Impact of BIM on Field Pipeline Installation Productivity Based on System Dynamics Modeling

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Abstract –

It is well documented that Building Information Modeling (BIM) can significantly improve project performance and productivity. Although the construction phase typically involves in the largest part of financial cost during the project life, insufficient attention has been paid in academia to quantitatively address the impact of BIM on labor productivity. This paper studies the effects of BIM on field pipeline installation productivity using system dynamics modeling. The critical impact factors of BIM on pipeline installation productivity are identified and a system dynamics model is established to map the impact mechanism and quantify the BIM impact on labor productivity. The model is applied to evaluate the pipeline installation productivity of three large scale buildings and their productivity indices are compared. The comparison shows a positive impact of BIM on pipeline installation productivity, resulting in 13~38% of increase in labor productivity dependent on different trades and project phase of BIM application.

Keywords –

Information technology impact; BIM; system dynamic modeling; field productivity

1. Introduction

Labor productivity (LP) is an important index of project performance that reflects the cost conversion efficiency of a project. As reported by the US Bureau of Labor Statistics, the construction LP has been declining in recent years mainly due to the gap between design and construction, relatively low systematic information technology (IT) application and insufficient investment of research and innovation [1]. To improve the LP of the construction industry, significant changes are required in the development of information tools and the formulation of collaborative strategies. Embedding parametric design in a 3D platform, BIM has been proposed to improve construction LP since its emergence. The past decades have seen wide application of BIM in the global construction industry.

One typical example of BIM implementation in construction is to optimize complicated utility pipeline design and coordinate the field installation. There are a large number of utility pipelines with different functions such as water supply, gas supply, electricity circulation, and ventilation in residential and commercial buildings. Design errors and collisions happen frequently in traditional 2D design [3]. Through the application of BIM to arrange pipelines in a 3D space and coordinate on-site installation, the LP of pipeline installation could be improved from 75~240% [4]. According to statistics in China, the production value of the utility pipeline installation in 2016 is 250 billion USD accounting for 8% of the total value of construction industry. The BIM application in this field has the potential to save substantial resources and generate significant benefits. However, improper BIM application may result in negative effects, such as project shutdown or even engagement of lawsuits and claims [5]. Therefore, study on impact factors and quantify the interaction among these factors is of critical significance to ensure effective BIM implementation. Limited research has been conducted in this field.

The construction activities in the supply chain are closely related and actively interacted, but the interaction between construction tasks is difficult to elaborate in the traditional network diagram due to the nonlinear impact of these activities. System dynamics (SD) is an approach to understanding the nonlinear behavior of complex systems over time using stocks, flows, internal feedback loops, table functions. It can explain system evolution trend and describing the dynamic influence of the internal links. This paper studies the effect of BIM on the LP of complex pipeline installation based on SD modeling. The critical impact factors of BIM on pipeline installation labor productivity （PILP）are identified and a SD model is established. The model is applied to evaluate the PILP of three large scale buildings and the task-level productivity indices are compared.

Table 1. Impact factors of pipeline installation productivity

Impact Factors	Organization	Management	Technical
(1)	Collaboration Degree	Change Orders	Model Precision
(2)	BIM Execution	Quality Control	IFC Application
(3)	BIM Specialist	Plan Compliance	Data Diversity
(4)	Owner’s Support	Risk Control	Localization
(5)	Teams BIM Expertise	RFIs (Requests for Information)	Add-on Development
(6)	Project Delivery Method	Time Delay	Software Function
(7)	BIM Applications	Total Workload	Data Exchange

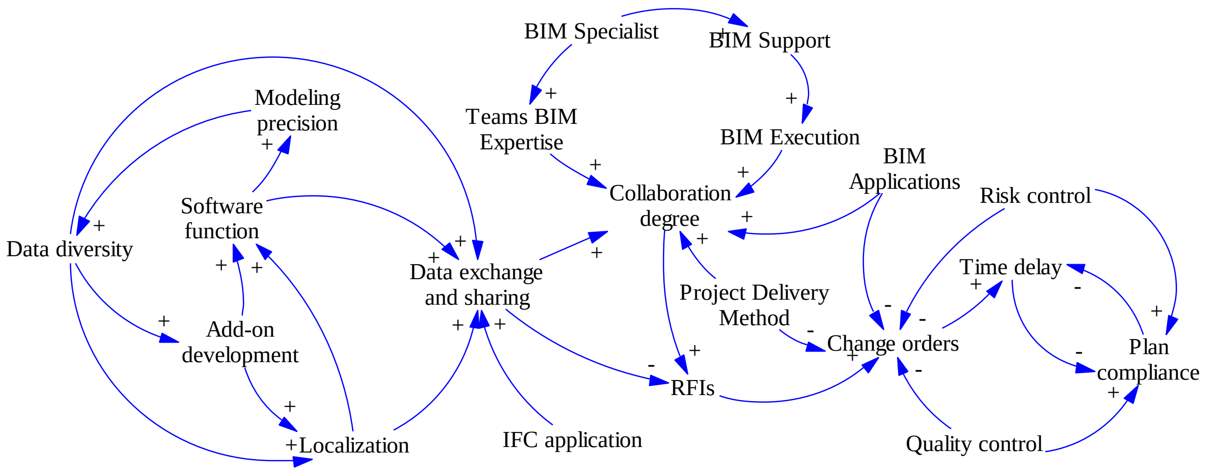

Figure 1. Overall casual loop diagram of impact factors

2. LP impact factor identification

The impact factors of BIM on PILP can be grouped into three primary categories related to the organization, management, and technical aspects of the project, respectively. Within each category, the major factors are identified as listed in Table 1. In total, 21 major impact factors are identified for further system modeling.

3. System dynamics (SD) modeling

In order to study the impact mechanism, a casual loop diagram is developed to qualitatively describe the logical causal relationship between the factors, then a stock and flow diagram is developed to quantitatively illustrate the interrelationship of variables, and the equations for deriving each variable are presented to form a SD model

.3.1 Causal loop diagram

The causal loop diagram describes the feedback structure of a complex system. It reflects the dynamic environment of a causal cycle and visualize relationship between variables and their interaction. By forming a closed feedback loop, the logical causal relationship between the factors are clarified.

The inter-relationship of the impact factors is visualized using a causal loop diagram as shown in Figure 1. By forming a closed feedback loop, the logical causal relationships among the factors impacting the BIM aided pipeline installation productivity are clarified. The factors are with both positive and negative feedbacks and different subsystems interact with each other.

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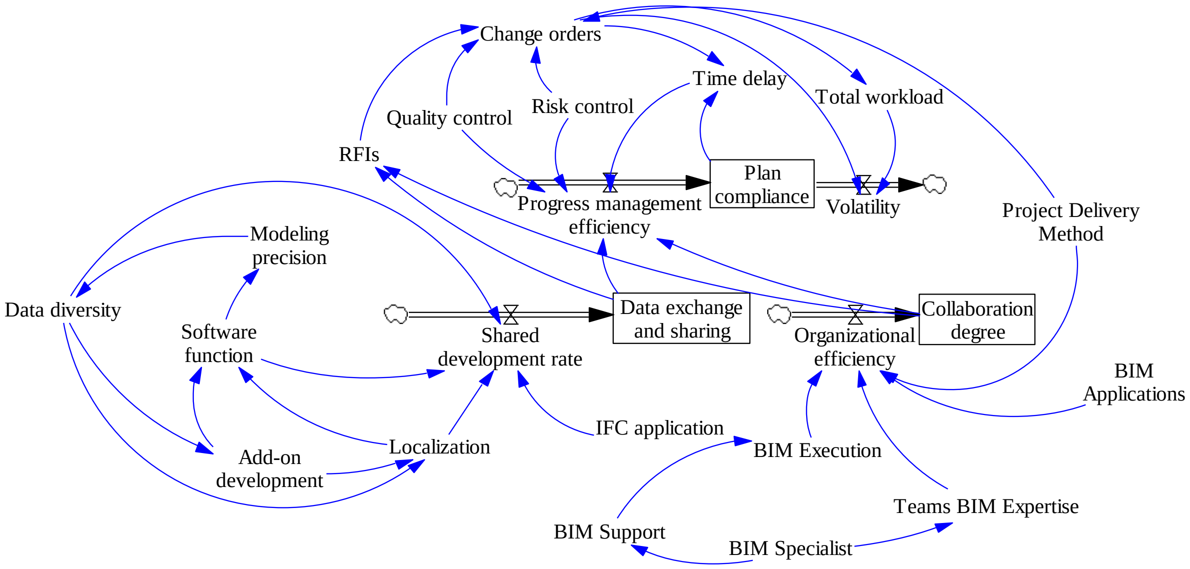

Figure 2. Stock and flow diagram of BIM impact model

3.2. Stock and flow diagram

The causal loop diagram sorts out the model effectively and analyzes the system qualitatively but it is not capable of performing quantitative analysis. The stock and flow diagram is based on the causal loop diagram to distinguish different types of variables, and thus establishing the mathematical relationship between variables. The stock and flow diagram is shown in Figure 2. The plan compliance degree directly reflects the progress control level, and ensures the implementation of the project according to the plan. Engineering changes caused by various factors lead to delay and affect the degree of plan compliance. Measures such as quality assurance and risk control reduce engineering changes and improve plan-compliance. Data exchange and sharing degree improve the speed and effect of information transmission, enhance communication efficiency, and then increase productivity

3.3 SD Equations

Based on the variable analysis and the stock flow diagram, the level variables (L), rate variables (R) and auxiliary variables (A) that describe quantitative relationship between the impact factors are defined as follow

3.3.1 SD equation of organization subsystem

(1) Collaboration degree equation

The collaboration degree (*CO_DEGREE*) is a level variable whose value is affected by organizational efficiency (ORG_E), DT is time interval. It is defined as

L $CO\_DEGREE.K = CO\_DEGREE.J + DT * ORG\_E$

(2) Organizational efficiency equation

The organizational efficiency (*ORG_E*) is a rate variable whose value is the sum of BIM executive, Teams BIM Expertise, project delivery method mode and BIM applications. It is defined as

R

$$ORG_E = EXCUTION + T\_EXPERTISE + D\_MODE + APPLICATIONS$$

The teams BIM expertise is a table function of BIM Specialists number and is defined as

A

$$T\_EXPERTISE = WITH\_LOOKUP(SPECIALISTS)$$

3.3.2 SD equation of technical subsystem

The data exchange and sharing degree (*D_ENJOY*) is a level variable affected by the rate of shared development.

1) Data exchange and sharing degree equation

L $D\_ENJOY.K = D\_ENJOY.J + DT * DEV\_RATE$

2) Shared development rate equation

As a rate variable, the shared development rate (*DEV_RATE*) is the sum of data diversity, localization, software function and the application of IFC standards. It is defined as

R $DEV_{RATE} = D\_DIVERSITY + D\_LOCAL + FUNCTION + IFC$

The degree of localization (*D_LOCAL*) and software function (*FUNCTION*) are table functions of add-on development (*REDEV*) and are defined as

A $D\_LOCAL = D\_DIVERSITY + REDEV$

A $FUNCTION = WITH\_LOOKUP(REDEV)$

The add-on development (*REDEV*) is a table function of data diversity and is defined as

A $REDEV = WITH\_LOOKUP(RICHNESS)$

3.3.3 SD equation of management subsystem

1) Plan compliance degree equation

The plan compliance degree (*D_FOLLOW*) is a level variable whose value is positively related to the BIM based schedule management efficiency (*MAN_E*) and negatively related to the change rate (CHANGE_RATE). It is defined as

L

$$D\_FOLLOW.K = D\_FOLLOW.J + DT * (MAN\_E - CHANGE\_RATE)$$

2) Schedule management efficiency equation

The schedule management efficiency (*MAN_E*) is a rate variable that directly impacts the project compliance degree (*D_FOLLOW*). Its value is equal to the sum of risk control level (*M_RISK*) and quality assurance (*M_QUALITY*) minus time delay (*DELAY*) which is the table function of the change orders (*CHANGES*).

R $MAN\_E = M\_RISK + M\_QUALITY - DELAY$

A $DELAY = WITH\_LOOKUP(CHANGES)$

The change order (*CHANGES*) is equal to the number of information requests RFI minus the quality assurance (*M_QUALITY*) and the risk control level.

A $CHANGES = RFI - M\_QUALITY - M\_RISK$

3.3.4 Initial value and variable table function

According to "China Construction Industry Informatization Development report (2015): BIM depth Application and Development") and previous study [3], the initial values of variables are determined. The table function describes the nonlinear relation between some variables whose data source could be historical and literature. Data range is determined by the variation trend and the key points between variables. The interaction effect curve of variables can be obtained by the analysis of VENSIM software， the equation for the variable table function is as follow:

(1) Add-on development equation [30]：

REDEV= =WITH LOOKUP (RICHNES, ([(2000, 0)-(2500, 0.012)], (2000, 0.0101), (2030, 0.0102), (2060, 0.0103), (2090, 0.0104), (2120, 0.0105), (2150, 0.0106), (2180, 0.0107), (2210, 0.0108), (2240, 0.0109), (2270, 0.011)))

(2) Software function equation：

FUNCTION=WITH LOOKUP (REDEV, ([(0，0.4)-(0.011，0.8)], (0，0.4), (0.0102，0.402), (0.0103，0.404), (0.0104,0.406), (0.0105，0.408), (0.0106，0.41), (0.0108，0.412), (0.0109，0.414), (0.011，0.416)))

(3) Time delay equation：

DELAY=WITH LOOKUP (CHANGES, ([(0.08，0.1)-(0.126，0.33)](0.08，0.1), (0.126，0.33)))

(4) BIM level equation：

SPECIALITY=WITH LOOKUP (SPECIALIET, ([(1000, 0.026) -(4000, 0.032)], (1000, 0.026), (1500, 0.028), (2000, 0.03), (2500, 0.032), (3000, 0.034), (3500, 0.036), (4000, 0.038)))

(5) Modeling accuracy equation [29]：

PRECISION=WITH LOOKUP (FUNCTION, ([(0.4, 0.45)-(0.5, 0.6)], (0.4, 0.45), (0.41, 0.47), (0.42, 0.48), (0.43, 0.5), (0.44, 0.52), (0.45, 0.54), (0.46, 0.56), (0.47, 0.58), (0.48,0.6)))

3.4Validation

In order to test the stability of the model, three different time intervals of DT=1, 0.5 and 0. 25 are set in the three subsystem models, respectively. The initial parameter of the model is INITIAL TIME=1, FINAL TIME=15, TIME STEP=1, 0.5, and 0.25. When the interval DT is set to 0.25 and 1, the curves of collaboration degree, schedule compliance degree and data exchange and sharing ability tend to be consistent, so the model is stable to perform sensitivity analysis.

4. Significance evaluation of impact factor

Through sensitivity analysis with initial value of productivity is 0, the significance of the management factor is 0. 56, the technical factor is about0. 29, and the organizational factor is about 0.15. Significance level of each secondary impact factors and overall productivity for 3 subsystems are as follow in Table 2:

5. Case studies

5.1 Background

To evaluate the effects of BIM application, this study compares the installation LP of three cases, a five-star Intercontinental hotel adopted BIM in late construction phrase mainly for facility management, an International Conference Center, which is located next to Continental Hotel, applied BIM from early construction coordination to operation phrase, and the World Trade Square adopted BIM from design review to construction coordination and operation phase. As complexity and size is the most significant factors of projects classification. The three cases are all large-scale with complex pipeline layout, BIM implemented projects and are constructed by contractors with same qualification, such that the installation LP is comparable.

Table 2. Significance level of LP factors

Primary Factor （Significance）	Secondary Factor	Secondary Factor Significance	Significance on Productivity
Organizational Factors （0.15）	BIM Applications	0.284	0.0426
	BIM Execution	0.241	0.0362
	Teams BIM Expertise	0.154	0.0231
	BIM Support	0.148	0.0222
	Project Delivery Method	0.091	0.0136
	BIM Specialists	0.082	0.0123
Management Factors （0.56）	Quality Control	0.324	0.1814
	Change Orders	0.241	0.1350
	RFIs (Requests for Information)	0.158	0.0885
	Risk Control	0.138	0.0773
	Time Delay	0.118	0.0661
	Total Workload	0.021	0.0118
Technical Factors （0.29）	Modeling Precision	0.302	0.0876
	Data Diversity	0.238	0.0690
	Localization	0.151	0.0438
	Add-on Development	0.143	0.0414
	IFC Application	0.090	0.0261
	Software Function	0.079	0.0229

Table 3. Installation LP statistics for three projects

Installation Tasks	HVAC (m^2/man-hr)	Bracket (kg/ man-hr)	Cable trays (m/ man-hr)	Fire control (m/ man-hr)
Intercontinental Hotel	2.60	40.10	1.39	3.70
Conference Center	3.20	45.30	1.70	4.50
World Trade Square	3.60	47.57	1.86	4.74

5.2. Measurement of MEP installation site productivity

The working hours and number of workers are determined according to the records of the weekly reports and construction plan collected from 3 cases. Productivity statics of HVAC (Heating Ventilating and Air Conditioning), bracket, cable trays and fire control pipelines are calculated as

LP=Installed Quantities/Working Time

The results of the LP of the 3 cases are shown in Table 3. Table 3 shows the productivity of the four trades of the three BIM projects. Through field investigation, the conference center and World trade Square showed in higher level of quality control, change orders, BIM Execution and model precision. The installing productivity statics reflect efficiency of working process including components assembling, connecting, erecting. Compared to the Intercontinental projects, which applied BIM in late construction phrase, early BIM utilized projects, the Conference Center and World Trade Square projects, increased LP between 13% and 38% dependent on different trades

6. Conclusions

In this paper, the critical impact factors of BIM on pipeline installation productivity are identified and a system dynamics model is established to map the impact mechanism and quantify the BIM impact on labor productivity. The model is applied to evaluate the pipeline installation productivity of three large scale buildings and the task-level productivity indices are compared. The comparison shows a positive impact of BIM on pipeline installation productivity, resulting in 13~38% of increase in labor productivity dependent on different trades and project phase of BIM application.

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