PROJECT PLANNING AND SCHEDULING USING SYSTEM DYNAMICS FOR DEALING WITH COMPLEXITY ON CONSTRUCTION PROJECTS

Mehran Barani Shikhrobat[1], Shabnam Kabiri and Roger Flanagan

School of Construction Management and Engineering University of Reading, Chancellor's Building, Whiteknights, Reading, RG6 6DF, UK

Classical static project planning methods, such as CPM, was developed for a construction industry with more certainty, less complexity, and not having to cope with the speed of change experienced today. Many projects using traditional planning methods fail to deliver projects on time. The results are deterministic and unreliable to deliver the project objectives. This originates from ignorance of understanding the cause and effect relationships of different internal and external elements in a modern construction project. Increased complexity is one of the fundamental issues causing project failure. Planning systems must deal with increased complexity, which traditional systems do not manage. Projects can be technically complex, organisationally complex, and environmentally complex. The research uses a bottom-up approach to develop a conceptual framework to map complexity and improve the flow of information in the project planning stage of construction projects. The expectation is to understand the realistic view of project scheduling considering projects complexity and uncertainties and project factors interactions. This is based on project scheduling with simulation using system dynamics. The proposed framework in this research aims to provide an enhanced method of considering a project different parts behaviour and the consequence. This study contributed to the existing literature of understanding the complexity degree of dynamic scheduling. Furthermore, in the presented holistic analysis by identifying different complexity causes elements and prioritise those allows project planners and engineers to minimize the scheduling variance of operation in reality. There is no evidence showing this has been done before.

Keywords: scheduling, complexity, system dynamics, project planning

INTRODUCTION

Planning, sometimes called programming, is about breaking down a project into individual operations/activities/work packages and defining a logical sequence of events that will deliver a completed project. Managing the dependencies between those operations and the resources requires an understanding of the design and complexity of the project. Planning is effectively defining what is to be done and how; scheduling is the when. Providing a reliable project planning and scheduling method is increasingly important for construction projects (Serrador and Turner, 2015). Projects run over budget and over time for a variety of reasons, often the construction programme produced at the commencement of the project is wrong, based on incorrect assumptions and incomplete information. Programmes are often

[1] mshikhrobat@yahoo.com

Shikhrobat, M B, Kabiri, S and Flanagan, R (2019) Project Planning and Scheduling Using System Dynamics for Dealing with Complexity on Construction Projects *In:* Gorse, C and Neilson, C J (Eds) *Proceedings of the 35th Annual ARCOM Conference,* 2-4 September 2019, Leeds, UK, Association of Researchers in Construction Management, 689-698.

over optimistic and fail to recognise incomplete design and the overlap of design and production. Current methods and applications have remained theoretically and objectively static, using primarily deterministic planning approaches. Deterministic planning involves selecting one course of action for activities; this makes consideration of alternative options very limited and whilst CPM has float times, the programme follows a pre-determined course of action. Probabilistic planning allows for alternative course of action at the planning stage. It is more difficult to implement, because of the need for information about the different options, which presents challenges. Researches has attempted to remove or reduce the dissatisfaction with the programming systems, with little progress (Andersen, 1996; Collyer *et al.,* 2010). One important difficulty argued by Collyer and Warren (2009, 355) is that "any project has some "degree of dynamism". Dynamic is a term used in project planning as describing that a project is not characterised by a solid and predefined environment; it is influenced by constant change. This has resulted in a poor or inadequate planning expectations, which negatively links to project outcomes, and creating problems that impact on construction project management. The pre-project planning process must be recognized as a formal, well-organized planning process, with specific deliverables (Hamilton and Gibson Jr. 1996, 32). Significant project planning is designed and developed as a crucial part of the system development process (Chatzoglou and Macaulay, 1996). For project planning it is vital to distinguish between two types of contingency. Contingency can facilitate project planning by preparing several possibilities on activities of duration to minimise what time is needed for activities (Laufer and Tucker, 1987). However, construction projects are executed in a complex dynamic environment, characterized by uncertainty and risk (Schatteman *et al.,* 2008). Complex means many parts are included, often interrelated that can make the settings complicated or difficult to understand. Deterministic outcomes exist in a vacuum, frequently ignoring other influences on the work breakdown structure. Hence, planning and scheduling is not a linear process, just like design it is iterative, yet planning systems assume linearity and sequential connections. They do consider interdependence, but the problem is that planning is a system, made up of many interdependent sub-systems. The framework in this research brings a structure using system dynamics to include the entire elements of scope of project, work breakdown structure (WBS), design team, supply chain, resources, performance and objectives of a project. System dynamics is design to cope with complex systems.

Scheduling Robustness

Robust scheduling is a method of multi-objectives consideration. While in a stochastic scheduling method, the probability distribution of the uncertainty is essential; in a robust optimization, it is not necessarily required. The aim of robust optimization is to reflect flexibility by applying the possibility for the uncertainties. However, two shortcomings are important in a robust scheduling method: 1) a robust solution may suffer from poor representation on objective values truthiness; 2) the unpredictability perspective of the robust solution to variation in the uncertainty set is not considered (Coleman *et al.,* 2013). A fundamental scheduling problem as Lyneis *et al.,* (2001, 238) argues is that most project management tools assume sequential linearity, with the belief that interconnected activities are controllable. They either (1) view a project statically, or (2) take a partial, narrow view to allow managers to cope mentally with the complexity. Such approaches are unrealistic in practice because regular or irregular surprises and uncertainties arise in project execution, many of which are uncontrollable, they can cause disruptions on scheduling. Nevertheless, "a project schedule can rarely be implemented exactly in a realistic project environment such that the planned optimal project completion time is achieved" (Yang 1996, 256). Due to frequent re-scheduling, scheduling disruptions increases the complexity of scheduling system (Herroelen and Leus, 2004). The validity of project scheduling with its static deterministic products have been severely critiqued (Goldratt, 1997). The consequences of those uncertainties on project performance creates severe damage to the original expectations. Consequently, any generated solution of these approaches is becoming absolute from the starting point of project execution. Herroelen and Leus (2004, 550) highlighted that "the development of a pre-computed baseline schedule (pre-schedule) with the objective of assuring stability in the start times of the activities, rather than the minimization of the expected project duration or some other regular objective function, has been mostly overlooked so far".

Scheduling Methods, Complexity Variables and Degree

Traditional planning systems such as CPM and PERT fail to take account of complexity, which results from uncertainty and the dynamic environment of a construction site. Fuzzy logic, stochastic scheduling, and sensitivity analysis do not solve the problem of better decisions, because they rely on optimization. A new approach is needed that can measure complexity at the outset of a project to alert the site production team. Gidado (1996) summarises the complexity meaning from the interview results from expert's viewpoint of construction projects into two managerial and technical perspectives. Understating the effects of strategies, policies and techniques that are having impacts on the performance are underlined in the research of Vieira *et al.,* (2003). Rather than focusing on minimizing the number of activities, they presented an alternative justification for decreasing the complexity index. Complexity index describes as a developed method to define complexity as practised (Mattsson *et al.,* 2012). Kamburowski *et al.,* (2000) states that understanding the complexity index (CI) of scheduling network of project management techniques is the most fundamental factor. However, in the event that the number of nodes is not limited or not clearly well-known, has found hard to decreasing complexity index (CI) factor. Furthermore, Bregman (2009) to control the probability completion for pre-defined due dates, introduced a dynamic matrix simulation method for selecting possibilities. In this research, the uncertainty sources are excluded. Therefore, many reality behavior of project's activities may not be included. Ouelhadj and Petrovic (2009) divided dynamic scheduling into resource-related and job-related categories. Resource-related are human resources, material shortages, operational machine failure, and delays based on resources preparation. Job-related are changes on due dates, priority changes, time processing changes, and new activities arrival or removal. In reality, construction projects are highly dynamic and dealing with complexity and uncertainty. This emerge scheduling a consideration for the purpose of effective planning success. Thus, it is vital to understand the major variables of scheduling complexity. Faniran *et al.,* (1998) literature review from various studies have highlighted scope of project, work breakdown structure (WBS), design team, supply chain, resources, performance and objectives as the main variables of construction project planning and scheduling. Therefore, dynamic scheduling method in this study focus is to present a framework of understanding expectations based on complexity degree towards a focus on the dynamic interactions between complexity, influencers and objectives within which project operates. For this aim, understanding the system thinking idea as a purposive classification, and the significance of "system's boundaries" and "interfaces" is essential. This can improve the understanding of project scheduling system in an imperfect word dealing with complexity, interdependence, uncertainty, risk, constant changes, speed of change and properties that are out of control. However, the literature review found no evidence showing how to consider complexity degree as a technique of understanding and controlling uncertainties to achieve the desired scheduling objectives.

METHODOLOGY

Dynamic Scheduling Framework

In reality, the intended pre-plan structure is constantly changes regarding to dynamic behaviour of construction projects. The dynamic behaviour that increases the complexity of project scheduling. Figure 1 shows the proposed conceptual framework. This includes two different variables consisting of controllable and uncontrollable. Controllable variables are referring to the variables that are in control of project management team. Controllable variables used in this framework are consisting of scope of project, work breakdown structure (WBS), design team, supply chain, resources, performance and objectives. Also, uncontrollable variable is referring to those that are out of control for instance weather changes or inflation rate changes. This is turned up as externalities variable in the proposed framework. Furthermore, system dynamics is used in dealing with cause-effect and stock and flow diagrams analysis to understanding the complexity degree of pre-plan scheduling. Design and implementation of dynamic scheduling conceptual framework is shaped by using systems thinking and system design. The conceptual framework proposed in this research enables project scheduling derived by practitioners and engineers to be more realistic. Therefore, the project scheduling conceptual framework proposed aim is to understand the dynamic scheduling elements used to analyse the complexity degree. This is leading to considerate the flow of changes regarding to complexity degree on the desired objective. These essential factors are targeted to decrease the scheduling variance as aimed in the research. However, this may include a broad range of further objectives depends on a specific scheduling plan. This is regarding to different internal and external parties, limitations and expectations to operate a finalized plan.

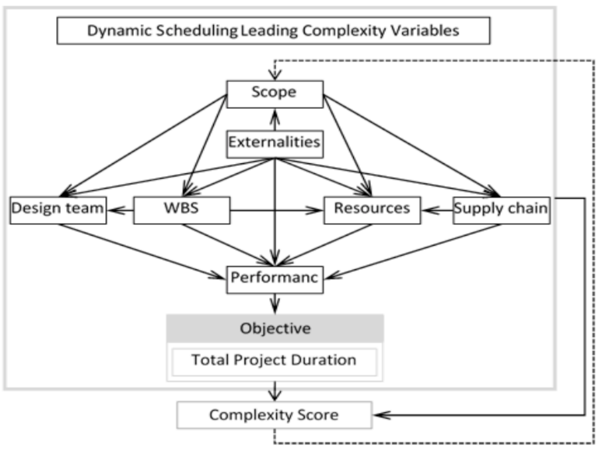


Figure 1: Dynamic scheduling for complexity control model

Figure 1 proposed a model for complexity control of a dynamic scheduling. Total project duration expectation, a more reliable scope, understanding scheduling expectations that are not considered in the initial scheduling and those changes that may appear in further steps, a brighter understanding of the total project duration of estimation. The classical scheduling tools and techniques are not practically designed to include the complexity degree, for instance CPM and PERT. The proposed framework is capable to build a bridge between targeted objective and reality of dynamic behaviour of construction projects by considering the complexity degree constructed on both controllable and uncontrollable variables.

System Dynamics Used in Modelling

The application of system dynamics was proposed Jay Forrester (1961) in the book on Industrial Dynamics. System dynamics was developed by engineers as either the strategic management design or decision-making tool across different industries from construction to manufacturing and IT development (Rodrigues and Bowers, 1996). The system dynamic emphasis is on understanding the dynamic form and the internal interactions role of different variables in reality of a system. It "addresses problematic behaviour patterns caused primarily by the feedback structure of the setting" (Barlas 2007, 470). The main focus of system dynamics is on dynamic changes and the strength of the interactions of elements over time. The four basic elements of the system dynamics method (Richardson, 2011) are 1) information of feedback from systems theory, 2) understanding of decision-making procedure, 3) the empirical approach of complex method, and 4) the simulation of realistic assumptions. Multiple influencers with negative and positive feedback are the behaviour modes of nonlinear systems. For the structure theory of the model, it is initiated a four substantial level mode consisting of "The Closed Boundary", "The Feedback Loop", "Levels" and "Flows" (Forrester 1968, 406). The model can capture reactions and delays in time in a broad margin of limitations (Sterman, 2002). System dynamics is not a model to create, but to solve the systematic issues reflected in a management behaviour. The benefits of using system dynamics varies from "strategy support" to managing industry changes (Dangerfield *et al.,* 2010, 411). One of the most significant tasks in the development of system dynamics is the model conceptualisation (Luna-Reyes, 2003). Randers (1980, 117) introduced an "effective procedure" of "model conceptualisation", consisting of 1) conceptualisation, 2) formulation, 3) testing and 4) implementation. Conceptualisation defines the questions to be addressed, sets the boundaries of the system, time distribution, and describe the casual diagram form as the basic mechanism. Formulation to conjecture of detailed structure. Testing either model assumptions or the dynamic behaviour. Implementation to understanding the model behaviour. The content is on understanding how to control the complexity as the core factor of project scheduling and planning variance based upon understanding the relationships between the complexity factors (influencers) and scheduling objectives.

DATA ANALYSIS

Expected Value Factors and Weight Scores

Eight factors are weighed, making a matrix of eight column and eight rows. The factors are the scope of project, work breakdown structure (WBS), design team, supply chain, resources, externalities, performance and objectives. This needs to be combined with a decision-making method for instance Analytic Hierarchy Process (AHP). AHP is developed by (Saaty, 1980) and is known as a decision-making process. It aims to quantify the priorities from a set of relative objectives based on the judgment with considering multi-criteria factors. The focus of AHP method is to understand the consistency of the alternative comparison in the process of decision-making (Saaty, 2008). It is able to organise factors in a systematic and structured way with simple clarification to the decision-making difficulty (Skibniewski and Chao, 1993). The weight factor is generally a measure of relative quantity meaning for each objective. Furthermore, selecting weight is to reflect the preference of the objectives. AHP method identifies the accurate weight for factors used in the matrix organization analysis of related accurate eigenvectors (Forman and Gass, 2001). (Saaty, 2008) considered for steps for AHP process. First, developing a matrix to determining the hierarchy organisation for instance. Then, developing the matrix to show a set of comparison pairwise. After, consistency evaluation for the judgment, and finally, prioritising.

$$S = \begin{pmatrix} \frac{a1}{a1} & \frac{a1}{a2} & \cdots & \frac{a1}{an} \\ \frac{a2}{a1} & \frac{a2}{a2} & \cdots & \frac{a2}{an} \\ \cdots & \cdots & \cdots & \cdots \\ \frac{an}{a1} & \frac{an}{a2} & \cdots & \frac{an}{an} \end{pmatrix} * \begin{pmatrix} w1 \\ w2 \\ \cdots \\ \cdots \\ wn \end{pmatrix} = \lambda max * \begin{pmatrix} w1 \\ w2 \\ \cdots \\ \cdots \\ wn \end{pmatrix} = \begin{pmatrix} b1 \\ b2 \\ \cdots \\ \cdots \\ bn \end{pmatrix} \text{ (equation 1)}$$

Which $\lambda max = \left(\frac{1}{n}\right) * \sum_{i=1}^{n} \frac{bi}{wi}$ (equation 2); Consistency Index (CI) = (λmax - n) / (n - 1) (equation 3); Consistency Ratio (CR) = CI / RI (Average Random Consistency Index (RI) (equation 4) is taken from the following table 1 presented by (Saaty, 1980)).

Table 1: Average random consistency (RI)

Strength	Quantity	Description
A	1	A and B are equally important
B	3	A is moderately more important than B
C	5	A is strongly more important than B
D	7	A is much more important than B

The eight factors presented in dynamic scheduling framework (Figure1) prescribed in an 8*8 matrix shown in Table 3.

Table 3: A Pairwise comparison of factors in AHP

	Scope	Externalities	Design team	WBS	Resources	Supply chain	Performance
Scope	0.20	1	1	5	1	1	1
Externalities	0.20	1	1	1	1	1	1
Design team	0.14	0.20	1	1	1	1	1
WBS	0.33	1	1	1	1	1	1
Resources	0.14	1	1	1	1	1	1
Supply chain	0.20	1	1	1	1	1	1
Performance	0.20	1	1	5	1	1	1
Objective	1	1	1	1	1	1	1
Total	3.22	11.20	12.00	18.00	10.00	14.00	12.00

The random index is equal to 1.40, and therefore the consistency ratio is equal to 0.02.

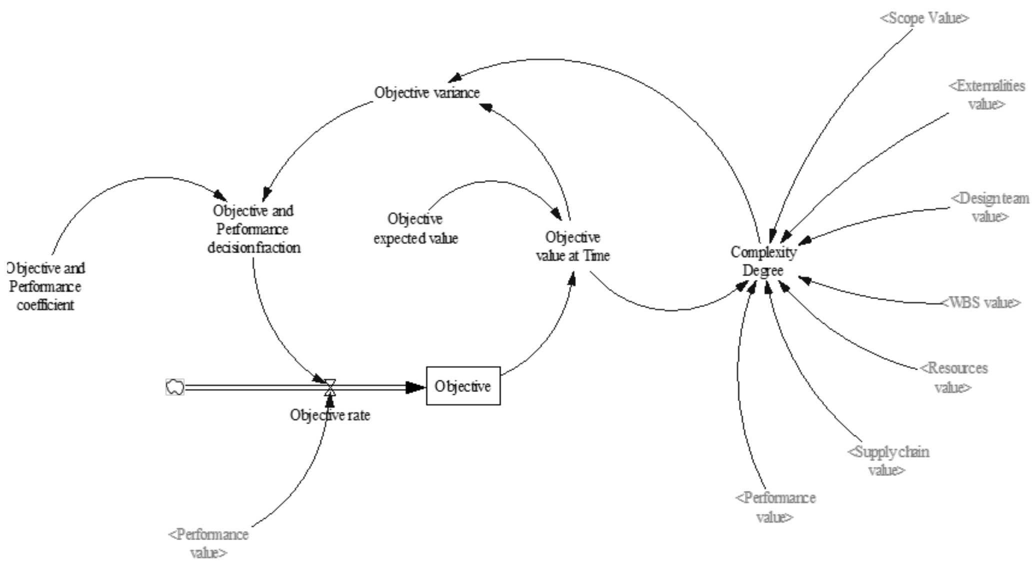
The final stage shown in Table 4, is to use a mathematical method, for instance Least Square Linear regression to understand the coefficients between different variables presented in Figure 1.

Table 1: Summary of factors coefficients

Variables	Dependants	Coefficient
Design team	Externalities	0.48
Design team	Scope	0.25
	Externalities	0.46
	WBS	0.27
WBS	Scope	0.16
	Externalities	0.26
Resources	WBS	0.17
	Externalities	0.08
	Scope	0.17
Supply chain	Scope	0.23
	Externalities	0.18
Performance	Design team	0.22
	WBS	0.11
	Resources	0.04
	Supply chain	0.35
	Externalities	0.21
Objectives	Performance	0.03

System Dynamics Model Development

The system dynamics model presented in Figure 2 shows that dynamic scheduling allows consideration of the possible uncertainties regarding the complexity of project scheduling.



Simulation Results

Dynamic project scheduling using system dynamics are simulated using Vensim software. The results consist of different components of scheduling complexity control, dynamic scheduling information and objectives. The simulation graphs demonstrate the behaviour of different component over time shown in Figure 3.

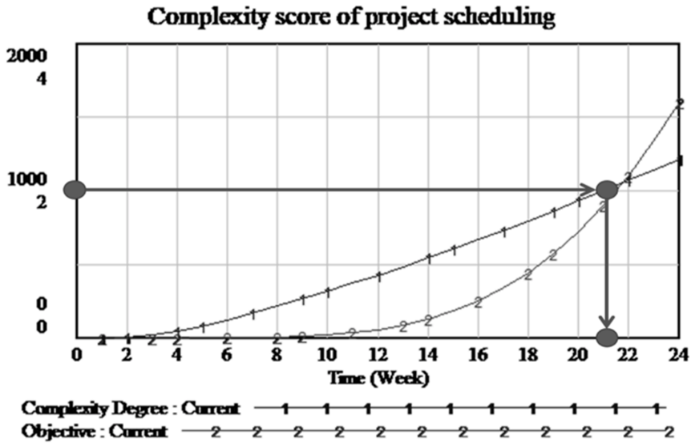


Figure 3: Complexity and Total Project Duration over time

Figure 3 illustrates the changes of both the complexity degree and objectives for a project with 11 weeks period. Initial value for all variables is planned at 1000 for the running period. The graph shows to reach the 1000 value assumed in the case study; the objectives are changing too. The total project duration with considering complexity degree based on the given assumptions is equal to 21 weeks.

CONCLUSIONS

This paper proposes a new approach by using system dynamics to identify causal loops and flow components to help in the planning and scheduling process. The technique needs further development and testing, but the idea is to stimulate a new approach to producing more reliable planning and scheduling. The dynamic scheduling model will be validated by more case studies in further steps of the research.

REFERENCES

Ackoff, R (1970) A concept of corporate planning, *Journal of the Operational Research Society*, 22(**2**),193-194.

Allam, S I G (1988) Multi-project scheduling: A new categorization for heuristic scheduling rules in construction scheduling problems, *Construction Management and Economics*, 6,93-115.

Andersen, E S (1996) Warning: Activity planning is hazardous to your project's health! *International Journal of Project Management*, 14(**2**), 89-94.

Barlas, Y (2007) Leverage points to march 'upward from the aimless plateau', *Built Environment*, 23(**4**), 469-473.

Belhe, U and Kusiak, A (1997) Dynamic scheduling of design activities with resource constraints, *IEEE Transactions on Systems*, 27(**1**), 105-111.

Bregman, R L (2009) A heuristic procedure for solving the dynamic probabilistic project expediting problem, *European Journal of Operational Research*, 192, 125-137.

Chatzoglou, P D and Macaulay, L A (1996) A review of existing models for project planning and estimation and the need for a new approach, *International Journal of Project Management*, 14(**3**),173-183.

Coleman, T F, Moazeni, S and Li, Y (2013) Regularized robust optimization: The optimal portfolio execution case, *Computational Optimization and Applications*, 55(**2**), 341-377.

Collyer, S and Warren, C M J (2009) Project management approaches for dynamic environments, *International Journal of Project Management*, 27(**4**), 355-364.

Collyer, S, Warren, C, Hemsley, B and Stevens, C (2010) Aim, fire, aim-project planning styles in dynamic environments, *Project Management Journal*, 41(**4**), 108-121.

Cowling, P and Johansson, M (2002) Using real time information for effective dynamic scheduling, *European Journal of Operational Research*, 139, 230-244.

Dangerfield, B, Green, S and Austin, S (2010) Understanding construction competitiveness: the contribution of system dynamics, *Construction Innovation*, 10(**4**), 408-420.

Dumond, J and Mabert, V. A (1988) Evaluating project scheduling and due date assignment procedures: An experimental analysis, *Management Science*, 34(**1**), 101-118.

Egan, J (1998) Rethinking construction: Report of the construction task force on the scope for improving the quality and efficiency of UK construction, *Structural Engineer*, 80(**14**), 2.

Faniran, O O, Oluwoye, J O and Lenard, D J (1998) Interactions between construction planning and influence factors, *Journal of Construction Engineering and Management,* 124(**4**), 245-256.

Fisher, A C, Liebman, J S and Nemhauser, G L (1968) *Computer construction of project networks*, *Communication of the ACM*, 11(**7**), 493-497.

Forman, E H and Gass, S I (2001) The Analytic Hierarchy Process: An Exposition, *Operations Research*, 49(**4**), 469-486.

Forrester, J W (1968) Industrial dynamics - After the first decade, *Management Science*, 14(**7**), 398-415.

Gidado, K I (1996) Project complexity: The focal point of construction production planning, *Construction Management and Economics*, 14(**3**), 213-225.

Goldratt, E (1997) *Critical Chain*. Great Barrington, MA: The North River Press.

Hamilton, M R and Gibson Jr, G E (1996) Benchmarking preproject planning effort, *Journal of Management in Engineering*, 12(April), 25-33.

Herroelen, W and Leus, R (2004) The construction of stable project baseline schedules, *European Journal of Operational Research*, 156(**3**), 550-565.

Kamburowski, J, Michael, D J and Boulevard, E L C (2000) Minimizing the complexity of an activity network, *Networks*, 36(**1**), 47-52.

Kotter, J P (1995) Leading change: Why transformation efforts fail the promise of the governed corporation, *Harvard Business Review*, (March-April), 59-67.

Krishnamoorthy, M S and Deo, N (1979) Complexity of the problem in a Pert network, *Networks*, 9, 189-194.

Laufer, A and Tucker, R L (1987) Is construction project planning really doing its job? A critical examination of focus, role and process, *Construction Management and Economics*, 5(**3**),243-266.

Luna-Reyes, L (2003) Model conceptualization: A critical review, *In: Proceedings of the 21st International Conference of the System Dynamics Society*, 1-11.

Lyneis, J M, Cooper, K G and Els, S A (2001) Strategic management of complex projects: A case study using system dynamics, *System Dynamics Review*, 17(**3**), 237-260.

Mattsson, S, Gullander, P, Harlin, U, Bäckstrand, G, Fastha, Å and Davidssond, A (2012) Testing complexity index - A method for measuring perceived production complexity, *Procedia CIRP*, 3, 394-399.

Monroy-licht, M and Alberto, C (2017) The rescheduling arc routing problem, *International Transactions in Operational Research*, 24, 1325-1346.

Morris, P W G (1983) Managing project interfaces - Key points for project success, *Project Management Handbook*, 16-55.

Ouelhadj, D and Petrovic, S (2009) A survey of dynamic scheduling in manufacturing systems, *Journal of Scheduling*, 12(**417**).

Randers, J (1980) *Guidelines for Model Conceptualization, Elements of the System Dynamics Method*. Cambridge, MA: MIT Press, 117-139.

Richardson, G (2011) Reflections on the foundations of system dynamics, *System Dynamics Review*, 27(**3**), 219-243.

Rodrigues, A and Bowers, J (1996) The role of system dynamics in project management, *International Journal of Project Management*, 14(**4**), 213-220.

Saaty, T L (2008) Decision making with the analytic hierarchy process, *International Journal of Services Sciences,* 1(**1**),83-98.

Saaty, T L (1980) *The Analytic Hierarchy Process*. New York: McGraw-Hill.

Schatteman, D, Herroelen, W, Vonder, S Van De and Boone, A (2008) Methodology for integrated risk management and proactive scheduling of construction projects, *Journal of Construction Engineering and Management*, 134(11), 885-893.

Serrador, P and Turner, R (2015) The relationship between project success and project efficiency, *Project Management Journal*, 46(**1**), 30-39.

Skibniewski, M J and Chao, L (1993) Evaluation of advanced construction technology with AHP method, *Journal of Engineering Management*, 118(**3**), 577-593.

Sterman, J D (2002) *System Dynamics: Systems Thinking and Modeling for a Complex World*. Cambridge: Cambridge University Press.

Stoop, P P M and Wiers, V C S (1996) The complexity of scheduling in practice. *International Journal of Operations and Production Management*. 16(**10**), 37-53.

Vieira, G E, Herrmann, J W and Lin, E (2003) Rescheduling manufacturing systems: A framework of strategies, policies and methods, *Journal of Scheduling*, 6, 39-62.

Yamamoto, M (1985) Scheduling/rescheduling in the manufacturing operating system environment, *International Journal of Production Research*, 23(**4**), 705-722.

Yang, K K (1996) Effects of erroneous estimation of activity durations on scheduling and dispatching a single project, *Decision Sciences*, 27(**2**), 255-290.