A case-based reasoning technique for evaluating performance improvement in automated construction projects

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Abstract –

Automation of construction processes facilitates increased productivity and overall higher project performance. This paper presents a methodology for comparative assessment of different construction processes and selection of an optimal solution based on appropriate automation implementation. Construction processes are quantitatively evaluated using a methodology combining case-based reasoning and compositional modeling.

Through the generation of many combinations of process fragments that are compiled from case libraries, potential solutions are explored and evaluated. An example involving solutions such as RCC frame construction, precast construction, and modular steel frame construction is described in this paper. The study demonstrates the possibility of selection of suitable construction processes based on the quantitative assessment of a large number of potential solutions. Processes are modelled by decomposing them up to the elementary tasks and appropriate level of automation is identified in all the tasks.

Keywords-

Case Based-Reasoning; Compositional Modeling; Discrete Event Simulation; Construction automation; Level of Automation; Therbligs; Project Performance Improvement.

1 Introduction

Construction industry, due to its complexity and diversity, has high potential for the application of automation. Over the years, various automation systems have been developed [1-2] that demonstrate their capabilities to perform many of the basic building activities [3]. However, implementing automation systems in construction is quite challenging since the nature of construction is highly heterogeneous with high variability in the working environment [4]. Construction automation has the capacity to eliminate manual-labour oriented non-value adding processes, and improve those manual-labour processes that contribute to value addition. Thus, construction automation can deliver improvement in project performance. This can be achieved with relevant process planning methods and tools [5]. Though there is broad consensus that construction automation achieves reduction in time and cost, the research based on quantitative methodologies that evaluate the improvement of productivity by implementation of suitable automation is not sufficiently explored [6].

Recently, the authors have developed a systematic methodology for productivity analysis of automated construction processes [7]. The study specifically explores the use of simulation tools to predict productivity improvement through creating multiple processes by combining process fragments from a case base. The aim of this paper is to demonstrate the methodology of generating simulation models of construction processes for identifying optimal levels of automation.

2 Literature Review

Study of various literature by authors [8] reveal that analysing the performance of construction projects is very powerful and advantageous using discrete event simulations [9-14], especially those involving time-cost based evaluations [15-18]. This gives rise to a research question:

How to select an optimal typology of construction process that maximises the overall project performance from a given set of possibilities?

Based on the literature review, the following specific knowledge gaps are identified.

1. There exists limited research that evaluates the productivity of automated construction processes.

2. The prevalent discrete event simulation models are based on static process models in which the structure of the process is fixed a-priori. They are not capable of evaluating multiple options for the activities in the process.

The challenge of optimizing processes using appropriate automated methods is addressed by the authors through a new methodology [7]. This research work is inspired from the concept of compositional modelling from the domain of computer science [19]. Previously, it has been applied for design problem solving [20-21] and system identification [22].

The authors followed design science research methodology [23] approach to develop this framework. This involved problem identification and objectives development. This was followed by search for solutions from the literature and exploratory implementation. Demonstration and evaluation of simulation methodologies. The issues and challenges were identified. Through iterations, modifications to the solution were done.

This paper demonstrates the evaluation of different construction process typologies showcasing its application for complex problems in construction. For demonstration, the authors have considered three types of construction process typologies, with different levels of decompositions with different automation possibilities (For example, rebar cutting process has possibilities of execution through mechanical saw, electrical circular saw, and automated rebar cutter machine among systems). The methodology is able to evaluate the potential for different types of automation through search and exploration approach.

The remaining portion of this paper explains the methodology, its application through demonstration, results of study and evaluation, and lastly summary and conclusion.

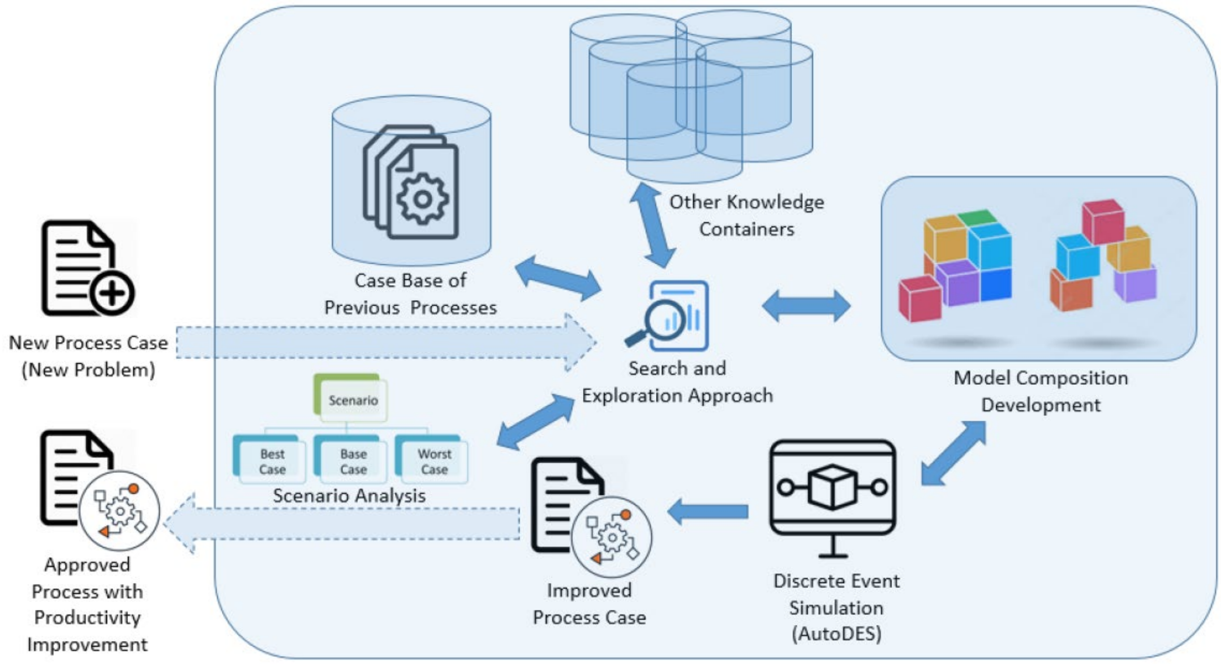


Figure 1. A case-based reasoning methodology using compositional modelling for construction process evaluation [7]

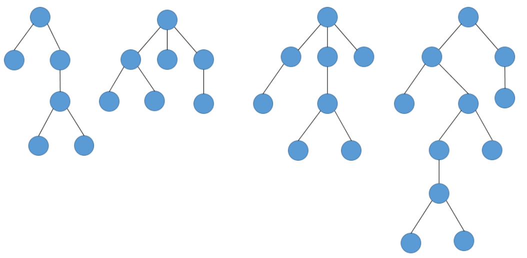
3 Combining compositional modeling and case-based reasoning

The present methodology (Figure 1) involves a combination of case based reasoning and compositional modelling (This is explained in detail by authors in [7], is briefed in the following portion). Multiple discrete event simulation models are generated by combining fragments of models using the methodology of compositional modelling. Model fragments are compiled from cases. A search and exploration approach using time and cost as parameters is used to identify optimal level of automation for construction process. The construction process is decomposed into fragments up to the basic task level or therbligs (Table 1). This is useful for the assessment of manual labour and suitability of introducing appropriate automation as replacement.

Table 1. Therbligs and their symbols

Sl. No.	Therblig	Symbol	Sl. No.	Therblig	Symbol
1	Search		10	Use	
2	Find		11	Disassemble	
3	Select		12	Inspect	
4	Grasp		13	Preposition	
5	Hold		14	Release Load	
6	Transport Loaded		15	Unavoidable Delay	
7	Transport Empty		16	Avoidable Delay	
8	Position	9	17	Plan	
9	Assemble	#	18	Rest	

Past construction processes that are decomposed in this form are stored in case libraries (Figure 2). In the present work, the libraries are created from cases with data collected from various sources such as construction sites, laboratory experiments, and videos from the world-wide-web. The sources for the web-based videos are primarily from 81 videos taken the YouTube involving the RCC construction process execution through different execution modes. This exercise was performed to increase the multitudes of variations of process fragment cases to generate combinatorial solutions during simulation.



(a) (b) (c) (d)

Figure 2. A schematic representation of multiple activity cases in case library

The objective is to capture various modes of performing activities with different levels of automation.

For each construction process fragment, there are multiple possible modes of execution; a top-level process fragment may be performed through several sub-processes. An object oriented representation is used for process fragments. Fragments are grouped into classes based on standard object oriented representation concepts such as inheritance. Fragments that are at the top of the inheritance hierarchy represent generic activities and those at the lower levels represent specialized modes of execution of these activities. The inheritance hierarchy represents "type-of" relationships. Children classes are special types of parent classes.

The work breakdown structure [24] of the overall construction process contains fragments of process that are in "part-of" relationship (Table.2). This decomposition is down to the level of basic tasks or therbligs (also refer section 4.1).

Table 2. Construction process typology-1: RCC frame assembly: portion of work breakdown structure

ACTIVITY CASES AND DESCRIPTION
<!-- 1.1.1 RCC COLUMN CONSTRUCTION -->
<!-- 1.1.1.1 STEEL REINFORCEMENT ASSEMBLY -->
<!-- 1.1.1.1.1 (A) FABRICATION -->
<!-- 1.1.1.1.1.1 (A.1) MAIN REINFORCEMENT -->
<!-- 1.1.1.1.1.1.1 (A.1.1) TRANSPORTING .... -->
.
.
<!-- 1.1.2 RCC BEAM CONSTRUCTION -->
<!-- 1.1.2.1 STEEL REINFORCEMENT ASSEMBLY -->
.
.
<!-- 1.1.2.2 CONCRETING -->
<!-- 1.1.2.2.2.1 (B.1) CONCRETE MIX PREPARATION -->
<!-- 1.1.2.2.2.2 (B.2) TRANSPORTING TO .. LOCATION -->
<!-- 1.1.2.2.2.3 (B.3) CONCRETE POURING -->
<!-- 1.1.2.2.2.4 (B.4) COMPACTING -->
.
.

During case adaptation, similar fragments that belong to the same parent class are interchanged provided the constraints are satisfied. Therefore, it becomes feasible to generate multiple processes for any top-level task by using different combinations of fragments for sub-activities at lower levels.

For example, a combination of different case options involving, say, transportation of resources from stockyard to site location, assembly of column components, stirrup bending, and more cases, give rise to millions of combinations with varying degrees of automation containing manual, mechanical, electromechanical, electronic, and automation systems.

(a) (b) (c)

Figure 3. Construction process typology cases: (a) RCC frame assembly, (b) steel frame assembly, and (c) precast frame assembly

3.1 Description of Construction process typology cases

An example involving the construction of a structural frame is considered here. Figure 3 shows three cases having different construction typologies.

The first one is a conventional RCC frame construction involving tasks such as preparation and assembly of the rebars and stirrups, formwork preparation, and preparation of concrete mix, transporting, and casting. The second one involves a steel structural frame in which mild steel pipes are used to construct columns. Cylindrical couplers with internal threading are used for connections. Beam modules are also made of steel pipes and connected using couplers mentioned before. The third case involves a precast frame assembly. Eight RCC columns containing hollow square steel tubes instead of conventional reinforcement are used. The steel tubes project 75 mm outwards to create a moment resisting connection with the beam.

Certain assumptions are made in the simulations: the foundation work is completed, and the frame above is assembled. All the required resources are available at project location.

3.2 Data collection

Data was collected from mutiple sources such as onsite project construction activities, laboratory based construction assembly experiments, and construction videos from multitudes of videos from world-wide web resource, such as YouTube. For each activity, the time is compiled from process fragment cases. Moreover, for each activity, the resources required were identified: such as the labour, helper, tools and equipments utilised, operating staff, and materials handled. The costs for activities were based on CPWD rates [25] and cost details collected from other sources such as brochures and online sources.

4 Evaluation of the performance of the process typologies

A new project scenario is taken to demonstrate case-based model composition. Cases are adapted through substitution of similar and suitable cases based on the consideration of inheritance relationship. An in-house software (called AutoDES) developed for this research performed the discrete event simulation for estimating the time taken for completing the construction. The detail of implementing the model and performing the simulation is described below.

4.1 Generation of model cases

Cases are represented in XML format. Each case is not only a decomposition of the process but it also contains the various resources involved. The decomposition is performed up to the basic level tasks or Therbligs. For example (Figure 4), in the rebar bending process fragment, the task is broken down into basic fragments or therbligs comprising search, find, select, grasp, hold, position, use, and so on. Each therblig has time data in seconds.

These activities may be run in parallel or in sequence depending on the case being considered. Their durations are stored in the cases. The specification of the number of cycles of therbligs is also included in case.

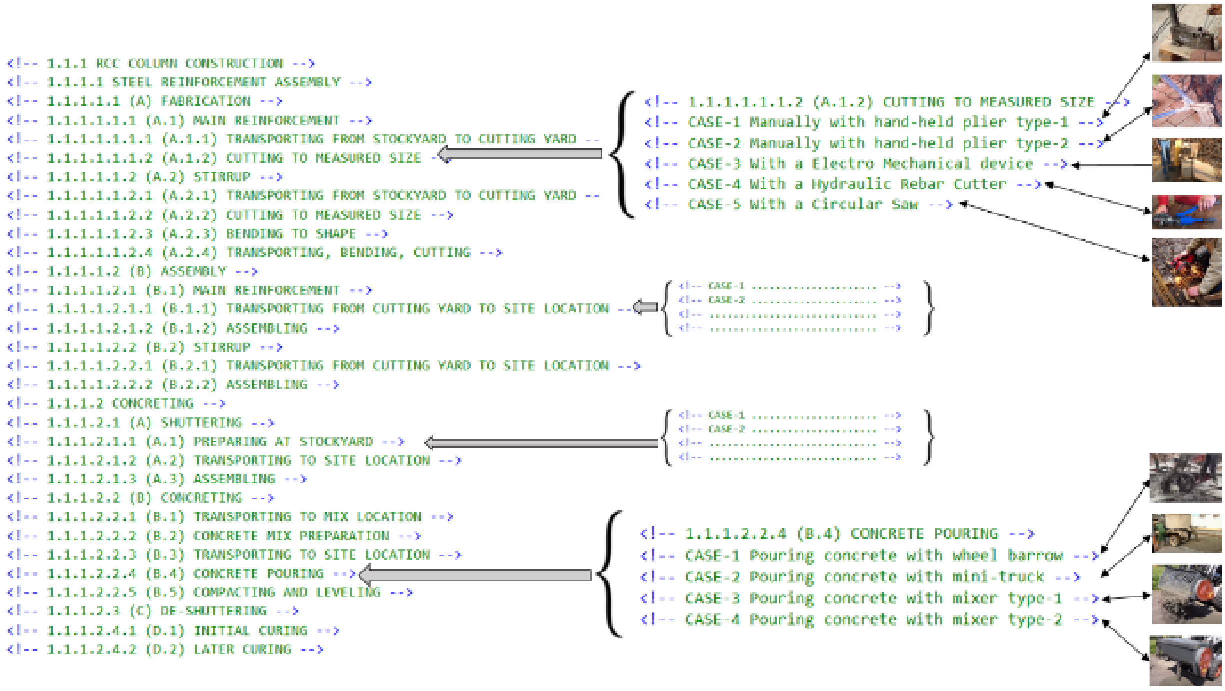


Figure 5. A portion of RCC frame construction process with search and substitution of process fragments

```
<bending_stirrup_using_MechanicalBender1>
  <!-- bending stirrup using Mechanical Bender1,

  <Resource>
    <!-- Resource required for this activity -->
    <labor> 1 </labor>
    <MechanicalBender1> 1 </MechanicalBender1>
  </Resource>

  <Activities>

    <therblig_Search>
      <Duration> 0,2 </Duration>
    </therblig_Search>

    <therblig_Find>
      <Duration> 0,2 </Duration>
    </therblig_Find>

    <therblig_Select>
      <Duration> 0,2 </Duration>
    </therblig_Select>

    <therblig_Grasp>
      <Duration> 0,3 </Duration>
    </therblig_Grasp>

    <therblig_Hold>
      <Duration> 0,3 </Duration>
    </therblig_Hold>
```

Figure 4. A portion of schematic of therbligs based XML coding for rebar bending activity

The classification of all the activities is done using inheritance relationships. For example, bending stirrups using mechanical bender is specified as a special case of bending stirrups. Similarly, manually bending bars to make stirrups is also a special case of the same parent class. Both the children classes might be replaced with each other to create new processes having different sets of requirements for resources, resulting in different times of execution.

4.2 Generating solutions for a new problem

To the case based reasoning module, sufficient data with respect to a new project is input. This includes the resources (such as labour, and equipment), and inheritance relationships (part-of relationships of the group cases).

Through case adaptation, multitudes of processes are generated through a random search algorithm. For generating a new solution, every adapted case undergoes a combination of portion of activities from the previous cases. This combinatorial model generation approach end in generating new processes based on the combinations of process fragments in the case library.

For example, in the RCC frame construction process (Figure 5), each fragment has multiple case possibilities of substitution containing manual, mechanical, electromechanical, and automated systems.

AutoDES, a simulation tool developed in-house for this research, is applied for the performance of discrete event simulation. The AutoDES executes simulations involving scanning of activities. It contains a simulation clock which, at a given time step, checks the availability of any activities that requires to be scheduled. Once, all the activities are completed, the simulation stops.

The output of the simulations provide with the results in the form of time durations for every process fragment. For each process solution, the capital and resource costs are derived separated.

5 Results

After simulations of processes generated through compositional modeling, potential solutions are selected based on their time and cost. Millions of combinations of process fragments are generated during this procedure.

In the illustrative example considered in this study, for RCC frame construction, the stages up to concreting is included. The curing stage is excluded. The manufacturing of the steel modules of the steel assembly process typology is excluded from the scope. The three construction process typologies contain a combination of activities that involve manual, mechanical, and electromechanical, tools and devices. The time duration for each stirrup rebar bending (process fragment) using mechanical plier type-1, type-2, and automatic bending machine are: 84 sec, 24 sec, and 04sec, respectively. The time is drastically reduced by using an automation machine, however, it comes with high investment cost. Similarly, in another instance, during concrete mix preparation (process fragment), the time varied with different mixer types: 84, 59, and 38 sec. The first two durations were from drum mixers, while the third duration was from handheld power mixer. The substitution of process fragments from the above mentioned examples and others process fragments in to the overall RCC construction process gave significant performance improvement in the results.

The durations for RCC frame assembly, steel frame assembly, and precast assembly (in minutes) are 1214.07, 68.23, and 984.90 respectively. The optimal solution obtained for the selected example, involves process typology-2 (steel frame assembly) based on time alone. The most appropriate process based on combined time and cost performance involves pre-cast frame assembly.

6 Summary and Conclusion

This paper demonstrated the application of a methodology combining case-based reasoning and compositional modeling for identifying the optimal level of automation in construction. Cases of construction processes consisting of three process typologies were used: RCC frame construction, precast frame construction, modular steel construction.

For exploring the different approaches of construction with various levels of automation, case libraries were generated based on quantitative data inputs from site, laboratory experiments, and web-based resources. Every case is unique with the construction methods and tools adopting manual, mechanical, electro-mechanical or other approaches. Multiple cases are represented through breaking down the entire construction process into fragments of activities to the level of elementary tasks or Therbligs.

It is concluded that a comparative analysis of different typologies of construction processes leads to better decision making for appropriate level of automation in construction implementation and achieving project performance improvement. Results show that implementation of automation facilitates significant saving of construction time through selecting an appropriate process typology. The savings in time and cost can be quantified and could be used in decision making depending on the preferences of the user.

Research Contributions:

This research facilitates early decision making of appropriate automation to achieve overall construction process enhancement. This study demonstrates the application of compositional modeling, a concept in computer-science domain, to the field of construction automation.

Limitations and future work:

Present study focuses on low-rise residential construction projects and has limited number of cases at present. Future work involves better algorithms for time-cost trade-off.

The stages that are currently not included in the present study of overall construction processes, such as curing of RCC, are considered for accommodating in the future research work for a more comprehensive study.

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