A MULTI-AGENT MODEL OF TYPICAL COMPETITIVE BIDDING PROCESS IN CONSTRUCTION

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ABSTRACT
At some point in the lifetime of a construction contractor company, it has to engage in a competitive bidding process as a means of acquiring work. The competitiveness of its bid ultimately determines whether or not it is awarded the project. However, prior to this, the company has to make a decision on whether or not to bid on the project. Making this decision is usually challenging, even for experienced practitioners. Moreover, generating a competitive bid is a non-trivial process. These challenges are attributed to the stochasticity and dynamics that surround the bidding process in the construction industry. A Multi-Agent Model is proposed in this paper that emulates the typical bidding process and environment. A design for the model is first presented then details on how it was implemented with AnyLogic simulation system are explained. An experiment is run to demonstrate how the model can be used.

Keywords: competitive bidding, multi-agent model, AnyLogic, construction industry

1. INTRODUCTION
Competiveness in the construction domain is a phenomenon that is broad and very complex. It can be assessed from different perspectives and at different levels: by the owners, the users of the facilities built by the companies, or by the companies themselves. Competition can also be studied at an industry level or at an individual company level. At each of these levels, issues are different, but competition at each level is inter-dependent and equally important for the benefit of individual companies and the industry at large.

Some scholars argue for a top-bottom approach (i.e. solve industry problems first and then address individual companies) in tackling competitiveness, while others advocate a bottom-top approach. The authors propose the adaptation of a holistic concurrent approach that deals with prevailing issues in a systematic fashion at both levels. Although the sequence in which competitiveness problems are addressed at the two different levels is important, it is not the focus of this study and will not be discussed further. An approach that can be adopted to experiment with competitiveness issues at an individual company level is presented.

Various methods have been proposed and used in the past to manage the performance of a company. Examples include the Balanced Score Card (BSC) (Kaplan and Norton 1996), Key Performance Indicators (KPIs), and EFQM Excellence Model (European Foundation for Quality Management - EFQM 1999). These techniques have a number of pitfalls: 1) they can only tell what might have gone wrong in the past but give no insights into how things might turn out in the future if changes are implemented; 2) some are self-assessing, so they don't compare performance to competitors in the industry or globally; 3) in some techniques, the perspective from which performance is assessed is very limited and certain key measures are left out; and 4) they are not automated, and hence, are cumbersome to use.

The authors propose a simulation-based performance management approach that addresses these problems. This simulation-based approach is comprised of a number of components, one of which is an Agent-Based Model (ABM). The main focus in this paper is to discuss the design and specifications of the ABM for bidding in the construction industry, and its implementation in AnyLogic simulation system. The verification and validation work for this model was successfully done but is not elaborated due to space constraints; highlights of how verification and validation processes were carried out are presented.

The developed model can be used in practice in various ways. First, it can be used to guide individuals in-charge of running operations at a construction company on workload planning issues to achieve a balance between running their companies over capacity and below capacity. The model can also be used to guide practitioners on which type of bidding strategies to adopt to ensure that they match that capacity. The simulation model can be extended to gain insights into the type of projects a construction company should go after in order to match its internal competencies and capacity.

1.1 Simulation-Based Approach for Contractor Performance Management

In order to objectively assess an individual company's overall performance, the entire life cycle of the business operations at the company must be considered. This involves examining the process through which the company competes for work and how it executes the work that it has been awarded. The former is referred to as the front-end of the company's business operations, while the latter refers to the tail-end of its business operations. To develop a simulation model that can be used to manage a company's performance, the company's core processes must be abstracted accurately. Figure 1 summarizes a concept model proposed for implementing the simulation model. This model illustrates the components envisaged as part of the developed system. It also details the communication protocols to take place between these components.

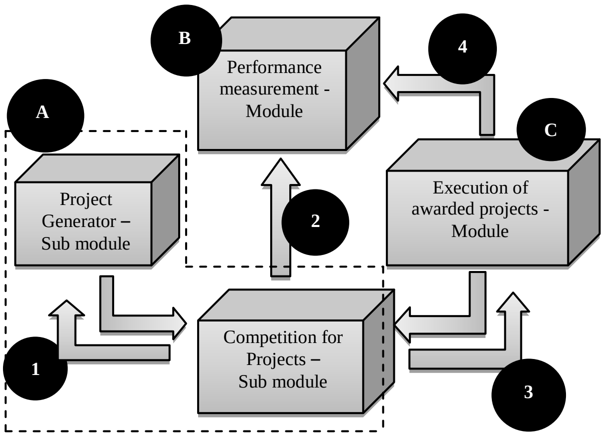

Figure 1: Layout of Simulation-Based Performance System Components/Modules

The letters "A," "B" and "C" represent the modules that exist in the company simulation system. "A" represents a "Tendering" Module. "B" and "C" represent the "Performance Measurement" and "Operations" Modules, respectively. The Tendering Module models project arrivals and the competition for these projects by companies operating within a virtual construction industry. The Operations Module processes projects awarded to the "Company of Interest." The Performance Measurement Module collects observations on performance measures from all other modules and generates an overall performance rating for the company at the end of the simulation. The numbers 1-4 represent the communication that takes place between the modules during the simulation: "1" represents bid submissions and companies being notified of the winning bid, "2" represents the collection of statistics/observations on tendering performance as the simulation progresses, "3" represents communication between the Operations Module of the Company of Interest to the user and the Tendering Module. Information transferred includes data on prevailing conditions in the Operations Module at project arrival so that this can aide with the Company of Interest's bid/no-bid decision, and it represents notification of the Operations Module of projects that have been awarded to the Company of Interest and that need to be processed. The number 4 represents the collection of performance measures (e.g. quality, production efficiency, safety, cost slippage, schedule slippage, etc.) as the simulation advances.

Figure 2 shows details for each of the components and how they interact with each other. This figure also shows the simulation method intended for implementation of each component and the integration of these components into a distributed simulation environment using a synthetic environment, COnstruction SYnthetic Environment (COSYE) (AbouRizk and Hague 2009). The Tendering Module is implemented using an Agent-Based approach while the Operations and Performance Modules are implemented using a discrete event simulation (DES) approach.

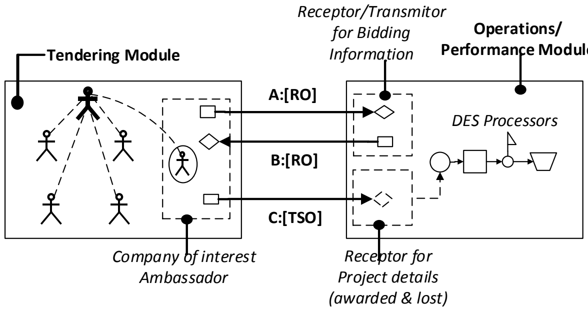

Figure 2: Modeling Paradigms Used to Implement Simulation-Based Performance System

Presenting design and implementation details of the entire company simulation system is not possible in one paper, so only one component of the system will be covered: the system that models the front-end of the business. This front-end system models a typical competitive bidding process involving a finite number of companies operating in a virtual industry.

1.2 Competitive Bidding in Construction

Bidding is an offer (often competitive) of a price that one is willing to pay for something or for a demand that something be done (Oxford Press 2014). This process is one through which most work/projects get awarded to contractor companies within the construction domain. It is one of those processes that are least understood by members of the construction domain in both academia and practice, hence the vast amount of research that has been done on the subject. Two threads of research have emerged in the subject of competitive bidding. The first attempted to propose models that emulate the bid/no bid decision that companies undertake on a project-by-project basis. The second thread strived to generate ways of enhancing the chance of a bidder being awarded a project. In principle, this thread delivered research work that can be further sub-categorized into: those that estimated the chance of winning a bidding context and those that proposed ways of estimating the markup to carry in a bid to guarantee success.

1.2.1 Bid/No-Bid Decision

When a company encounters a potential project, it will perform a formal or informal evaluation to decide whether or not to pursue that project. This decision is not a trivial one and for this reason has resulted in a number of research studies that have attempted to propose algorithms that can be used to guide this decision making process. Examples of these studies include work done by Egemen and Mohamed (2007; 2008), Bagies and Fortune (2006), Lin and Chen (2004), and El-Mashaleh (2010). Although the approaches proposed in these studies are viable, they pose application limitations, especially due to the number of input factors required to make the decision. Moreoever, implementing them in a computer-based simulated environment is likely to be quite challenging as a result of the static nature of some of the variables proposed for use in the decision making process.

Consequently, this study adopted a more robust and easy-to-apply approach for the bid/no-bid decision. It was based on a comparison of project attributes with company torlerance levels for these attributes (i.e. internal company policies) and available production capacity at the time a potential project opportunity is realized.

1.2.2 Winning Probability and Markup Generation Algorithms

Research done in the area of competitive bidding along the second thread was most likely started in the 1950s by Lawrence Friedman when he first proposed a probabilistic approach for estimating the chance of a competitor winning a bid given that their bid price is set to a specified value (Friedman 1956). Since that time, other mathematical models for tackling the same problem have emerged. Some of these have been for Friedman's approach, while others have been against it. There are numerous examples of these studies published in journal and conference papers (Benjamin 1972, Dixie 1974, Gates 1967, Morin and Clough 1969, Rosenshine 1972, Fuerst 1976, Wade and Harris 1976, Griffis 1992, Ioannou 1988).

It is worth noting that from a practical applications perspective, most of these studies have major pitfalls. For example, they heavily relied on an assumption that the analyst has a good understanding of their competitor's behavior. In other words, the analyst would need to know how their competitors bid on past competitions and assume that they would stick to the trend. Bid price data is not always accessible and contractors change their behavior from time-to-time depending on the conditions/situation. This makes these models limited from an applications stand-point.

There have been studies done within the construction domain that endeavored to overcome this challenge by attempting to predict the markup to carry in a bid to guarantee success. Examples include work done by Hegazy and Moselhi (1994), Dozzi, AbouRizk, and Schroeder (1996), Marzouk (2002), Li (1996), Fayek (1998), and Cui and Hastak (2006). The techniques used in these studies included fuzzy logic, artificial neural networks, genetic algorithms, system dynamics, utility theory, etc.

These studies overcame the problems of the lack of past bidding data with the exception of the artificial neural network based algorithms. However, implementing these in a computer-based simulation environment would result in a model that is cumbersome to develop and use as a result of the vast number of input variables required to generate an output. In addition, some factors proposed by the authors are static in nature and in some cases don't represent the reality in bidding practices. As a result, a Monte Carlo simulation-based algorithm was utilized in this study. The approach was first proposed by Winston in 2001 in a book that he wrote on Simulation Modeling Using @Risk (Winston 2001). We modified and extended his model to closely match reality and to suit our development work.

2. MODELING APPROACH ADOPTED: ABM

Different methods exist for abstracting and analyzing systems with simulation, but the ultimate choice of method is guided by the nature of the problem at hand, presence of sufficient knowledge and skills in the method and access to a simulation system that supports the method.

The problem in this study is best analyzed using simulation methods because it is stochastic and dynamic in nature. The stochastic nature arises from the fact that output for the system will vary even if the input is the same each time the system is experimented with. The dynamic nature is due to the fact that in each run, future events are affected by past and current events.

In the bidding problem, time between new project arrivals varies stochastically. This stochastic behavior is in part attributed to variations in investment practices amongst owners within a given construction industry. The stochastic behavior is also applicable to the attributes of these projects e.g. cost, duration, complexity, etc. The decision of companies to bid these projects is also stochastic in nature. In fact, this decision has dynamic aspects to it to some extent. This is because a company's decision to bid or not to bid on a project will depend on what happened in the recent past i.e. was it awarded projects or not and how many, and what is happening at the current time i.e. what types of projects are up for bid, what are its internal policies, etc. These facts make the problem suitable for modeling using a simulation-based approach.

Given that the bidding problem comprises a number of distributed constructs such as the community of owners and the construction contractor companies, which operate in an autonomous or semi-autonomous fashion within the same environment, i.e. the construction industry, the problem lends itself to an ABM paradigm. This assertion is made because the construction industry can be mapped to a virtual environment within which agents thrive. The autonomous self-executing constructs (community of owners and construction contractor companies) can be directly mapped to agents that encapsulate their corresponding behavior. Moreover, the ABM would be developed using simple rules which would result in more complex emergent behavior as agents interact; something that is evident in the course of competition for projects by companies in the construction industry. An ABM paradigm was therefore chosen for use in modeling this problem.

The community of owners is represented by a bid manager agent. This agent is modelled as a singleton. Companies are modelled using three types of agents: "small company agent," "medium company agent" and "large company agent."

2.1. ABM Design and Specifications

There are numerous tools available for the design and specification of ABMs. It is usually advised that the modeler undertake a comprehensive design process before they embark on developing their ABM, regardless of whether it is a simple or complex one. In this way, the designs can be assessed for accuracy (validity), which in turn guarantees the generation of reliable models. In this study, design aides used include a block diagram and a sequence diagram.

2.1.1 UML Class Diagram for the ABM

A block diagram summarizes the constructs in the real world system that is being abstracted which map onto classes and objects in the model. It also documents the attributes and operations for these constructs. The relationship between these classes is also documented. This concept is adopted from a Universal Markup Language (UML). Figure 3 summarizes the block diagram for the tendering module.

The Figure summarizes the agents (Company and Bid Manager Agent) in the model along with the container in which these agents thrive (Main Agent). A composition relationship exists between the Company Agent and the Main Agent and the Bid Manager Agent and the Main Agent. The diagram also documents a class referred to as a "project entity," which wraps information about a specific project under tender. Instances of this class are passed around between the Bid Manager Agent and Company Agents in the course of their communication. An association relationship exists between project entity and the Bid Manager Agent and project entity and the Company Agents.

2.1.2 Sequence Diagram for the ABM

Communication between agents is an essential part of ABM. It is advised to design the entire communication protocol between agents for every ABM before development work commences. Sequence diagrams are typically used to design and specify the communication protocols existing between agents in a planned model. Communicating agents could belong to the same type or may be of different types. In this model, it was envisaged that communication would take place between Bid Manager Agent and Company Agents. No communication was to take place between Company Agents. This was done deliberately to avoid situations identical to collusion which conflict bidding ethics and practices in a practical bidding setting. The sequence diagram designed for this communication is presented in Figure 4.

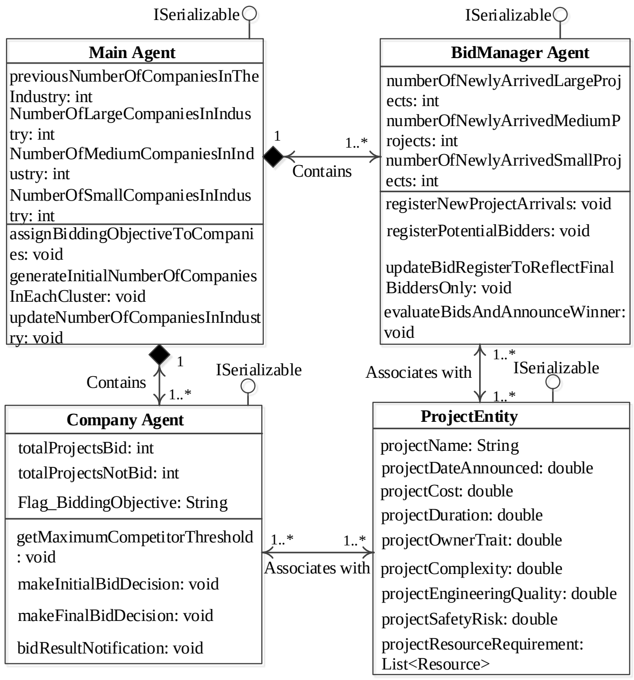

Figure 3: A UML Class Diagram for the Bidding ABM

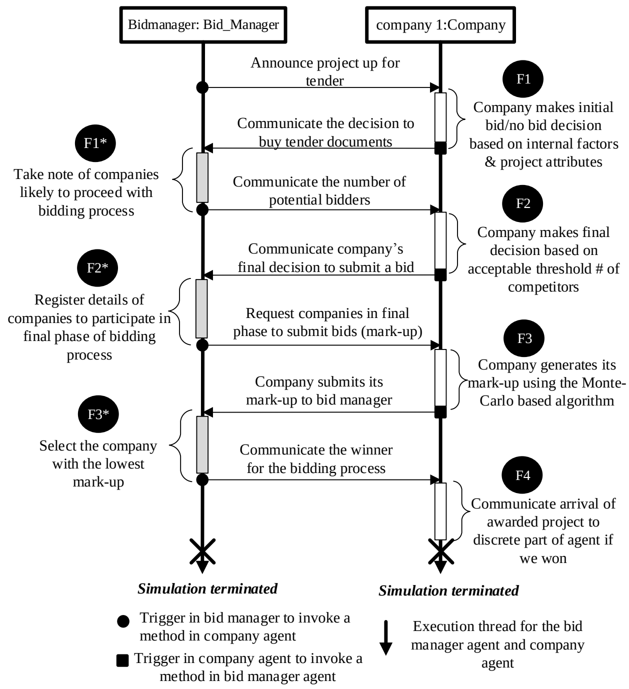

Figure 4: Sequence Diagram Detailing Communication between Bid Manager Agent and Company Agents

For simplicity, the company agents are represented as one block. Only one cycle of communication that is typical of information exchanged between Bid Manager

Agent and Company Agents is presented in this figure. The entire cycle of communication between Bid Manager Agent and Company Agents is triggered by the arrival of a project into the construction industry and terminated when the project is awarded to a winning bidder. There is no apparent advancement in simulation time in the course of communication. Furthermore, the communication between Bid Manager Agent and Company Agents is asynchronous: either agent cannot send two messages in sequence without hearing back from the other agent. The design specifications summarized in this sequence diagram served as a basis for implementing methods within each respective agent. The methods in the Bid Manager facilitate it to announce newly arrived projects to all Company Agents, receive bids from companies that decide to bid, evaluate them and announce the winner. The Company Agent on the other hand has methods that enable it to decide which projects to bid on, generate a bid price for those that it chooses to bid and pass awarded projects to its discrete event process flow model for execution.

2.2 Agents within the Competitive Bidding Model

When a multi-agent based approach is used to abstract and analyze a system, constructs within that system that are autonomous, have intelligence and a memory, are represented as agents. In this model, the construction industry (Main Agent) and companies (small, medium and large) are represented as agents. The community of owners is also represented as an agent i.e. the Bid Manager.

2.2.1 Bid Manager Agent

The designs for the Bid Manager and all other agents were implemented within the AnyLogic simulation system. The term "Bid Manager" is one that was coined in this study to refer to a construct that is used in the model to represent the community of owners and the role that they play within a typical construction industry. The owners are the party that primarily invests in construction projects. The owners are also in charge of the process required to select a contractor to perform the project—the bidding process.

To model the dynamics of projects arriving in a construction industry, the Bid Manager Agent samples the project arrival events from a statistical distribution. The attributes of these projects also get assigned to a project after they are sampled from statistical distributions. Large, medium and small projects are generated independently. Figure 5 shows the modeling elements (functions) required to achieve the Bid Manager Agent's behavior.

An event modeling element is embedded within the Bid Manager Agent (see Figure 6) that schedules the arrivals of new large projects by drawing inter-arrival times from a predefined uniform distribution. The parameters in Figure 6 are used to set values with which beta distributions are constructed for generating cost and duration attributes for new projects.

Figure 7 shows the controls embedded within the Bid Manager Agent for defining the resource requirements and setting other project attributes. The controls presented in Figures 6 and 7 are those dedicated to modeling new large projects only. Similar controls exist in this agent for small and medium size projects.

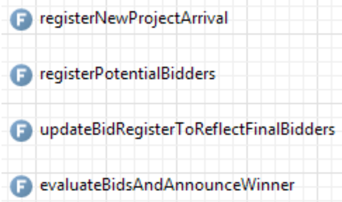

Figure 5: Functions Embedded in the Bid Manager

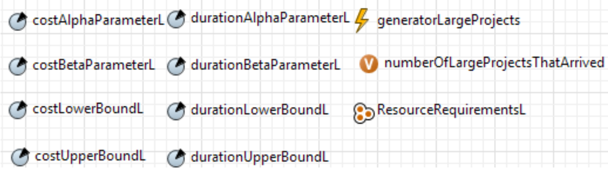

Figure 6: An Event Element and Parameters Used to Model New Large Projects

Figure 7: Controls for Modeling Project Resource Requirements and Other Project Attributes

2.2.2 Company Agents

Companies are modeled as autonomous intelligent agents that can decide on whether or not to bid on a project, generate a competitive bid if they decide to bid and process projects awarded to them. It was assumed that construction industries are comprised of small, medium and large companies.

Each of these company categories were modeled as an autonomous agent with unique attributes and behaviors. Company Agents are notified by the Bid Manager Agent when a project arrives in the virtual construction industry. The Company Agents then make internal decisions autonomously on whether or not to bid an announced project. If it decides to bid on the project, the Agent makes use of another algorithm to generate a bid price that it submits to the Bid Manager. Once a project is awarded to a company, it is passed on to the discrete event simulation model embedded within the Agent for processing. Figure 8 summarizes the methods embedded within each Company Agent to exhibit the above behavior. These methods are consistent with those presented in the sequence diagram in Figure 4. These screen shots are taken from the model developed within AnyLogic simulation system.

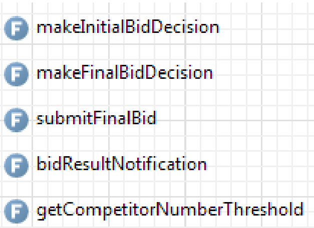

Figure 8: Functions Embedded in Each Company Agent

2.2.2.1 The Bid Decision Making Process in Company Agents

The decision on whether or not to bid on a specific project is implemented using a hierarchical approach. The first phase is referred to as an initial bid decision phase and the last is referred to as a final bid decision phase. The initial bid decision is made on a set of criteria that include the trait of the project owner, project complexity rating, project safety risk ratings, engineering quality rating of the project, and availability of sufficient capacity to process the project.

In order for a Company Agent to decide to bid on a project, the attributes of that project, with respect to each of the above mentioned criteria, need to be within the tolerance limits predefined by the company. The final decision regarding whether the Company Agent will proceed to submit a final bid is based on whether the anticipated number of final bidders exceeds the company's set limit for the maximum number of bidders it is willing to compete against.

The screen shot presented in Figure 9 summarizes the parameters in the Company Agent that store the threshold values for its tolerances for each of the different project attributes. The first four parameters represent the definition of a company's production capacity.

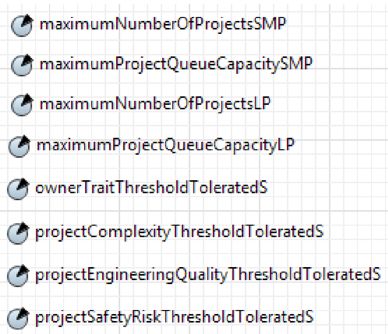

Figure 9: Parameters Embedded in Each Company Agent

2.2.2.2 Processing Projects Awarded to Company Agents

When a project is awarded to a Company Agent, it passes it on to the appropriate discrete event process flow model for execution. The models are set up to be resource constrained. Projects are modelled as entities (i.e. flow units). Projects granted their requested resources are processed in a cyclic fashion on a day-by-day basis. After it has been processed for its duration, it releases the resource and is destroyed because it is considered to have been fully processed. Figure 10 presents the DES models used for processing small and medium size projects (top layout) and large projects (bottom layout).

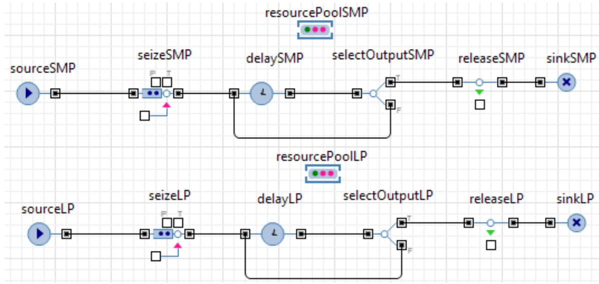

Figure 10: Discrete Event Models Embedded Within Each Company Agent

2.4 Construction Industry (Main) Agent

The Main Agent represents the top/global level of the model where all Agents thrive (Figure 11) in the AnyLogic simulation system.

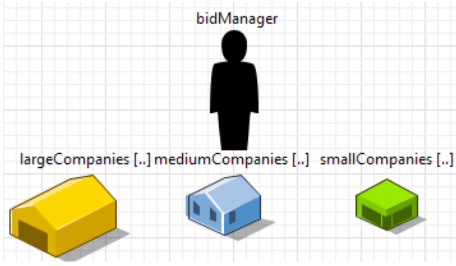

Figure 11: Agents Embedded within the Main Agent i.e. at the Top Level of the Model

Other controls and parameters are set up at this level. These are used, for example, for defining the total number of Company Agents in the industry and within each category. Other controls enable assigning bidding strategies to companies and their tolerance levels for different types of projects.

3. MODEL VERIFICATION AND VALIDATION

Verification and validation of the model developed in this paper was done in a fashion similar to that employed in most standard simulation models: trace output was generated in the console of the AnyLogic simulation system.

The trace captures details summarizing the chronology of simulation events processed during the tendering cycle for one project. The details match the logic that was intended to be simulated, hence, the model behavior was verified. For example, bid decisions are made soon after a project has been announced in the market, bid price generation follows that and then the project is awarded to the least bidder.

Validation work was also done which involved sensitivity analysis of the different model parameters. The simulated experiments on sentivity analysis involved varying the number of projects generated within a specific period, varying the type of projects generated, varying the number of competitors, their bidding strategies and that of the company of interest. The experiments that involved these tests confirmed that the model was valid. Details of this work are not presented within this paper because of space constraints.

4. EXPERIMENTAL SETUP

The objective of running this experiment is to determine a number of issues: 1) the number of projects that arrived in the industry within the simulated period; 2) the distribution of those projects i.e. relative number of small, medium size and large projects; 3) the quality of projects that arrived in the industry with respect to owner trait, complexity, engineering quality and project safety risks; 4) the distribution/allocation of those projects to companies in the industry i.e. proportions that went to small, medium and large companies; and 5) the reason(s) for the distribution/allocation of projects to these companies in the industry.

In order to set up and run the experiment, hypothetical values were chosen for the different model parameters and set prior to simulation. First, values used to model the rate of project arrivals are specified. Then distributions used to generate the attributes for each generated project are summarized. Finally, the tolerances that guide Companies' behavior in making decisions on which projects to bid or not are defined. The values for these parameters are specified as statistical distributions to ensure that there is variation in project instances and decisions made by companies, which is in-line with this phenomenon in a real-life setting.

4.1 Rationale for Project Attribute Selection

When setting up the parameters that will be used to model the dynamics of projects arriving in the industry and the subsequent execution of these projects, attributes were selected so the model closely emulates the true behavior in the industry. From the perspective of work/projects, i.e. keeping all other conditions at a company constant and assuming that they are favorable, the dynamics of projects can still affect the performance of a company in two respects: 1) a company may start to perform badly when it starts suffering from extreme work conditions i.e. too little or too much work; and 2) even when a company strikes the right balance in its workload, its performance may still be affected by the type of work it acquired. If the work is generally bad (i.e. has bad owner traits, is poorly engineered, too complex or has high safety risks), the company may be more susceptible to failure.

4.2 Model Setup and Industry Details

The simulation model was set up to run for 1,000 days. After this time was reached, the model terminated. The unit of measure of time used in the model was days. A total of 20 Company Agents were created; 50% of these were large, 30% medium size and 20% were small companies. Values used to generate the attributes of newly created projects are summarized in Table 1.

Table 1: Model Inputs – Attributes for New Projects

Parameter	Unit of Measure	Small Projects	Med. Projects	Large Projects
Inter-arrivals	Days	14~100	90~180	180~540
Cost	Million $	10~100	100~300	250~1000
Duration	Days	300~540	450~750	600~1200
Owner Trait	Scale (0-1)	0.00~0.50	0.40~0.80	0.75~1.00
Complexity	Scale (0-1)	0.00~0.40	0.25~0.75	0.65~1.00
Engineering Quality	Scale (0-1)	0.80~1.00	0.25~0.85	0.00~0.30
Safety Risks	Scale (0-1)	0.00~0.70	0.35~0.85	0.70~1.00

4.4 Company Project Tolerances

Companies have internal policies regarding the type of projects they will bid and work on. These policies are referred to as the company's tolerances to specific types of projects. These tolerances are all inline attributes related to projects, including owner trait, complexity, engineering quality, and safety risks. The ranges of values for each of these criteria are summarized in Table 2. Each of these parameters/criteria is discussed in detail from the perspective of company tolerances for projects.

Table 2: Model Inputs – Company Tolerances for Projects

Parameter	Unit of Measure	Company Size		
		Small	Medium	Large
Owner Trait	Scale (0-1)	0.00~1.00	0.40~1.00	0.80~1.00
Complexity	Scale (0-1)	0.00~0.40	0.00~0.85	0.00~1.00
Engineering Quality	Scale (0-1)	0.15~1.00	0.30~1.00	0.60~1.00
Safety Risks	Scale (0-1)	0.00~0.50	0.00~0.75	0.00~0.90

Owner trait indicates the degree of unnecessary interruptions to the contractor's work rhythm caused by the owner during project execution. This property is thought to affect the contractor's morale and in turn their productivity. Informal discussions with experienced practitioners in the construction industry revealed that this attribute plays a significant role when a contractor is deciding whether or not to bid on a project.

The extent to which a project is engineered prior to construction and the quality of the engineering affect the production efficiencies during project execution. This attribute also affects the quality of work done i.e. the amount of rework experienced in a project. The quality of engineering for a project under tender can affect a contractor's decision on whether or not to bid on the project.

The complexity of a project along with the potential safety risks associated with executing a project can also affect a contractor's decision on whether or not to bid on a project. These are defined using scales ranging from 0 to 1. For the complexity attribute, a value of 0 indicates no complexity, while a value of 1.0 indicates an extremely complex project. A value of 0 for project safety risk indicates low likelihood of safety incidents while a value of 1.0 indicates a very high likelihood of safety incidents.

High values for engineering quality and owner trait for any given project are good, while low values are bad. On the other hand, high values for complexity and safety risk are bad, while low values are good.

The semantics discussed above apply to the demand side of projects. On the supply side, issues to do with company tolerances with respect to each of these attributes are dealt with. Rating scales identical to those used for the projects are used for each attribute (from 0 to 1). A low value (0) indicates that the company has an extremely low tolerance for the attribute, while a value of 1.0 indicates a very high tolerance for the negative extreme of the attribute.

Both the demand and supply side values for these parameters influence a company's decision on bidding on a project-by-project basis. Under normal circumstances, a company will decide to proceed to bid on a project based on the engineering quality and owner trait criteria, when the ratings of these attributes for the project are higher than the tolerances set by the company. On the other hand, the company will proceed to bid when the ratings for the project, with respect to complexity and safety risks, are lower than the tolerance levels for the company.

At the start of the simulation, Company Agents are created by the Main Agent. Each Company Agent is assigned tolerance values through a process that involves randomly sampling from a statistical distribution. A uniform distribution is constructed from the ranges provided in Table 1 and used to sample the values for ratings assigned to the company. This means that companies will end up having different tolerance levels for each of the criteria, something that is evident in practice.

5. SIMULATION RESULTS

Results generated by the simulation model are displayed in charts to ease their interpretation. The results indicate a number of things: the number of projects generated, the quality of these projects and who these projects were awarded to, as well as the reasons why they were awarded in that fashion.

5.1 Projects Generated and Their Attributes

During the simulated period, a total of 11 projects are generated and passed into the virtual construction industry (see Figure 12).

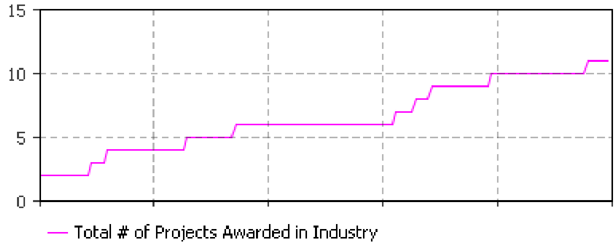

Figure 12: Total Number of New Projects Generated During the Simulated Period

For projects generated, the large size projects had a higher average owner trait, and higher complexity relative to medium size and small projects. The large projects also had the poorest engineering quality and the highest project safety risks compared to medium and small projects. These trends are evident in Figures 13, 14, 15, and 16. These results are consistent with the input data summarized in Table 1 and used in the model.

The trends indicate that small projects have extremely good attributes with the exception of the owner trait. Medium size projects on the other hand possess moderate attributes across the board. All attributes of large projects are bad with the exception of the owner trait. This implies that a company that is inclined to acquire more large projects than small ones would be more susceptible to failure. Values indicated are averages for the projects generated during the simulated period of 1,000 days.

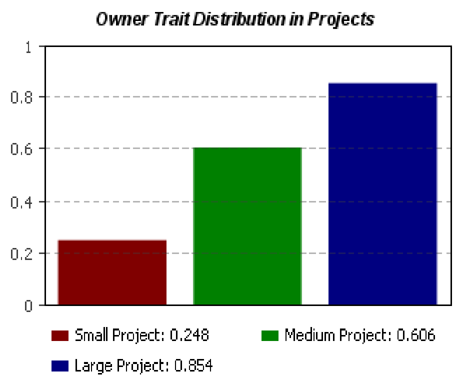

Figure 13: Owner Trait Attributes of Generated Projects

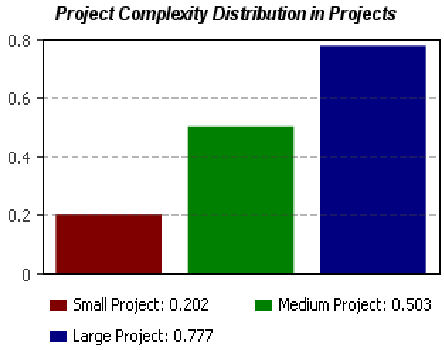

Figure 14: Complexity Attributes of Generated Projects

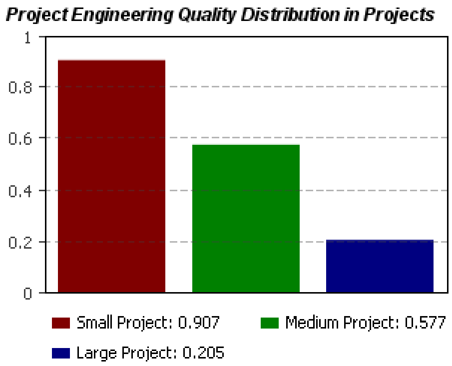

Figure 15: Project Engineering Quality Attributes of Generated Projects

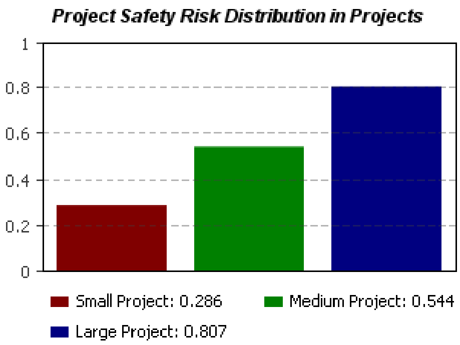

Figure 16: Project Safety Risk Attributes of Generated Projects

5.2 Results Summary: Projects Allocated to the Companies

Figure 17 indicates that large companies were awarded a total of 3 projects, medium size companies, 6 projects, and small companies, 2 projects. Despite this small number of projects, the projects awarded to large companies had the highest total values $1.492 billion. $754 million and $124 million worth of projects were awarded to the medium and small companies, respectively. Results displayed in Figure 17 indicates that the bulk of the projects were awarded to medium size companies. Small companies were awarded the least number of projects.

Figure 18 indicates that even though large companies were awarded an intermediate number of projects, the total worth of these projects was the highest ($1.5 billion). Small companies were awarded the least number of projects and projects that had the least total value.

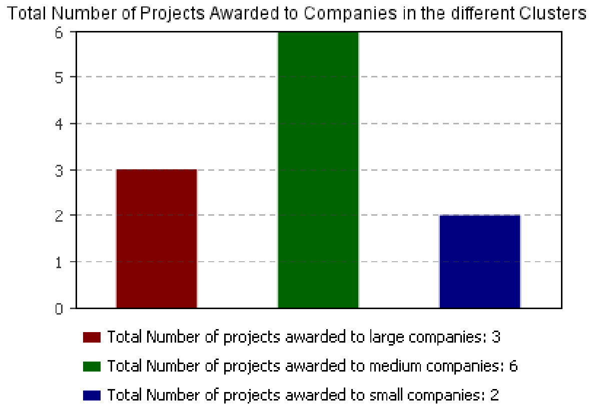

Figure 17: Total Number of Projects Awarded

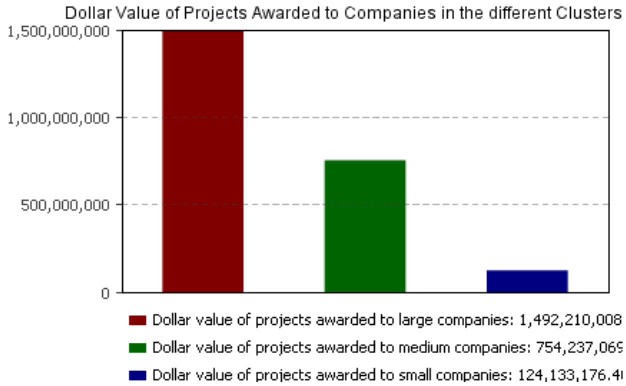

Figure 18: Total Value of Projects Awarded

5.3 Reasons for Companies Losing Project Bids

The model tracks the projects that Company Agents either don't bid on or that they bid on and lose. The reasons behind these occurrences are also tracked and reported in the form of pie charts for small companies, medium size companies and large companies, separately (see Figure 19 for an example – small companies). These reasons include insufficient production capacity, competitor number exceeded threshold, bid was not competitive, owner trait very bad, projects too complex, project engineering quality poor, and project safety risks too high.

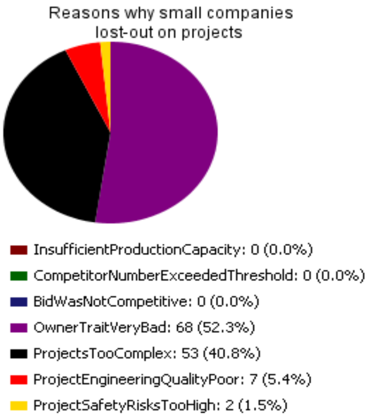

Figure 19: Why Small Companies Lost Projects

To a large extent, all companies opted not to bid on specific projects mainly because the trait of the project owner was bad. The project owner trait in these cases was worse than the tolerances that were predefined by the company. There were no cases in which the companies could not bid on a project due to insufficient production capacity.

6. CONCLUSIONS

This paper discussed details of work that was done on the abstraction and implementation of a typical bidding process on a computer using an ABM paradigm in AnyLogic simulation system. The paper also documented the process of abstracting, designing and implementing an ABM that can be useful when analyzing problems in the construction domain.

An experiment set up and run using the model was outlined to show how the model can be put to practical use. The model can be put to various uses. From an owner's perspective, the model can serve as a tool to guide when to invest in projects based on the available company resources in the industry. From a construction contractor's perspective, the model can be used to gain insights into the amount and type of work to go after. These insights can then be used to devise appropriate strategies that ensure that a reasonable work balance is achieved which guarantees good company performance.

In addition, this model can be used as a training tool in both industry and academic institutions to train novices on how to set up internal policies at a company to bid on projects as part of a work acquisition process. The model can also be used as a module within a bigger simulation system to model company performance related issues.

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