

**DEVELOPMENT OF A MANY-OBJECTIVE MODEL
BASED ON NSGA-III FOR CONSTRUCTION PROJECTS**

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OCTOBER 2019

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BASED ON NSGA-III FOR CONSTRUCTION PROJECTS**

by

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Submitted

In fulfillment of the requirements of the degree of Doctor of Philosophy

to the



INDIAN INSTITUTE OF TECHNOLOGY DELHI

OCTOBER 2019

Dedicated to my beloved and loving Mother,

Lalita

CERTIFICATE

This is to certify that the thesis entitled “**Development of a Many-Objective Model Based on NSGA-III for Construction Projects**”, being submitted by **Ms. Abhilasha Panwar** to the Indian Institute of Technology Delhi for the award of the degree of **Doctor of Philosophy** is a bonafide record of the research work carried out by her under my supervision and guidance. The thesis work, in my opinion, has reached the requisite standard, fulfilling the requirements for the degree of Doctor of Philosophy.

The contents of this thesis, in full or in parts, have not been submitted to any other University or Institute for the award of any degree or diploma.

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ACKNOWLEDGEMENTS

First and foremost, I would like to thank God for guiding and helping me to complete this thesis.

I would like to extend my sincere gratitude to my guide Prof. Kumar Neeraj Jha, Department of Civil Engineering, IIT Delhi, for his constant support, encouragement, consistent, inspiring guidance and utmost cooperation at every stage throughout the duration of the study. It was a highly educative and memorable experience working under his supervision.

I am thankful to my student research committee members, Prof. J. T. Shahu and Dr Uma Maheswari of Department of Civil Engineering, IIT Delhi, and Prof. Ravi Shankar, Department of Management Studies, IIT Delhi, for providing me with their valuable inputs throughout my study.

I wish to take this opportunity to extend my sincere thanks to Prof. K. C. Iyer, and other faculty members of IIT Delhi with whom I interacted occasionally. I also thank all the staff members of the Department of Civil Engineering, IIT Delhi, specially Mr Randheer Kumar Jha, Mr Rajeev Aggarwal, Mr Jeet Ram and Mr Amit, for all possible help and guidance rendered by them during my research work.

I have earned very good souls as friends during these years in IIT Delhi. In particular, I cherish the moments spent with Shruti Sharma, Radha Kushwaha, Neelu Nandan Vibhakar, Chirag Kothari, Shivam, Parteek, Harshada Sharma, Kavita, Sathiya , and Arun.

I thank my research group colleagues and friends Dr. Dilip Patel, Dr. K.K. Tripathi, Dr. Gayatri Sachin Vyas, Dr. Prachi Kaushtub Sohoni, Mr. Ajit K. Sinha, Dr. Satish Kumar V, Ratnesh Kumar, Sreenivas, Soumya Jain, Durva Gupta, Sparsh Johari, Santu Kar, Ravindra, Sakshi, Fekreysus, Saddek, Abdul, and Mr. O. P. Tripathi with whom I have spent a lot of time in technical discussions at various stages of my research.

I would like to extend my deepest gratitude to my parents (Father: Daljeet Singh Panwar and Mother: Latita Panwar), and in-laws (Sakeel Verma, Bimla Verma and Priyanka Verma) for their constant support and encouragement throughout the course of study. I whole heartedly thank my loving brother J. P. N. Nitin Panwar, and husband Hitendra Verma for their unconditional love and cooperation, without which this study would not have been possible at all.

Abhilasha Panwar

ABSTRACT

In recent years, there has been a considerable increase in the number of stakeholders working with different objectives in any construction project. This has necessitated simultaneous achievement of competing objectives, such as: reduction in time, cost, resources, and adverse environmental impact on a project. In order to achieve a balance among these objectives, several multi-objective construction scheduling models have been reported in the literature. However, several challenges and complexities have also been encountered while incorporating and visualizing more than three objectives simultaneously in such models. Some other challenges faced in the model development are: (i) issues related to large non-dominated population, (ii) being computationally expensive, (iii) difficulties in representation of trade-off surfaces, etc. Some of these challenges have been addressed in this work. The aim of this research is to develop a many-objective scheduling model (MOSM). In order to achieve the aim, the following five research objectives have been set-out.

- (i) To develop a qualitative framework for the selection of the most appropriate optimization algorithm for the construction scheduling model.
- (ii) To develop a many-objective trade-off scheduling model for construction project.
- (iii) To check the applicability of the developed many-objective scheduling model (MOSM).
- (iv) To facilitate the activity-wise life cycle costing (LCC) of a construction project in the MOSM model.
- (v) To develop a many-objective model graphical user interface (MoMGUI) for the MOSM.

To achieve the first research objective, an extensive literature survey was carried out for identification of performance parameters and commonly used algorithms in the instant domain. The literature survey led to the finalization of 13 performance parameters and six optimization algorithms. A pairwise comparison using a questionnaire survey involving the six optimization algorithms was carried out and the responses were analyzed using the principles of consistent fuzzy preference relation (CFPR) method. The analysis using CFPR resulted in ranking the six

algorithms. The non-dominated sorting genetic algorithm (NSGA) was found to be the most appropriate algorithm for construction scheduling, while integer/linear programming was the least preferred among the six algorithms.

Subsequent to the identification of the NSGA as the most apt algorithm, a many-objective scheduling model (MOSM) was developed to cater to the second research objective. The developed model was validated using the two examples available in the literature.

To ascertain the applicability of the developed model for the many-objective trade-off, two additional case study examples adopted from the literature were solved to cater to the third research objective. The first case study example, dealt with project objectives of time-cost-environment-resource (TCER), whereas, the second one dealt with time-cost-quality-safety (TCQS).

For the first case study example, first the three objective (time-cost-environment [TCE]) trade-off problem was solved using the developed model. Subsequently, the developed model was used to solve by considering an additional objective that of resource moment to make it a four objective problem (time-cost-environment-resource (TCER)). This was required as a build-up to demonstrate the implication of adding the fourth objective on the solution obtained for the preceding three-objective problem. The results showed that the developed model was capable of achieving optimal trade-off solutions for the fourth objective, without compromising the other three. Similar results have also been observed in the case when an additional objective that of safety was added into the existing three objective model pertaining to time-cost-quality. This strongly justified the applicability of the developed model in the many-objective trade-off context.

The increasing industrialization demands a sustainable model which may benefit the construction industry in general and construction professionals in particular. The research objective 4 included achieving one of the sustainable pillars that is economy. This was attempted by integrating life cycle cost (LCC) in the scheduling model. To integrate the LCC, an activity-wise life cycle cost analysis (LCCA) was performed in a real-life case considering civil, and electrical and mechanical (E&M) items of works. Activity-wise LCC study was undertaken to gain new insight from the stakeholders in the cost-benefit analysis of a particular activity.

It also aimed to help stakeholders, concentrate on the previously neglected items of work that had a significant influence on the LCC of a structure. The results showed that the cost share of civil and E&M items of work were 80% and 20% respectively, of the construction cost. However, when LCC was the parameter, these percentages changed to 60% and 40% for civil and E&M items of work. Once the activity-wise LCC was calculated, they were carried forward in the trade-off model. This trade-off model integrated LCC with time. Subsequently, the time-LCC trade-off (TLT) was analyzed with MOSM. Further, the TLT model was compared with the time-cost trade-off model to have an insight into the results. It emerged from the results that TLT has advantages over TCT, to the extent that it offers a more economic method to execute any activity.

In the end, a many-objective model graphical user interface (MoMGUI) was developed to address the fifth research objective. The MoMGUI should facilitate easy application of the developed MOSM by practitioners. The model was developed in MATLAB 'app designer'. The MoMGUI was developed with the aim that it should be capable to deal with two objectives, three objectives and four objectives scheduling trade-off problems. The model was checked for its usability under five criteria comprising effectiveness, efficiency, engagement, error tolerance, and ease of learning. It was found to be working satisfactorily.

The devised MOSM provides a useful insight for the construction practitioners. This model is capable of preparing an optimal schedule considering two to four construction project objectives, very efficiently. Further, this study offers economic sustainability as an important ingredient which has been incorporated in one of the objectives and integrated into the model. This will encourage the decision-makers to use this holistic model in the project planning stage. Moreover, it will help stakeholders to ensure a safe working environment, time-bound completion, environmental friendly, economically sustainable, and a quality end product, in any construction project.

Keywords: Many-objective, scheduling, consistent fuzzy preference relation, activity-wise, life cycle cost, graphical user interface.

सार

वर्तमान वर्षों में, किसी भी निर्माण परियोजना में विभिन्न उद्देश्यों के साथ काम करने वाले हितधारकों की संख्या में काफी वृद्धि हुई है। जिससे प्रतिस्पर्धी उद्देश्यों की एक साथ उपलब्धि जरूरी बनाया है, जैसे: समय में कमी, लागत, संसाधन, और एक परियोजना पर प्रतिकूल पर्यावरणीय प्रभाव। इन उद्देश्यों के बीच संतुलन हासिल करने के लिए, साहित्य में कई बहुउद्देश्यीय निर्माण समयबद्धन मॉडल बताए गए हैं। हालांकि, ऐसे मॉडलों में एक साथ तीन से अधिक उद्देश्यों को शामिल करने और कल्पना करने के दौरान कई चुनौतियों और जटिलताओं का भी सामना करना पड़ा है। मॉडल विकास में सामने आई कुछ अन्य चुनौतियां हैं: (i) बड़ी गैर-आबादी वाले आबादी से संबंधित मुद्दे, (ii) कम्प्यूटेशनल रूप से महंगे होने, (iii) व्यापार बंद सतहों के प्रतिनिधित्व में कठिनाइयाँ, आदि। इनमें से कुछ चुनौतियों का समाधान इस काम में किया गया है। इस शोध का उद्देश्य कई-उद्देश्य-निर्धारण शेड्यूल मॉडल (एमओएसएम) विकसित करना है। उद्देश्य को प्राप्त करने के लिए, निम्नलिखित पांच शोध उद्देश्यों को निर्धारित किया गया है।

- (i) निर्माण शेड्यूलिंग मॉडल के लिए सबसे उपयुक्त अनुकूलन एल्गोरिदम के चयन के लिए एक गुणात्मक रूपरेखा विकसित करना।
- (ii) निर्माण परियोजना के लिए कई-उद्देश्य-व्यापार-बंद समयबद्धन मॉडल विकसित करना।
- (iii) विकसित कई-उद्देश्य-समयबद्धन-मॉडल (एमओएसएम) की प्रयोज्यता की जांच करना।
- (iv) एमओएसएम मॉडल में एक निर्माण परियोजना की गतिविधि-वार जीवन चक्र लागत (एलसीसी) को सम्मिलित करने के लिए।
- (v) एमओएसएम के लिए कई-उद्देश्य-मॉडल-ग्राफिकल-यूजर-इंटरफेस (एमओएमजीयूआई) विकसित करना।

पहला शोध उद्देश्य प्राप्त करने के लिए, प्रदर्शन मापदंडों की पहचान के लिए एक व्यापक साहित्य सर्वेक्षण किया गया और आमतौर पर तत्काल डोमेन में एल्गोरिदम का उपयोग

किया गया। साहित्य सर्वेक्षण में १३ प्रदर्शन मापदंडों और छह अनुकूलन एल्गोरिदम को अंतिम रूप दिया गया। छह ऑप्टिमाइज़ेशन एल्गोरिदम को शामिल करते हुए प्रश्नावली सर्वेक्षण का उपयोग करते हुए एक जोड़ी की तुलना की गई और लगातार फजी वरीयता संबंध (सीएफपीआर) विधि के सिद्धांतों का उपयोग करके प्रतिक्रियाओं का विश्लेषण किया गया। सीएफपीआर का उपयोग करने के विश्लेषण से छह एल्गोरिदम की रैंकिंग हुई। गैर-वर्चस्व वाली सॉर्टिंग जेनेटिक अल्गोरिदम (एनएसजीए) को निर्माण शेड्यूलिंग के लिए सबसे उपयुक्त एल्गोरिदम पाया गया, जबकि छह एल्गोरिदम के बीच पूर्णांक / रैखिक प्रोग्रामिंग को सबसे कम पसंद किया गया था।

सबसे उपयुक्त एल्गोरिदम के रूप में एनएसजीए की पहचान के बाद, दूसरे अनुसंधान उद्देश्य को पूरा करने के लिए कई उद्देश्य-निर्धारण शेड्यूल मॉडल (एमओएसएम) विकसित किया गया था। विकसित मॉडल को साहित्य में उपलब्ध दो उदाहरणों का उपयोग करके सत्यापित किया गया था।

कई-उद्देश्य व्यापार बंद के लिए विकसित मॉडल की प्रयोज्यता का पता लगाने के लिए, साहित्य से अपनाए गए दो अतिरिक्त मामले अध्ययन उदाहरणों को तीसरे अनुसंधान उद्देश्य को पूरा करने के लिए हल किया गया था। पहला मामला अध्ययन उदाहरण, समय-लागत-पर्यावरण-संसाधन (टीसीईआर) के परियोजना उद्देश्यों से निपटा, जबकि दूसरा, समय-लागत-गुणवत्ता-सुरक्षा (टीसीक्यूएस) से निपटा।

पहले मामले के अध्ययन के उदाहरण के लिए, पहले तीन उद्देश्य (समय-लागत-पर्यावरण [टीसीई]) व्यापार-बंद समस्या को विकसित मॉडल का उपयोग करके हल किया गया था। बाद में, विकसित मॉडल का उपयोग एक अतिरिक्त उद्देश्य पर विचार करके हल करने के लिए किया गया था, जो संसाधन के क्षण को एक चार उद्देश्य की समस्या (समय-लागत-पर्यावरण-संसाधन (टीसीईआर) बनाने के लिए था। इसका निहितार्थ प्रदर्शित करने के लिए बिल्ड-अप के रूप में आवश्यक था। पूर्ववर्ती तीन-उद्देश्य समस्या के लिए प्राप्त समाधान पर चौथा उद्देश्य जोड़ना। परिणामों से पता चला कि विकसित मॉडल अन्य तीनों से समझौता किए बिना चौथे उद्देश्य के लिए इष्टतम व्यापार-बंद समाधान प्राप्त करने में सक्षम था। इसी तरह के परिणाम भी देखे गए हैं। मामला जब सुरक्षा का एक अतिरिक्त उद्देश्य मौजूदा तीन उद्देश्य मॉडल में जोड़ा गया था जो समय-लागत-गुणवत्ता से संबंधित था। इसने कई-उद्देश्य व्यापार-बंद संदर्भ में विकसित मॉडल की प्रयोज्यता को दृढ़ता से उचित ठहराया।

बढ़ता हुआ औद्योगीकरण एक स्थायी मॉडल की मांग करता है जो सामान्य रूप से निर्माण उद्योग और विशेष रूप से निर्माण पेशेवरों को लाभ दे सकता है। अनुसंधान उद्देश्य चार में अर्थव्यवस्था में स्थायी स्तंभों में से एक को प्राप्त करना शामिल था। शेड्यूलिंग मॉडल में जीवन चक्र लागत (एलसीसी) को एकीकृत करके यह प्रयास किया गया था। एलसीसी को एकीकृत करने के लिए, एक गतिविधि-वार जीवन चक्र लागत विश्लेषण (एलसीसीए) को वास्तविक वास्तविक जीवन के मामले में नागरिक और इलेक्ट्रिकल और मैकेनिकल (इ एंड एम) कार्यों पर विचार किया गया था। गतिविधि-वार एलसीसी अध्ययन एक विशेष गतिविधि के लागत-लाभ विश्लेषण में हितधारकों से नई अंतर्दृष्टि प्राप्त करने के लिए किया गया था। इसका उद्देश्य हितधारकों की मदद करना है, जो काम के पहले उपेक्षित वस्तुओं पर ध्यान केंद्रित करते हैं जो एक संरचना के एलसीसी पर महत्वपूर्ण प्रभाव डालते हैं। परिणामों से पता चला कि निर्माण लागत की क्रमशः सिविल और ई एंड एम के काम की लागत हिस्सेदारी ८० % और २० % थी। हालाँकि, जब एलसीसी पैरामीटर था, तो ये प्रतिशत ६० % और ४० % सिविल और इ एंड एम आइटम के लिए बदल गए। एक बार गतिविधि-वार एलसीसी की गणना करने के बाद, उन्हें ट्रेड-ऑफ मॉडल में आगे बढ़ाया गया। इस व्यापार-बंद मॉडल ने समय के साथ एलसीसी को एकीकृत किया। इसके बाद, एमओएसएम के साथ समय- एलसीसी व्यापार-बंद (टीसीटी) का विश्लेषण किया गया। इसके अलावा, टीएलटी मॉडल की तुलना समय-लागत ट्रेड-ऑफ मॉडल के साथ की गई ताकि परिणामों में अंतर्दृष्टि हो। यह इस नतीजे से सामने आया कि टीएलटी के पास टीएलटी के फायदे हैं, इस हद तक कि यह किसी भी गतिविधि को निष्पादित करने के लिए अधिक आर्थिक तरीका प्रदान करता है।

अंत में, पांचवें अनुसंधान उद्देश्य को संबोधित करने के लिए एक कई-उद्देश्य मॉडल ग्राफिकल यूजर इंटरफेस (एमओएमजीयूआई) विकसित किया गया था। एमओएमजीयूआई को चिकित्सकों द्वारा विकसित एमओएसएम के आसान अनुप्रयोग की सुविधा प्रदान करनी चाहिए। मॉडल मेंटलेब 'ऐप डिजाइनर' में विकसित किया गया था। एमओएमजीयूआई को इस उद्देश्य के साथ विकसित किया गया था कि वह दो उद्देश्यों, तीन उद्देश्यों और चार उद्देश्यों के साथ व्यापार-बंद समस्याओं से निपटने में सक्षम होना चाहिए। मॉडल को प्रभावशीलता, दक्षता, सगार्इ, त्रुटि सहिष्णुता और सीखने में आसानी सहित पांच मानदंडों के तहत इसकी प्रयोज्यता के लिए जाँच की गई थी। यह संतोषजनक रूप से काम करता पाया गया।

तैयार एमओएसएम निर्माण चिकित्सकों के लिए एक उपयोगी अंतर्दृष्टि प्रदान करता है। यह मॉडल दो से चार निर्माण परियोजना के उद्देश्यों पर बहुत कुशलता से विचार करते हुए एक इष्टतम कार्यक्रम तैयार करने में सक्षम है। इसके अलावा, यह अध्ययन एक महत्वपूर्ण घटक के रूप में आर्थिक स्थिरता प्रदान करता है जिसे उद्देश्यों में से एक में शामिल किया गया है और मॉडल में एकीकृत किया गया है। यह निर्णय नियोजकों को परियोजना नियोजन चरण में इस समग्र मॉडल का उपयोग करने के लिए प्रोत्साहित करेगा। इसके अलावा, यह हितधारकों को किसी भी निर्माण परियोजना में एक सुरक्षित कार्य वातावरण, समय-समय पर पूरा होने, पर्यावरण के अनुकूल, आर्थिक रूप से टिकाऊ और गुणवत्ता वाले अंत उत्पाद को सुनिश्चित करने में मदद करेगा।

कुंजीशब्द: कई-उद्देश्य, शेड्यूलिंग, लगातार फजी वरीयता संबंध, गतिविधि-वार, जीवन चक्र लागत, ग्राफिकल यूजर इंटरफेस।

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LIST OF ABBREVIATIONS

ACO	Ant Colony Optimization
AHP	Analytical Hierarchy Process
AMC	Annual Maintenance Contracts
BOQ	Bill Of Quantity
CC	Construction Cost
CFPR	Consistent Fuzzy Preference Relation
CPM	Critical Path Method
CPWD	Central Public Works Department
CSM	Construction Scheduling Models
CSP	Construction Scheduling Problem
DM	Diversification Metric
E&M	Electrical and Mechanical
ECC	Engineered Cementitious Composite
EoLC	End-of-Life Cost
FPR	Fuzzy Preference Relation
FV	Future Value
GA	Genetic Algorithm
GHG	Greenhouse Gas
HM	Heuristic Methods
HVAC	Heating, Ventilation, and Air Conditioning
HypE	Hyper Volume Estimation
IP	Integer Programming
LCC	Life Cycle Cost
LCCA	Life Cycle Cost Analysis
LP	Linear Programming
MAD	Mean Absolute Deviation
MAPE	Mean Absolute Percentage Error
MID	Mean Ideal Distance

MOSP	Multi-Objective Scheduling Problem
MoMGUI	Many-objective Model Graphical User Interface
MOO	Multi-Objective Optimization
MOSM	Many-Objective Scheduling Model
MPR	Multiplicative Preference Relations
MSE	Mean Square Error
NIDR	Net Inflation Discounted Rate
NPV	Net Present Value
NS	Number Of Solutions
NSGA	Non-Dominated Sorting Genetic Algorithm
OC	Operational Cost
PERT	Program Evaluation Review Technique
PM	Polynomial Mutation
PSO	Particle Swarm Optimization
PV	Present Value
QM	Quality Matrices
R&MC	Repair and Maintenance Cost
RCC	Reinforced Cement Concrete
RCPSP	Resource Constraint Project Scheduling Problem
RepC	Replacement Cost
SBX	Simulated Binary Crossover
SM	Spacing Metric
SMA	Simple Moving Average
SNS	Spread of Non-Dominant Solution
TC	Time-Cost
TCQ	Time-Cost-Quality
TCQS	Time-Cost-Quality-Safety
TCER	Time-Cost-Environment-Resource
TCS	Time-Cost-Safety
TCT	Time-Cost Trade-off
TCTP	Time-Cost Trade-off Problems

TLT	Time-LCC Trade-off
TR	Thumb Rules
UX	User Experience