Modelling the Dynamics of Safety on Construction Projects: an Undiscovered Rework Perspective

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Abstract

Globally, the construction industry has a poor safety record. This paper is on understanding and modelling the dynamics of safety on construction projects. The methodology adopted was case-study research and system dynamics modelling of a hotel building complex in Wakiso District, Uganda. The case-study project recorded a major accident during the construction phase leading to death of eleven people and injuries of twenty six others. This accident was a result of design errors and poor construction practices. The scope of the developed safety model is restricted to the effects of undiscovered rework, schedule pressure and cost pressure on accident frequency. In this paper, the occurrence of accidents is hypothesised to depend on undiscovered rework (defined as the unnecessary effort of redoing a process or activity that is incorrectly implemented the first time). High levels of undiscovered rework lead to a high frequency of accidents on projects. The results of this study reveal that the time to detect rework is a possible safety policy parameter. By strengthening quality inspection of a project, faults are detected and corrected early enough before they lead to accidents. It was also observed that the tendency to accelerate projects can breed accidents on projects. Accelerated projects tend to experience high levels of unsatisfactory work compared to projects implemented following their planned schedule. From the management perspective, effective supervision of the design and construction process is recommended as the best strategy to avoid accidents. For further work, as a step towards developing a holistic view of safety, the model should be extended to capture the relationships between safety and equipment, safety and materials, and safety and labour.

Keywords: accident, construction industry, modelling, occupational safety and health, undiscovered rework.
1. Introduction

Construction is often identified as a high-risk industry and the reality is that the industry has injury and fatality statistics that make it one of the most dangerous industries in which to work (Rowlinson, 2004; Hinze, 2007). The construction process involves hazardous activities such as working at height, manual handling of equipment, exposure to harmful materials, structure demolitions, lifting operations, scaffolding, site clearance and earth works. Falls, contacts with electricity and accidents involving heavy equipment are the three foremost causes of occupation injuries in the construction sector (Mungen and Gurcanli, 2005). Other causes of accidents include collapse of earthwork, lifting of weights, toxic materials and suffocations, and fire and explosions, amongst others (Tam et al., 2003). Construction is also characterised by tight competition for contracts and site personnel are often under pressure to deliver work on schedule and within specific cost limits. Indeed, safety is often neglected.

In Uganda, there has been a proliferation of construction accidents in the recent past. Between 1996 and 1998 a total of 146 accidents were reported in the construction industry, 17 of which were fatal cases (Lubega et al., 2000). In relation to other industries, this translates into 31% of total industry accidents and 47% of the total industry fatality (see Table 1 and Table 2 for details).

Table 1: Distribution of accidents per industry in Uganda (1996-1998)

<table>
<thead>
<tr>
<th>Industry</th>
<th>Year 1996</th>
<th>Year 1997</th>
<th>Year 1998</th>
<th>Total</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Agriculture</td>
<td>2</td>
<td>1</td>
<td>4</td>
<td>7</td>
<td>3</td>
</tr>
<tr>
<td>Manufacturing</td>
<td>39</td>
<td>68</td>
<td>43</td>
<td>150</td>
<td>50</td>
</tr>
<tr>
<td>Electricity, gas and water</td>
<td>20</td>
<td>19</td>
<td>10</td>
<td>49</td>
<td>17</td>
</tr>
<tr>
<td>Construction</td>
<td>46</td>
<td>49</td>
<td>51</td>
<td>146</td>
<td>49</td>
</tr>
<tr>
<td>Transport and Communication</td>
<td>0</td>
<td>6</td>
<td>2</td>
<td>8</td>
<td>3</td>
</tr>
<tr>
<td>Government</td>
<td>8</td>
<td>1</td>
<td>1</td>
<td>10</td>
<td>4</td>
</tr>
<tr>
<td>Mining and Quarry</td>
<td>5</td>
<td>0</td>
<td>1</td>
<td>6</td>
<td>2</td>
</tr>
<tr>
<td>Commerce</td>
<td>6</td>
<td>5</td>
<td>7</td>
<td>18</td>
<td>6</td>
</tr>
<tr>
<td>Services</td>
<td>25</td>
<td>25</td>
<td>32</td>
<td>82</td>
<td>28</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>151</strong></td>
<td><strong>174</strong></td>
<td><strong>151</strong></td>
<td><strong>476</strong></td>
<td><strong>476</strong></td>
</tr>
</tbody>
</table>

Source: (Lubega et al., 2000:7)

Table 2: Distribution of fatal accidents per industry in Uganda (1996-1998).

<table>
<thead>
<tr>
<th>Industry</th>
<th>Year 1996</th>
<th>Year 1997</th>
<th>Year 1998</th>
<th>Total</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Agriculture</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Manufacturing</td>
<td>1</td>
<td>3</td>
<td>1</td>
<td>5</td>
<td>2</td>
</tr>
<tr>
<td>Electricity, gas and water</td>
<td>-</td>
<td>1</td>
<td>-</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Construction</td>
<td>4</td>
<td>6</td>
<td>7</td>
<td>17</td>
<td>6</td>
</tr>
</tbody>
</table>
From 1999 to 2010, the trend of accidents occurrence has not changed with the construction industry continuing to witness fatal accidents over the period (see Table 3). The major causes of construction accidents in Uganda have been cited as inadequate site supervision, use of incompetent personnel, and use of inappropriate construction techniques (Lubega et al., 2000).

Table 3: Examples of accidents on construction sites in Uganda (1999-2010).

<table>
<thead>
<tr>
<th>Date</th>
<th>Accident type</th>
</tr>
</thead>
<tbody>
<tr>
<td>26th January 2010</td>
<td>Collapse of an excavation for a commercial building on Plot 3, Luvum Street, Kampala City killing two people and causing injuries to five others.</td>
</tr>
<tr>
<td>15th March 2009</td>
<td>Collapse of Mirembe shopping Arcade on Plot 5A, Nasser road, Kampala due to failure of an excavation at an adjacent foundation. Four people died and twenty were injured.</td>
</tr>
<tr>
<td>26th February 2009</td>
<td>Collapse of an excavation for a foundation on Plot 5, Sny Bin Amir Street, Kampala. One person died and five were injured.</td>
</tr>
<tr>
<td>14th October 2008</td>
<td>Collapse of an excavation for NSSF Pension Towers on Plots 15A, 15B and 17 on Lumumba Avenue, Kampala. Seven people died and two were injured.</td>
</tr>
<tr>
<td>30th January 2008</td>
<td>Collapse of a four-storey building at St. Peters S.S, Nalya, Wakiso District. Eleven people died and fifteen were injured.</td>
</tr>
<tr>
<td>16th Sept. 2007</td>
<td>Collapse of the US$ one million perimeter wall fence under construction for Makerere University, Kampala. No injuries or fatalities were recorded.</td>
</tr>
<tr>
<td>20th Sept. 2006</td>
<td>Collapse of the building under construction for Tick Hotel, Kampala North killing two workers.</td>
</tr>
<tr>
<td>25th July 2006</td>
<td>The collapse of the walls of a trench to lay water pipes in Kansanga, Kampala, killing two workers of Sogea Satom construction firm.</td>
</tr>
<tr>
<td>8th March 2006</td>
<td>The collapse of a church building in Kalerwe, a suburb to the north of Kampala city, killing twenty people and injuring dozens of others.</td>
</tr>
<tr>
<td>21st October 2004</td>
<td>The collapse of a two-storey building at Seguku, Kajansi, Entebbe road trapping more than five workers in its rubble. The crash left the building flat on the ground.</td>
</tr>
<tr>
<td>31st August 2004</td>
<td>The collapse of a building at the proposed site for the five star J &amp; M Airport Hotel Apartment and Leisure Centre at Bwebajja, Wakiso District killing 11 people and injuring 26 others.</td>
</tr>
<tr>
<td>24th August 2004</td>
<td>Collapse of a five storey building at Good Hope Nursery and Primary School in</td>
</tr>
</tbody>
</table>
From the statistics and discussions above, it is evident that construction safety is a serious problem in Uganda as it is elsewhere. This paper is on understanding and modelling the dynamics of safety on construction projects based on a case-study of a failed hotel building complex in Uganda. In particular, the scope of the safety model discussed in this paper is restricted to the effects of undiscovered rework on safety. In the context of this paper, rework is defined as the unnecessary effort of redoing a process or activity that is incorrectly implemented the first time. Typically, rework is caused by errors made during the design and construction process.

Prior to studies by Love et al. (1999a, 1999b), it was generally accepted that rework is caused by uncertainty generated by poor information, which is often missing, unreliable, inaccurate, and conflicting. However, following studies by Love et al. (1999a, 1999b, 2000, 2002) and Love and Edwards (2004) rework is considered to be a consequence of numerous factors which can be categorised as technical, quality and human resource.

The technical factors include design errors, design changes, and construction errors originating from poor detailing and workmanship. Other technical factors that cause rework relate to poor quality of project documentation and the failure to follow building regulations. On the other hand, quality factors mainly relate to lack of quality assurance, lack of incentives and rewards and poor partnering relationships. Indeed, unpleasant relationships between designers and contractors inhibit the development of teamwork and joint problem solving and as a result design errors are more prevalent which may eventually result into structure failures and accidents during the construction stage.

Finally, the human resource factors relate to the support provided by the employee’s organisations so that they can perform their jobs effectively and productively. The important considerations are training, motivation and skill level. The main causes of rework resulting from poor skills are defective workmanship, disturbances in personnel planning, delays, alterations, failures in setting-out and coordination failures (Love et al., 1999a). In summary, the above technical, quality and human resource factors do not only lead to rework but equally compromise safety on construction sites.

2. Methodology

The methodology adapted was case-study research combined with system dynamics methodology. As noted by Yin (2003), case-study methodology investigates a phenomenon within its real-life context and this is particularly essential for safety research. Case-study research relies on multiple sources of
evidence and also benefits from prior theoretical prepositions (Yin, ibid.). The latter argument makes case-study research appropriate to system dynamics modelling which is based on the formulation of a dynamic hypothesis at the start of the modelling exercise. In this paper, the occurrence of accidents is hypothesised to depend on undiscovered rework. High levels of undiscovered rework lead to a high frequency of accidents on projects.

2.1 Case-Study Project:

The case-study project used in this paper was a failed hotel building complex in Busiro County, Wakiso District, Uganda. The choice of the hotel project as a case-study was largely due to its complexity in scope and design which made it suitable for system dynamics modelling. The hotel complex consisted of a high-rise apartment block, a hotel block, a queen’s suite, a swimming pool, cottages, a bar, an administration block, a health club, a conference centre and a shopping arcade. During construction, the apartment block which had reached third level suddenly collapsed (see Photos 1-2) resulting into the death of eleven workers and injuries to twenty-six others.

Following the accident, government appointed a nine-person technical committee to establish the cause of the accident. An investigation report by the committee revealed that the accident was largely due to lack of approved building plans and weak concrete columns (Mwakali, 2004). The columns were 50% of expected minimum size, had insufficient steel reinforcement which was less than 45% of the expected minimum steel and concrete was poorly mixed resulting into 30-78% of expected strength (Mwakali, ibid.).

Data collection included reviewing the project drawings to identify any design errors that could have resulted into failures. In addition to columns being undersize, five columns were omitted in the design and this greatly compromised the strength of the structure. There was also evidence of poor workmanship especially in the segregation of aggregates and honeycombing during the construction of columns (see Photos 3-4).

Through interaction with the Contractor and Wakiso District Engineering Office, project data including budgets, schedules and labour force was obtained. This data was used during the calibration of the developed model. Interviews were held with construction workers to gain insights into their skill levels and to study the safety practices on site before the accident occurred. It was observed that workers were not provided with basic safety gear and this contributed to the high incidence of fatalities and injuries which were registered when the building collapsed. Numerous variations were introduced without seeking approval by relevant departments as provided for by the laws governing the construction industry in Uganda.

Overall, based on the collected data, it was evident that the project was complex with magnificent architectural concepts and good investment ideas. However, the project was deprived of qualified consultants and contractors, and this contributed to its poor performance.

### 3. Model Formulation

#### 3.1 Overview of the modelling process

Modelling is an iterative process, and the System Dynamics (SD) modelling process starts and ends with understanding the system and thus forms a loop. The essential stages of a typical SD modelling effort include problem definition, formulation of the dynamic hypothesis, formulation of the model, testing, and policy formulation and evaluation (Sterman, 2000).

The model presented in this paper builds on the classical project management model by Richardson and Pugh (1981). The classical model was formulated to address the problems of overruns in cost, time and personnel for large Research and Development (R&D) projects. Despite efforts by managers to avoid them, overruns in R&D projects persisted. This prompted Richardson and Pugh (1981) to develop a computer model to improve management of such projects in such a way as to eliminate or minimise overruns. Large R&D projects involve a sizeable number of people, a large number of detailed tasks and a relatively long time frame which are also characteristics of large-size construction projects. The model by Richardson and Pugh (1981) is largely hypothetical consisting of subsystems...
on workforce, scheduled time, project progress and rework. In this paper, the subsystem on safety is added and the model calibrated in a real world environment by taking a case-study of a hotel building complex in Uganda. The classical model developed in DYNAMO has now been implemented in POWERSIM STUDIO 8 software, an environment with advanced programming capabilities.

The formulation of the subsystem on safety is based on the dynamic hypothesis centred on the concept of undiscovered rework. The other causes of accidents that have been considered in this paper are the effects of schedule pressure and cost pressure on accidents frequency. Notably, high schedule and cost pressure increase the risk of accident occurrence. The occurrence of accidents is a measure of quality of practice on construction projects. Typically, the occurrence of accidents is an indicator that the design is defective and/or supervision of construction work is not effective enough to identify construction errors on time so that corrective actions are taken to avoid accidents.

### 3.2 Definition of terms used in causal loop diagrams

System Dynamics is an established body of knowledge with a common language of communication and for purposes of this paper, a number of terminologies require to be defined. These terminologies are stated below and mostly relate to feedback systems and causal loop diagrams.

**Feedback systems:**

Put succinctly, feedback is the transmission and return of information (Richardson and Pugh, 1981). Feedback systems characteristically form loops of interconnections (i.e. loops of causes and effects) and these interconnected sets of feedback loops define a feedback system (Richardson and Pugh, ibid.). In any system, all dynamics arise from the interaction of two types of feedback loops, positive (or self reinforcing) and negative (or balancing) loops.

Positive feedback loops (labelled as ‘R’ in Figure 2) tend to reinforce or amplify whatever is happening in the system. A typical example of positive feedback is the scenario of overwork observed on construction sites. Heavy assignments increase the backlog of work to do, causing anxiety to rise amongst workers and as a result making it more difficult for them to concentrate and complete any given task. The time it takes to complete a task rises and as a result the rate of completion of tasks slows down. Thus, the job backlog rises still further and so will anxiety and the inability to cope with tasks. Positive feedback loops usually make system behaviour to get worse and worse until there is some form of external intervention to break the vicious cycle.

On the other hand, negative feedback loops (labelled as ‘B’ in Figure 2) counteract and oppose change (Sterman, 2000). Negative feedback loops are goal-seeking and most control functions used in construction projects operate in this way by attempting to correct deviations in cost, time and resources, and return them to what was intended in the client’s brief (Chapman, 1998).
Polarity of feedback loops:

To use causal loop diagrams, it is important to have a good understanding of the concept of polarity. Within causal loop diagrams, individual links between two variables can be labelled positive or negative in order to express the nature of the relationship between the two variables. Loosely speaking, a plus sign indicates that the variables at opposite ends of the arrow tend to move in the same direction (i.e. direct variation) while a minus sign indicates an inverse relationship. Chapman (1998) illustrates that a causal link from A to B is positive (1) if A adds to B, or (2) if a change in A produces a change in B in the same direction (see Figure 1 below). Similarly, Chapman (1998) also states that a causal link from A to B is negative (1) if A subtracts from B, or (2) if a change in A produces a change in B in the opposite direction.

![Figure 1: Polarity of feedback loops (adapted from Chapman (1998:239)](image)

**3.3 Causal loop structure of the safety model**

The structure of the safety subsystem illustrated as a causal-loop diagram (see Figure 2) is linked to six main stocks (i.e. variables which accumulate over time) within the overall project model: undiscovered rework, known rework, work accomplished, accident costs, project costs and scheduled completion date. Figure 2 suggests that when accidents occur, known rework increases requiring an extra effort and time to correct the work hitherto perceived complete. The net effect of above events is an adjustment in scheduled completion date which builds up schedule pressure on the project. When working under schedule pressure human errors are bound to increase and this increases the possibility of recording more accidents. Similarly, accidents impose an unplanned extra-cost which over time builds cost pressure and increases the possibility of registering more accidents on the project.
The structure for rework presented in Figure 2 includes a variable on discovered rework probability which indicates the probability of undiscovered rework being uncovered by quality inspection. Discovered rework probability was estimated based on the judgments of project managers because it is impossible to assess it correctly. The other key variable in the model is the rework discovery rate which is modelled as a function of the time taken to detect unsatisfactory work in a project. Notably, the process of discovering and correcting rework reduces the level of undiscovered rework and as a result lowers the frequency of accidents. During model construction, the causal loop structure presented in Figure 2 was converted into a stock-flow structure which was implemented in POWERSIM STUDIO 8 simulation software.

4. Model Validation and Testing

Model validation is the process of building confidence in the usefulness of a model (Barlas, 1996). In the formal system dynamics methodology, although model validation is typically (and technically) defined to take place right after model construction and before policy analysis, in practice it exists at every stage of the methodology. Barlas (1996) observes that during model validation, it is not sufficient to test how “accurate” the output behaviour is; what is crucial is the validity of the internal structure of the model. Thus, the general logical order of validation is, first to test the validity of the structure, and then start testing the behaviour accuracy, only after the structure of the model is
perceived adequate (Barlas, ibid.). Accordingly, validation and testing of the safety model was accomplished through conducting of structure and behaviour tests.

4.1 Structure tests of the safety model

Structure tests can be categorised as direct structure tests and structure-oriented behaviour tests. Direct structure tests assess the validity of the model structure by direct comparison with knowledge about the real system and structure-oriented behaviour tests assess the behaviour of the structure indirectly by applying certain behaviour tests on the model-generated behaviour patterns (Barlas, 1996). Direct structure tests are largely qualitative including checking dimensional consistency and extreme conditional tests in equations.

The structure-oriented behaviour tests were performed on the safety model by deactivating feedback loops responsible for behaviour and by replacing table functions with constants. For example, when the structure responsible for undiscovered rework was deactivated by setting the value of the parameter fraction satisfactory to 1 (literary meaning that all project work that is undertaken is satisfactory), the obtained results show that the accident frequency is zero throughout the simulation time, and there are no overruns in schedule and workforce. The above results illustrate that undiscovered rework has the power to cause the problematic behaviour of accident occurrence, and schedule and workforce overruns. Similarly, the structure responsible for accidents occurrence was deactivated by setting a very high value of average time to record an accident; this literally means that accidents cannot happen during the project life. The results obtained from this test revealed that when the average time to record an accident was set to an extreme value of 1,000,000,000 months, the scheduled completion date reduced from 63 months to 59 months and the workforce reduced from 58 to 54 persons at the close of the project. This means that by avoiding accidents, you minimise schedule and workforce overruns on projects.

4.2 Behaviour tests of the safety model

Behaviour tests measure how accurate the model can reproduce the major behaviour patterns exhibited by the real system (Barlas, 1996). As suggested by Richardson and Pugh (1981), the most common method of carrying out behaviour tests is through parameter sensitivity testing. Parameter sensitivity tests examine whether the patterns of behaviour exhibited by the model change with minor parameter value changes (Richardson and Pugh, ibid.).

During model testing, parameter sensitivity tests were carried out on the average time to record an accident and on discovered rework probability. The rationale was to select those parameters which have direct influence on the behaviour of the safety system. For example, when the value of discovered rework probability was changed from the default value of 0.5 (implying that there is a 50% chance that unsatisfactory work will be discovered by quality inspection) to 0.35 (a 30% reduction) the simulation results revealed that undiscovered rework increases (due to a reduction in discovered rework rate) and so does the accident frequency. Also observed is an increase in the scheduled completion date and a reduction in the workforce size. When the value of discovered rework probability is increased from the default value of 0.50 to 0.65 (a 20% increase), undiscovered rework
reduces (due to an increased rework discovery rate) and similarly does the accident frequency. Also observed is a reduction in the scheduled completion date and an increased workforce size. Overall, the parameter discovered rework probability is structurally insensitive but numerically sensitive.

5. Discussion of Model Results

The safety management model presented in this paper, in addition to presenting the dynamics of schedule and workforce overruns has developed an understanding of the possible structure and behaviour for safety as a quality factor on construction projects. The baseline data used to run the model was obtained from the baseline project plan of the case-study hotel complex presented in section 2 of this paper. According to the activity plan/gantt chart, the project was designed to be completed in 40 months with an initial scope of 1200 tasks. In the context of this paper, a task is defined as an activity which can be accomplished by a worker in one man-month of twenty man-days. As a result, activities with duration of more than twenty man-days were made up of more than one task. From the experience of similar past projects in the Ugandan construction industry, the productivity of workers was estimated to be 1 task per person per month. Therefore, the desired workforce at the start of the project is 30 persons. Figure 3 below presents an extract of the base run results obtained using the above project estimates.

Figure 3: Base run results of the safety model

During the first 20 months, the project is perceived to be on schedule, most of the unsatisfactory work is not detected and very few accidents do occur. The scope of the project does not significantly change and there is a small change in workforce size from 30 persons to 40 persons. Between 20 and 40 months, unsatisfactory work grows to high levels and many structure failures occur during this period. It also increasingly becomes evident that the project is behind schedule with only 57% of the work
completed after 30 months and 72% of the work completed after 40 months, supposedly the baseline planned completion date. The productivity of the workforce also drops to 0.90 tasks/person/month after 30 months and further to 0.82 tasks/person/month after 40 months. This means that management has to hire an even bigger workforce to put the project on schedule. Between 40 and 60 months, the effort of attaining adequate workforce pays off, more of the unsatisfactory work is detected and corrected, and the accident frequency significantly drops. Finally, the project is completed after 63 months with a workforce of about 58 persons.

A unique scenario that was observed during model test runs was the case of accelerating the scheduled completion date. For example, when the baseline completion date was reduced from 40 months to 30 months, the accident frequency increased from 1.1 tasks/month to 1.6 tasks/month and the workforce at project completion increased from 58 persons to 65 persons. These results suggest that, when the scheduled completion date is reduced to an earlier date, more workforce is required to accomplish the work within a shorter period of time. However, with a bigger workforce a lot of unsatisfactory work is generated and as a result more accidents are registered on the project.

6. Conclusion

This paper set out to understand and model the dynamics of safety on construction projects. It was hypothesised that undiscovered rework is a critical factor that compromises safety on projects. Indeed, the results obtained using the developed model support this theory. From the results of this study, it is evident that the time to detect rework is a possible safety policy parameter. By strengthening quality inspection of a project, faults are detected and corrected early enough before they lead to accidents. In the case study hotel building project, the technical committee that investigated the accident noted that if the local authority had inspected the site, detected the faults in time and taken appropriate action, the accident could have been averted. The accident which was registered on the case-study building project was a result of design errors and poor construction practices. During the study, it was also observed that the tendency to accelerate projects can breed accidents on projects. Accelerated projects tend to experience high levels of unsatisfactory work compared to projects implemented following their planned schedule. From the management perspective, effective supervision of the design and construction process is recommended as the best strategy to avoid accidents. For further work, as a step towards developing a holistic view of safety, the safety model should be extended to capture the relationships between safety and equipment, safety and materials, and safety and labour.

7. Acknowledgement

The authors would like to acknowledge Swedish International Development Cooperation (Sida) for sponsoring this research and the School of Graduate Studies at Makerere University and the Centre for Banking and Finance, The Royal Institute of Technology (KTH), Sweden for coordinating the research fund.
References


