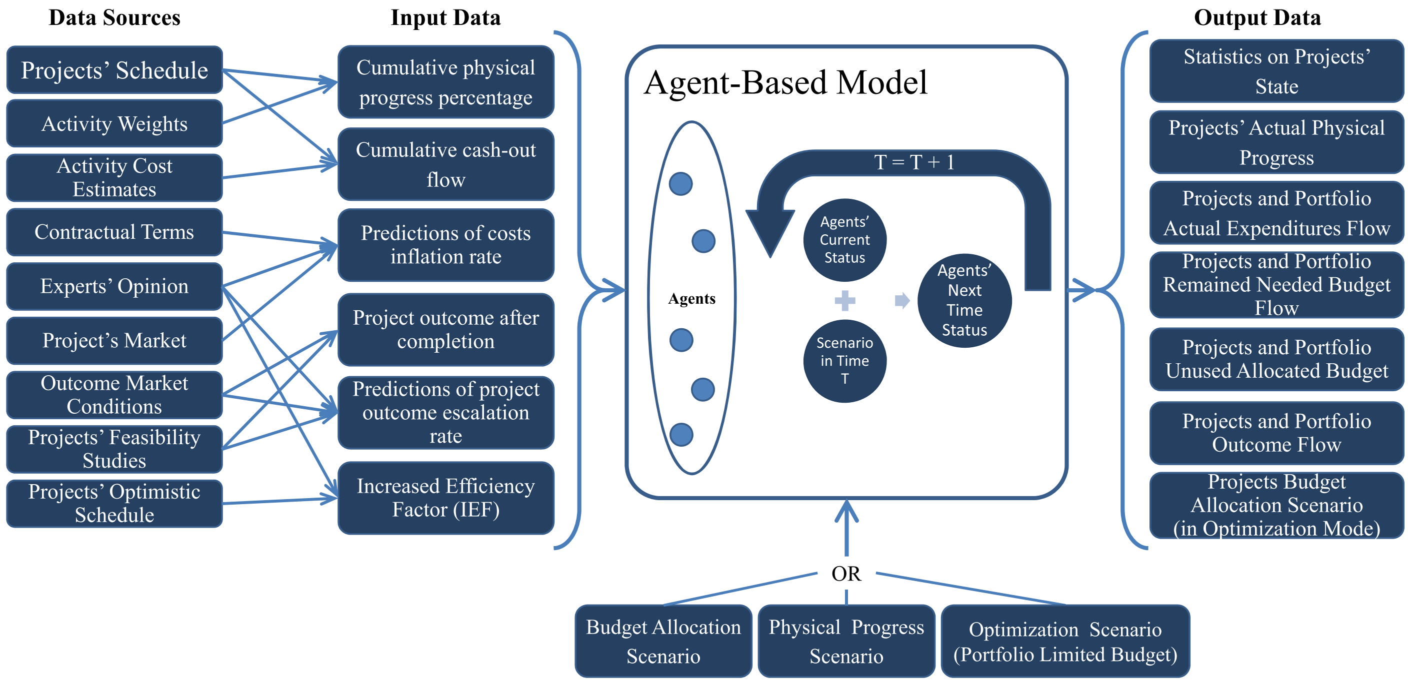


Fig. 2. Schematic view of agent-based model inputs and outputs

the ranking list never receive any financial resources as a result of budget restraints, and these projects may be delayed.

Projects' progress will be calculated based on their physical progress plan, cash-out plan, cost inflation rates, and finally allocated budget (in the first and third types of scenario) or physical progress target (in the second type of scenario). After completion of a project, its anticipated outcomes will happen in a timely manner, bearing in mind the anticipated growth rates.

In the first and third type of scenario, each project will have an amount of available budget (B_{Avbl}) in each time step. The model will calculate the NPV of the cumulative allocated budget ($B_{\text{Avbl}}^{\text{NPV}}$) for each project. Based on the physical progress plan and cash-out plan, $B_{\text{Avbl}}^{\text{NPV}}$ is equivalent to a specific percentage of physical progress (P_{Avbl}) that is available regarding the allocated budget. P_{Avbl} will be calculated regardless of the last time of actual physical progress. In the second type of scenario, P_{Avbl} will be defined in the scenario.

Projects, however, cannot progress faster than their schedule. For example, if the allocated budget was more than the projects' need or if targets were reached sooner than expected, the model considers the project schedule and calculates the project's actual progress properly. An outcome is launched each time the actual progress of a project reaches 100%.

At each time step in the model (which can be any unit of time, depending on modeling objectives and case portfolio; e.g., year, month, week, etc.), each agent calculates its maximum conceivable progress ($P_{\max}$) based on its last cumulative progress, ES, planned cumulative physical progress curve, and the IEF. Comparing the maximum conceivable progress to the available physical progress based on the scenario, each project identifies its next actual cumulative physical progress percentage [Eq. (2)]

$$P_{T=t+1} = P_{T=t} + \min(P_{\text{Avbl}}, P_{\max}) \qquad (2)$$

where $P_{T=i}$ = project's cumulative progress percentage at time i; P_{Avbl} = available progress based on the allocated budget; and $P_{\max}$ = maximum conceivable progress.

Fig. 3 illustrates a schematic example of how maximum conceivable progress of Time 8 is calculated based on project status in Time 7. First, the earned schedule (ES) of the project is calculated based on the physical progress in $T = 7$. Then, the planned cumulative physical progress in $T = (\text{ES} + 1)$ is calculated. The maximum conceivable progress in Time 8 is the planned cumulative physical progress in $T = (\text{ES} + 1)$ minus the actual cumulative progress in Time 7.

If the allocated budget enables the project to exceed the maximum conceivable progress ($P_{\text{Avbl}} > P_{\max}$), the remaining budget is reserved as Unused Allocated Budget, and it is available for the next time step.

The simulation produces a large amount of information. Some of this information is only applicable to the projects, some of it is only applicable to the portfolio, and some of this information applies to the projects and portfolio. In addition to identifying the projects' actual expenditures, state, and outcomes, the information about any budget deficit or budget surplus can help organizations predict the future state of the portfolio and its projects.

Model Validation

Historical data from 36 previously completed projects are used to validate the model. In the historical data validation technique, part of data is used to determine whether the model behaves as the system does (Sargent 2007). These data are provided by the Management and Planning Organization (MPO 2017) of Iran, and all the projects are categorized as transportation infrastructure projects. All the projects were started before 2010, and they were in the Construction in Progress state, except two projects that started in 2012. At the end of 2010, the projects were rescheduled for completion at the end of 2015. As a result of a budget deficit, 28 projects were delayed and rescheduled in late 2015, and the completion date was changed to 2016 and 2017. Although these 28 projects have not been completed historically based on the data, it is assumed that they will be completed; it is assumed that the plans for late

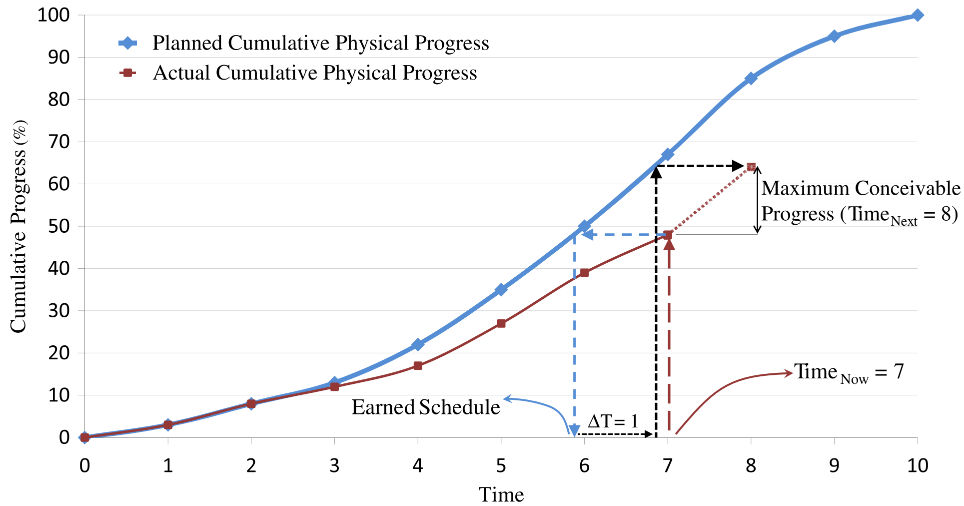


Fig. 3. Example of calculating maximum conceivable progress (IEF = 1.0)

2015 have exactly happened (using data on unfinished projects can show the capabilities of the model to find better allocation scenarios for an in-progress portfolio). Therefore, data from all 36 projects will be considered actual historical data in the upcoming sections. Table 2 provides some abstract information about the start and finish year of the projects of the case portfolio.

In the model, the plans for 2010 are used as the input data for cumulative planned physical progress and cumulative planned cash outflow. The actual inflation rate and IEF of the projects are calculated from the real data and entered into the model. The simulation scenario will be identical to the actual budget allocated to the projects.

The results of the simulation show that the model can simulate progress of the projects exactly as indicated by the historical data. The projects were finished by their actual finish date, and their expenditures were equivalent to the historical data. In addition, to estimate the effect of IEFs in a new experiment, this factor was assumed equal to 1.0 for all the projects. Table 3 describes the results of the simulation model with this assumption.

As depicted in the last column of Table 3, some projects have a cumulative progress percentage less than 100%, which indicates inaccuracy in the result of the model compared with the historical data. The average simulated progress of the projects at the time of their historical completion produced by the data is 91.07%.

Table 2. Count of Projects Starting and Finishing Each Year Based on the Data

Year	Started actually	Scheduled finish based on plan of end of 2010	Finished actually based on the historical data
Before 2001	8	—	—
2001–2005	9	—	—
2006–2010	17	—	—
2011	—	5	1
2012	2	15	3
2013	—	6	—
2014	—	4	2
2015	—	6	2
2016	—	—	10[a]
2017	—	—	18[a]

[a]These projects have not actually finished, but it is expected that they will be completed.

The 8.93% difference is acceptable, taking into account the changes to the projects' schedule (i.e., projects were rescheduled). The simulated completion times of 15 projects are identical to the historical data, 10 projects completed 1 to 3 time steps (i.e., years) later than their actual completion date, and 11 projects were not completed during the simulation period. It should be pointed out that these projects have progressed faster than the schedules proposed in 2010 in at least one period of time. Assuming IEF = 1.0, these projects were not able to absorb their entire allocated budget. Although the unused allocated budget is available to the projects, its value decreased because increased costs due to inflation caused delays or incomplete projects.

Projects 23, 27, and 28 have a fairly slow rate of progress, and their schedules should be revised in order to ensure they are completed in 2017. Projects 29 to 36 were actually completed before 2015. Results of the simulation (Table 3) show that the model was 99.99% accurate compared to the historical data regarding these projects. This precision may be the result of fewer changes in these projects' schedules after rescheduling at the end of 2010.

Case Portfolio

The first 28 projects in Table 3, which were delayed until 2016 and 2017, were considered a portfolio in this research in order to show the capabilities of the model in optimizing budget-allocation scenarios in a portfolio of in-progress projects. The results of the model can be compared to the plans of the projects and demonstrate the efficiency of the model in practice. These projects will be actually completed with the cost of $1,889.1 million until the end of 2017. According to the historical data, each project had a physical progress plan and budget at the end of 2010, and the following data were used as input data in the simulation:

- The inflation rate for each project from 2011 to 2015 was calculated and entered into the model; and
- IEFs were assumed to equal 1.0 for all 28 projects.

In order to identify the best solution for managing the budget and schedule, five scenarios (i.e., Progress as Planned, Minimum Remaining Cost, Minimum Next Time Budget, Maximum Production Rate, and Maximum Production Rate–Improved) were simulated in this study (Table 4). As described in Table 4, the first scenario (i.e., Progress as Planned) is a physical progress scenario, and the next four scenarios (i.e., Minimum Remaining Cost,

Table 3. Comparing Results of the Model with Historical Data Assuming IEF = 1.0

Project number	Planned finish (end of 2010)	Actual finish (historical data)	Simulated finish (model results)	Simulated progress percentage at the historical finish time in the third column (%)
1	2012	2016	NF	99.51
2	2011	2016	2016	100.00
3	2012	2017	NF	98.83
4	2011	2017	2017	100.00
5	2013	2017	NF	96.05
6	2012	2016	NF	96.49
7	2013	2017	2017	100.00
8	2013	2016	NF	96.66
9	2013	2016	NF	98.98
10	2012	2017	2017	100.00
11	2015	2017	(2019)	81.16
12	2015	2017	(2018)	84.96
13	2012	2017	NF	94.58
14	2015	2017	(2020)	71.79
15	2014	2017	(2018)	84.02
16	2012	2016	NF	97.52
17	2012	2017	NF	96.44
18	2014	2016	2016	100.00
19	2014	2017	(2019)	72.82
20	2012	2016	2016	100.00
21	2012	2017	2017	100.00
22	2013	2017	2017	100.00
23	2015	2017	(2020)	42.54
24	2012	2016	NF	95.60
25	2014	2017	(2019)	74.02
26	2013	2016	NF	99.49
27	2015	2017	(2019)	47.83
28	2015	2017	(2019)	49.46
29	2012	2012	2012	100.00
30	2012	2015	2015	100.00
31	2011	2012	2012	100.00
32	2012	2015	2015	100.00
33	2011	2011	2011	100.00
34	2012	2014	(2015)	99.91
35	2011	2014	2014	100.00
36	2012	2012	2012	100.00
			Average progress	91.07

Note: NF = not finished (these project were not completed with the allocated budget); numbers in the parenthesis represent finish times not equal to actual finish in the third column.

Minimum Next Time Budget, Maximum Production Rate, and Maximum Production Rate–Improved) are optimization scenarios with a limited yearly available budget at the portfolio level identical to the historical budget for the projects in the sample portfolio.

In the optimization scenarios, the projects are prioritized on two levels in order to identify the best solution for the projects' budget, schedule, and outcomes.

- In the Minimum Remaining Cost scenario, on the first level, the model will prioritize projects by their remaining time (i.e., ascending sort) and on the second level, projects will be sorted according to their remaining cost;
- In Minimum Next Time Budget scenario, the model will sort projects by their remaining time on the first level, and their next time needed budget at the second level (i.e., ascending sort); and
- In Maximum Production Rate and Maximum Production Rate-Improved scenarios, projects will be ranked based on descending ratio of outcomes to remaining time on the first level (i.e., production rate), and ascending amount of remaining cost on the second level.

Except for the fifth scenario (i.e., Maximum Production Rate–Improved), the optimization scenarios are set to allocate all the next time needed budget for each project or allocate nothing. In these scenarios, if the next time needed budget of a project is more than the available budget, it will not receive any budget in that time step. In the fifth scenario, the model will allocate the remaining part of the available budget to the highest ranked project that has not received any budget. Even if the allocated budget is not enough for the project to progress according to its schedule, it can move toward completion. Considering these scenarios, it was possible to identify better solutions for allocating budgets and meeting schedule targets show that the simulation model can manage a portfolio of in-progress projects and help portfolio managers understand the projects' behavior and uncertainties.

Progress as Planned Scenario

The results of simulated Progress as Planned (at the end of 2010) scenario are discussed in this section. To simulate the Progress as Planned scenario, a physical progress scenario was used to evaluate the budget needed to complete the projects as planned and find out how increased costs can affect the cost estimates. The physical progress scenario is designed same as the projects' physical progress plan at the end of 2010. The results of the Progress as Planned scenario are described in Table 5.

As depicted in Table 5, in order to complete the projects exactly as planned at the end of 2010, the budget needs to be increased by \$108.7 million in 2015. In the worst period, the budget needs to be increased by \$145.1 million in order to meet the schedule in 2012. Total actual allocated budget from 2011 until the end of 2015 is \$540.4 million, while the Progress as Planned scenario needed \$649.2 million in this period. This means that if approximately 20% more money was available from 2011 until 2015, the whole portfolio could be completed in 2015 for \$619.2 million less than if the projects are completed in 2017. The remarkable budget increase

Table 4. Description of Five Tested Scenarios

Number	Name	Description: First priority level	Description: Second priority level
1	Progress as Planned	The planned physical progress scenario is used to identify the budget and cash flow needed to complete the projects according to the plan at the end of 2010	
2	Minimum Remaining Cost	Least remaining time[a]	Least remaining cost
3	Minimum Next Time Budget	Least remaining time[a]	Least next time needed budget
4	Maximum Production Rate	Higher ratio of outcomes to remaining time	Least remaining cost
5	Maximum Production Rate–Improved	Higher ratio of outcomes to remaining time	Least remaining cost

[a]Time remaining until project completion from simulation time (simulation clock).

Table 5. Progress as Planned Scenario Budget Allocations Compared to the Historical Data

	Historical data (actual cumulative allocation)		Progress as planned scenario (simulation results)		Additional needed budget (simulation results−actual cumulative allocation)	
Year	Cumulative	Yearly	Cumulative	Yearly	Cumulative	Yearly
2010	620.8	—	620.8	—	—	—
2011	725.8	105.0	741.7	120.9	15.9	15.9
2012	800.5	74.7	961.5	219.8	161.0	145.1
2013	902.9	102.4	1,076.5	115.0	173.5	12.6
2014	1,008.6	105.7	1,159.4	82.9	150.8	(22.8)
2015	1,161.2	152.6	1,269.9	110.5	108.7	(42.0)
2016	1,295.7	134.5	1,269.9	—	(25.7)	(134.5)
2017	1,889.1	593.4	1,269.9	—	(619.2)	(593.4)

Note: All figures are in millions of dollars.

in the actual historical data in 2016 and 2017 is due to cost increases and the predicted inflation rate in these years.

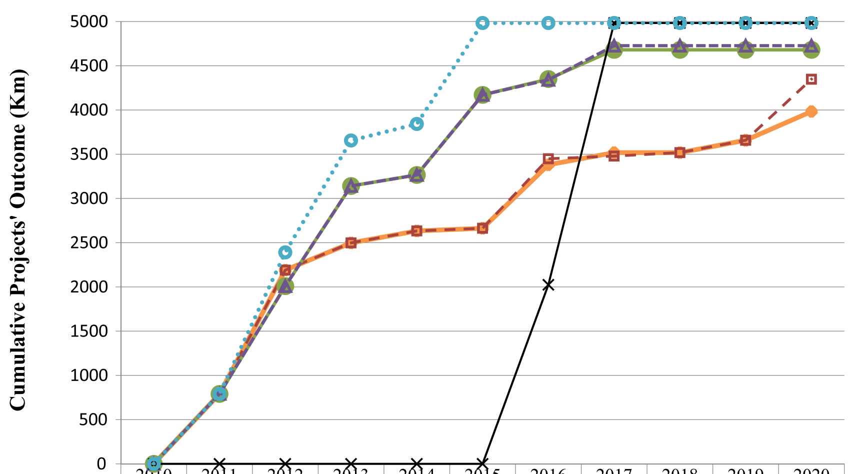
As quantified in Table 5, this portfolio could be completed with approximately 33% less money at the end of 2017. It shows that as a result of a cash shortage between 2011 and 2015, all 28 projects faced budget deficits, schedule delays, and increased costs.

Optimization Scenarios

The results of the simulated optimization scenarios (Table 4) are discussed in this section. In order to test the model's ability to simulate project outcomes and identify the best solution for allocating budget to achieve these outcomes, the projects' deliverables are used as outcomes because the historical data do not contain data about the projects' financial income. As the projects are transportation projects, their outcome is some type of transportation infrastructure, including railroads, expressways, roads, and so forth. Therefore, the common point of outcomes (i.e., kilometers) is inputted to the model as an outcome. The other outcome is the project itself, which is entered into the model as another outcome (i.e., 0 or 1).

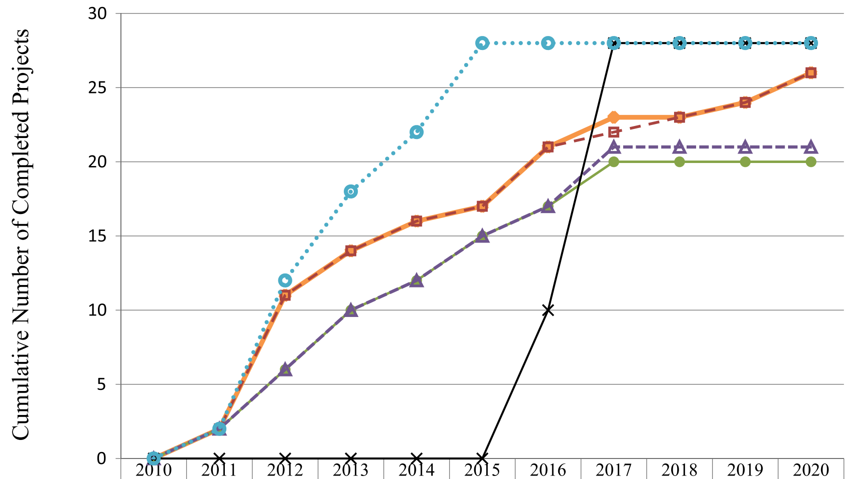
Fig. 4 shows the outcomes of the portfolio in the four optimization scenarios.

As illustrated in Fig. 4, the flow of outcomes is greatly improved in all four optimization scenarios compared to the historical data. Although there are more outcomes in 2017 based on the historical data (all projects have finished in 2016 and 2017), the early completion of some projects can help the portfolio manager finance other projects. According to the results shown in Fig. 4, the Maximum Production Rate–Improved scenario worked better than the other three scenarios. The outcome in this scenario is 4,727 km, while the outcome for the total portfolio is 4,983 km. The Minimum Remaining Cost and Minimum Next Time Budget scenarios, however, have better outcomes at the start of the projects (i.e., in 2012), but these outcomes are not as good at the end of the simulation as the Maximum Production Rate–Improved scenario due to allocation of budget to the projects with a higher production rate. While the Maximum Production Rate scenarios reach their highest outcomes in 2017, the first two scenarios reach their highest outcomes in 2020. In addition, the Maximum Production Rate–Improved scenario has the nearest results to the Progress as Planned scenario compared to other scenarios. When the Improved and non-improved Maximum Production Rate scenarios are compared, it is clear that the improvement method worked well and resulted in an additional 47 km of infrastructure.



	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Min Remaining Cost	0	791	2190	2498	2633	2663	3381	3518	3518	3658	3983
Min Next Time Budget	0	791	2190	2498	2633	2663	3449	3479	3518	3658	4348
Max Production Rate	0	791	2009	3141	3266	4171	4350	4680	4680	4680	4680
Max Prod. Rate – Improved	0	791	2009	3141	3266	4171	4341	4727	4727	4727	4727
Historical Data	0	0	0	0	0	0	2024	4983	4983	4983	4983
Progress As Planned	0	791	2390	3655	3842	4983	4983	4983	4983	4983	4983

Fig. 4. Outcomes flow of the portfolio in the four optimization scenarios



	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Min Remaining Cost	0	2	11	14	16	17	21	23	23	24	26
Min Next Time Budget	0	2	11	14	16	17	21	22	23	24	26
Max Production Rate	0	2	6	10	12	15	17	20	20	20	20
Max Prod. Rate – Improved	0	2	6	10	12	15	17	21	21	21	21
Historical Data	0	0	0	0	0	0	10	28	28	28	28
Progress As Planned	0	2	12	18	22	28	28	28	28	28	28

Fig. 5. Flow of project completion in the four optimization scenarios

Fig. 5 shows the flow of project completion in the four optimization scenarios.

The nearest optimization scenario to the Progress as Planned scenario is the Minimum Remaining Cost. In this optimization scenario, 23 and 26 projects will be completed in 2017 and 2020, respectively. It is interesting that considering the number of completed kilometers, the results of the Maximum Production Rate-Improved scenario are better than the other scenarios (Fig. 4), but the number of its completed projects is not as high as the other scenarios (Fig. 5). This situation is the result of the defined priorities and selection of projects based on the priorities. Although the number of completed projects in 2016 and 2017 is higher in the historical data, finishing projects earlier (as in the optimization scenarios) can help the organization have income from the completed projects.

Table 6 shows the kilometers of road infrastructure each project produces and their finish year in the four optimization scenarios. Although the sum of completed projects in the Minimum Remaining Cost and Minimum Next Time Budget scenarios are very similar in each year, the completed projects are different (i.e., Projects 11, 14, 15, 25, 27, and 28). Regarding the improved and nonimproved Maximum Production Rate scenarios, the finish year of Projects 19, 27, and 28 are different, which leads to different number of completed kilometers in 2016 and 2017. Comparing the Maximum Production Rate–Improved and Minimum Remaining Cost scenarios in 2013, it is clear that the two scenarios have allocated budget to different projects, which leads to more outcomes in the Maximum Production Rate–Improved scenario in that year (Fig. 4). Projects 5 and 7, which are selected for budget allocation in the Maximum Production Rate–Improved scenario in 2013, have more than 700 km more outcomes than projects selected by Minimum Remaining Cost scenario (i.e., Projects 6, 9, and 22).

Table 6. Finish Year of Each Project in the Four Optimization Scenarios

		Optimization scenarios			
Project number	Project products (km)	Minimum remaining cost	Minimum next time budget	Maximum production rate	Maximum production rate–improved
1	997	2012	2012	2012	2012
2	506	2011	2011	2011	2011
3	120	2012	2012	2012	2012
4	285	2011	2011	2011	2011
5	612	2016	2016	2013	2013
6	200	2013	2013	2017	2017
7	410	NF	NF	2013	2013
8	90	2014	2014	2014	2014
9	53	2013	2013	NF	NF
10	40	2012	2012	2012	2012
11	225	2020	NF	2015	2015
12	100	2020	2020	2017	2017
13	35	2012	2012	2014	2014
14	590	NF	2020	2015	2015
15	90	2017	2016	2015	2015
16	60	2012	2012	2013	2013
17	50	2012	2012	2013	2013
18	37	2016	2016	NF	NF
19	30	2015	2015	2017	2016
20	11	2012	2012	NF	NF
21	61	2012	2012	2012	2012
22	55	2013	2013	NF	NF
23	140	2019	2019	2016	2016
24	25	2012	2012	NF	NF
25	30	2016	2017	NF	NF
26	45	2014	2014	NF	NF
27	39	2016	2018	2016	2017
28	47	2017	2016	NF	2017
Total number of completed projects		26	26	20	21

Note: NF = not finished.

The four optimization scenarios produced better results than the actual historical data and identified better solutions for allocating budgets and completing every project on schedule. The results suggest, for example, that the organization could help finance in-progress projects using income from earlier completed projects. These optimization scenario simulations show that the model is capable of identifying the best solution for managing projects in the sample portfolio, and this information could help the organization make more-informed decisions for managing a portfolio of projects.

Discussion

A portfolio with 28 projects was simulated in order to test the agent-based simulation model. A Progress as Planned scenario and four optimization scenarios were simulated and the results were compared to historical data from a group of transportation infrastructure projects in Iran. In the first scenario, the amount of budget and cash flow needed to complete the projects according to the plan at the end of 2010 was examined using the Progress as Planned scenario. The projects were prioritized in the four optimization scenarios, and these scenarios were used to examine the budget allocation to each project of the portfolio.

The results of the simulation show that there are more cost-effective ways to manage the portfolio of projects. The amount of produced transportation infrastructure (i.e., number of completed kilometers) was considered the more important parameter, and the Maximum Production Rate-Improved optimization scenario produced better results than what has happened actually based on the historical data. The Minimum Remaining Cost scenario is the best optimization scenario if the number of completed projects is the most important factor to the portfolio manager. Although the optimization scenarios can be improved to identify better solutions, the four scenarios used in the model produced better results than the actual results of the Iranian projects. The information from this simulation could help portfolio managers with limited budgets complete all the projects in a portfolio by focusing on the most-important projects and using the income from the completed projects to finance other projects in the portfolio.

Some previous studies focused on multiproject resource allocation and finance-based scheduling and examined the activities of each project of the portfolio. The agent-based simulation model takes a broader view of the projects. It uses basic elements (i.e., cost and schedule plans) that are part of every construction project. As a result, this model can be used by organizations with a large number of projects that may have different scheduling software, work breakdown structure, and so forth.

Conclusions

This paper presents an agent-based simulation model developed to simulate the process of budget allocation and progress of projects in an owner's portfolio of construction projects. The proposed simulation model contributes to the portfolio management body of knowledge helping organizations optimize budget allocation scenarios and find an efficient scenario that could lead to earlier commissioned projects, reduced construction costs, and fewer construction delays. The model simulates the way projects behave according to the available budget, using the projects' cumulative planned physical progress and cumulative planned cash outflow. In this model, NPV formulas are used to calculate the effect of increased costs using inflation rates for each project. In addition, the outcomes of the projects (e.g., income and derivatives) and their growth are simulated in the model. As the results show, the model is able to optimize and allocate limited budgets based on priority of projects and identify the most efficient way to complete the projects. Every project has a maximum conceivable progress calculated using the ES of the project at every time step and it's IEF, a novel factor used to simulate the effect of a budget surplus on a project's progress.

The model is validated based on simulating the historical data of a portfolio of 36 projects. The results of the simulation were the same as the historical data when the exact IEFs were used in the model, and almost the same when the IEF was 1.0 for all 36 projects.

A portfolio of 28 projects, as a case portfolio, was simulated in the model in order to examine more cost-effective scenarios, and these scenarios identified organizational strategies that could improve the projects' outcomes when compared to the historical data. In particular, the use of an optimized scenario could result in the early completion of some projects. In this situation, income from the completed projects could be used to finance other projects.

The results of the agent-based simulation model discussed in this paper show that the model can help portfolio managers reduce their concerns about budget allocation and schedules. This model can be used to identify efficient scenarios for budget allocation that could lead to earlier commissioned projects and incomes and reduced costs caused by delayed projects.

Various scenarios (e.g., budget allocation, physical progress, or optimization scenarios) can be assessed using this model. This model can be used to identify the effect of budget allocation on projects' progress and the amount of money needed to meet scheduled targets. This model can also be used to identify the most effective way to rank projects in a portfolio and allocate budgets. The model is novel, and future research should investigate more areas in the construction process that concern portfolio managers.

References

Abd El-Razek, M., Bassioni, H., and Mobarak, A. (2008). "Causes of delay in building construction projects in Egypt." *J. Constr. Eng. Manage.*, 10.1061/(ASCE)0733-9364(2008)134:11(831), 831–841.

Aibinu, A., and Odeyinka, H. (2006). "Construction delays and their causative factors in Nigeria." *J. Constr. Eng. Manage.*, 10.1061/(ASCE)0733-9364(2006)132:7(667), 667–677.

Al-Kharashi, A., and Skitmore, M. (2009). "Causes of delays in Saudi Arabian public sector construction projects." *Constr. Manage. Econ.*, 27(1), 3–23.

Araúzo, J. A., Galán, J. M., Pajares, J., and López-Paredes, A. (2009). "Multi-agent technology for scheduling and control projects in multi-project environments. An auction based approach." *Intelligencia Artif.*, 13(42), 12–20.

Araúzo, J. A., Pajares, J., and Lopez-Paredes, A. (2010). "Simulating the dynamic scheduling of project portfolios." *Simul. Model. Pract. Theory*, 18(10), 1428–1441.

Assaf, S. A., and Al-Hejji, S. (2006). "Causes of delay in large construction projects." *Int. J. Project Manage.*, 24(4), 349–357.

Beşikci, U., Bilge, Ü., and Ulusoy, G. (2015). "Multi-mode resource constrained multi-project scheduling and resource portfolio problem." *Eur. J. Oper. Res.*, 240(1), 22–31.

CBC News. (2015). "Shell scraps Carmon Creek oilsands project over pipeline uncertainty." ⟨http://www.cbc.ca/news/canada/calgary/shell-carmon-creek-oilsands-pipeline-uncertainty-1.3292093⟩ (May 16, 2016).

Elazouni, A. (2009). "Heuristic method for multi-project finance-based scheduling." *Constr. Manage. Econ.*, 27(2), 199–211.

Elazouni, A., and Abido, M. (2011). "Multiobjective evolutionary finance-based scheduling: Individual projects within a portfolio." *Autom. Constr.*, 20(7), 755–766.

Frimpong, Y., Oluwoye, J., and Crawford, L. (2003). "Causes of delay and cost overruns in construction of groundwater projects in a developing countries; Ghana as a case study." *Int. J. Project Manage.*, 21(5), 321–326.

Gabriel, S., Ordóñez, J., and Faria, J. (2006). "Contingency planning in project selection using multiobjective optimization and chance constraints." *J. Infrastruct. Syst.*, 10.1061/(ASCE)1076-0342(2006)12:2(112), 112–120.

Gajpal, Y., and Elazouni, A. (2015). "Enhanced heuristic for finance-based scheduling of construction projects." *Constr. Manage. Econ.*, 33(7), 531–553.

Iamratanakul, S., Patanakul, P., and Milosevic, D. (2008). "Project portfolio selection: From past to present." *Proc., 2008 IEEE ICMIT*, IEEE, New York, 287–292.

International Energy Agency. (2009). "World energy outlook." Paris.

Kao, H. P., Wang, B., Dong, J., and Ku, K. C. (2006). "An event-driven approach with makespan/cost tradeoff analysis for project portfolio scheduling." *Comput. Ind.*, 57(5), 379–397.

Kazaz, A., Ulubeyli, S., and Tuncbilekli, N. A. (2012). "Causes of delays in construction projects in Turkey." *J. Civ. Eng. Manage.*, 18(3), 426–435.

Kishore, V., Abraham, D., and Sinfield, J. (2011). "Portfolio cash assessment using fuzzy systems theory." *J. Constr. Eng. Manage.*, 10.1061/(ASCE)CO.1943-7862.0000299, 333–343.

Larsen, J., Shen, G., Lindhard, S., and Brunoe, T. (2015). "Factors affecting schedule delay, cost overrun, and quality level in public construction projects." *J. Manage. Eng.*, 10.1061/(ASCE)ME.1943-5479.0000391, 04015032.

Lee, Y. H., Kumara, S. R., and Chatterjee, K. (2003). "Multiagent based dynamic resource scheduling for distributed multiple projects using a market mechanism." *J. Intell. Manuf.*, 14(5), 471–484.

Le-Hoai, L., Dai Lee, Y., and Lee, J. Y. (2008). "Delay and cost overruns in Vietnam large construction projects: A comparison with other selected countries." *KSCE J. Civ. Eng.*, 12(6), 367–377.

Lipke, W. (2013). "Earned schedule-ten years after." *PM World J.*, 3(1), 1–11.

Liu, S., and Wang, C. (2010). "Profit optimization for multiproject scheduling problems considering cash flow." *J. Constr. Eng. Manage.*, 10.1061/(ASCE)CO.1943-7862.0000235, 1268–1278.

Liu, S. S., and Wang, C. J. (2011). "Optimizing project selection and scheduling problems with time-dependent resource constraints." *Autom. Constr.*, 20(8), 1110–1119.

Mahamid, I., Bruland, A., and Dmaidi, N. (2012). "Causes of delay in road construction projects." *J. Manage. Eng.*, 10.1061/(ASCE)ME.1943-5479.0000096, 300–310.

Marzouk, M. M., and El-Rasas, T. I. (2014). "Analyzing delay causes in Egyptian construction projects." *J. Adv. Res.*, 5(1), 49–55.

Mostafavi, A., Abraham, D., and DeLaurentis, D. (2014). "Ex-ante policy analysis in civil infrastructure systems." *J. Comput. Civ. Eng.*, 10.1061/(ASCE)CP.1943-5487.0000350, A4014006.

Mostafavi, A., Abraham, D., DeLaurentis, D., Sinfield, J., Kandil, A., and Queiroz, C. (2016). "Agent-based simulation model for assessment of financing scenarios in highway transportation infrastructure systems." *J. Comput. Civ. Eng.*, 10.1061/(ASCE)CP.1943-5487.0000482, 04015012.

MPO (Management and Planning Organization of Iran). (2017). "Largest governmental establishments in Iran." ⟨http://www.mporg.ir⟩ (Jan. 26, 2017).

Navon, R. (1996). "Company-level cash-flow management." *J. Constr. Eng. Manage.*, 10.1061/(ASCE)0733-9364(1996)122:1(22), 22–29.

Salamon, T. (2011). *Design of agent-based models*, Eva & Tomas Bruckner Publishing, Repin, Czech Republic.

Sambasivan, M., and Soon, Y. W. (2007). "Causes and effects of delays in Malaysian construction industry." *Int. J. Project Manage.*, 25(5), 517–526.

Sargent, R. G. (2007). "Verification and validation of simulation models." *Proc., 2007 Winter Simulation Conf.*, IEEE, New York, 124–137.

Shakhsi-Niaei, M., Shiripour, M., and Iranmanesh, S. H. (2015). "Application of genetic and differential evolution algorithms on selecting portfolios of projects with consideration of interactions and budgetary segmentation." *Int. J. Oper. Res.*, 22(1), 106–128.

Shehu, Z., Endut, I. R., and Akintoye, A. (2014). "Factors contributing to project time and hence cost overrun in the Malaysian construction industry." *J. Financial Manage. Property Constr.*, 19(1), 55–75.

Taghaddos, H., AbouRizk, S., Mohamed, Y., and Hermann, U. (2012). "Simulation-based auction protocol for resource scheduling problems." *J. Constr. Eng. Manage.*, 10.1061/(ASCE)CO.1943-7862.0000399, 31–42.

Taghaddos, H., Hermann, U., AbouRizk, S., and Mohamed, Y. (2014). "Simulation-based multiagent approach for scheduling modular construction." *J. Comput. Civ. Eng.*, 10.1061/(ASCE)CP.1943-5487.0000262, 263–274.

Tavana, M., Keramatpour, M., Santos-Arteaga, F. J., and Ghorbaniane, E. (2015). "A fuzzy hybrid project portfolio selection method using data envelopment analysis, TOPSIS and integer programming." *Exp. Syst. Appl.*, 42(22), 8432–8444.

Touran, A. (2010). "Probabilistic approach for budgeting in portfolio of projects." *J. Constr. Eng. Manage.*, 10.1061/(ASCE)CO.1943-7862.0000128, 361–366.

van Dam, K. H., Nikolic, I., and Lukszo, Z., eds. (2012). *Agent-based modelling of socio-technical systems*, Springer Science & Business Media, New York.

Wood Mackenzie. (2016). "Deferred upstream projects tally reaches 68." ⟨http://www.woodmac.com/media-centre/12530462⟩ (May 16, 2016).