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Using social network theory and simulation to compare traditional versus BIM–lean practice for design error management

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ABSTRACT

Early efforts injected into design can improve design quality and reduce errors in deliverables, project costs, and negative iterations. Previous studies only focused on exploring design errors from a static cognitive perspective and on solutions targeting individuals' actions in isolation. The purpose of this research is to understand the process of design error emergence and assess the use of social network theory and simulation to compare traditional versus BIM/lean-based environments for design error management. This study presents a novel design error management strategy that focuses on team structures, interaction dynamics, and error diffusion. Theoretical results show that the use of BIM and lean practice reconfigures the structures and communication of design teams to identify errors earlier, reduce their reoccurrence, and restrict their diffusion.

1. Introduction

1.1. Design error management

Errors produced during the design phase can have severe impacts on subsequent phases and the overall project. Omissions or errors in design that are discovered late or during construction are responsible for approximately one third of the contract's value [1]. They also lead to schedule delays due to rework and changes required to mitigate the errors. More importantly, serious errors committed during design that are not resolved during the course of a project, can result in catastrophic construction failures [2–4].

The presence and severity of design errors have driven researchers and industry practitioners to find effective solutions to minimize their occurrences. Researchers in this regard have worked first on determining the root causes and different classifications of errors using human error theory [5,6] and distributed cognition [7]. Other researchers have assessed the performance of Architect/Engineer (A/E) consultants during design by providing indices for the quality of design deliverables, where low errors and omissions are necessary to consider the deliverables accurate and usable [8]. While the occurrence of design errors and failures is often attributed to innate human cognitive limitations and influences from the surrounding environment, neglecting the underlying forces of error mechanisms within a social context seems to conceal the potential to address the fundamental issues of design errors.

To decrease the generation of errors, previous studies have suggested prevention techniques for individuals and organizations by anticipating how and why errors occur [1,5,7]. However, they failed to look at the dynamic nature of error generation and propagation, how designers interact with each other and other project players within a social network, and how the network's structure and properties impact the diffusion of errors and information. Social network analysis (SNA) is a science and a tool that examines relationships, information exchange, physical attributes, and several other characteristics between people in a social network [9].

The SNA in this context enables researchers to track different pathways of error diffusion, determine the severity of error propagation within a network, and compare different network structures and the respective mechanisms of error behavior within them. Hence, by being able to analyze errors from a broader and a more realistic angle, better defense schemes targeting individuals and team structure of social networks against the generation and diffusion of errors can be established. In this regard, building information modeling (BIM) and lean practice which empower information exchange and team communication have the potential to shape the design process by minimizing the occurrence and diffusion of errors during design and reducing the undesired impacts of defective design diffusion.

The motivation of this paper stems from the need for a novel perception and a more effective management of design errors to improve the current solutions that are not always effective. They either tackle superficial manifestations of design errors or target individuals' actions in isolation of the environment, both which do not efficiently reduce

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design defects. Therefore, the objective of this paper is to understand the process of design error emergence and assess the use of social network theory and simulation to compare traditional versus BIM/lean-based environments for design error management. The approach aims at understanding the impact of the communication and interaction networks and the dynamics involved in detecting and eliminating errors.

The contributions of this paper include: (1) charting the emergence of design errors due to information flow patterns, (2) presenting a frame work for design error management in reactive and proactive environments, (3) mapping and analyzing the structure of communication/information exchange networks among project players during design for two environments (hypothetical project types): traditional and BIM/lean-based, and (4) simulating the diffusion of design errors within each network/environment, based on theoretical assumptions, to assess the potential benefits of BIM and lean practice for managing design errors. The paper presents a novel approach to bridge the missing gap in the effective management of design errors employing social network theory and agent-based simulation.

1.2. Background of design errors in construction projects

An error, as defined by Kaminetzky [10], is a "deviation from the true value, lack of precision, and variation in measurement because of a lack of human and mechanical perfection". In design, the errors are manifested as omissions or mistakes in drawings, calculations, and specifications. Since design is mostly a result of human input, the errors are majorly attributed to human generated errors [5]. Examining case studies that document failures resulting from errors in construction projects has failed to highlight the root causes for errors and the mechanisms of error generation and propagation. However, various analytical and quantitative models are derived for prediction of errors [11].

Busby [7] presents a model that differentiates various modes of errors' occurrence during the design process. The study findings show that distributed cognition theory reveals nested levels of assumptions made between design participants that result in design defects [7]. However, a limitation of this model is the subjectivity of participants who provide such qualitative assessments.

Later research categorizes errors into different types and contributing factors, and present methods for managing errors [1,5,6,12,13]. Yet, it is not sufficient to solely consider the participants' behaviors and output in isolation as this would prevent researchers and practitioners from seeing the broader cycle of errors during design. In fact, it is critical to consider interactions within and between the design teams of different disciplines, and assess what has been previously explored in the light of the interdependent nature of the design. Moreover, the dynamics of error progression from an individual to another, the existing social network structures, the position of each participant and design group, and the current links or connections between project players require further exploration. This paper investigates the potential to better manage defective designs and combine what has been previously studied with a new perspective of social network theory to provide a more profound understanding of the dynamics of errors and how they could be effectively counteracted.

1.3. Background of social network theory and applications

Social network analysis (SNA) is a method for studying interactions and relationships among people. It provides both visual and quantitative analyses for the interpretation of human associations. Sociologists and scientists have been researching and applying the theory of social networks since the early years of the 20th century in diverse fields, mainly sociology, anthropology, biology, communication studies, economics, information science, and several others. Not only does SNA examine the structure of the relationships between the individuals, it also studies the natural mechanics occurring within [14].

The visual graphs used to map social networks consist of nodes, representing the individuals or any component under study, which are connected via links representing the relationships, connections, or modes of interaction (e.g., Fig. 6). These graphs map the overall interconnected relationships between people and networks. SNA helps researchers understand the network data visually, convey the results of the analysis, and reveal any hidden properties that might not have been captured through qualitative measurement [15]. Quantitative analysis can also be performed to relationships, connections, and characteristics pertaining to an individual node and to the network structure as a whole. Network metrics translate complex visual analysis into quantitative values for interpreting existing behaviors and node features. Table 1 lists the definitions, adapted from [15] of some important metrics used in this research.

The SNA has been gaining momentum in fields other than social sciences. In communications engineering, the SNA has been adopted to develop patching schemes to contain the spread of worm and viral applications in cellular-phone networks [19]. Other applications were highly favorable in the field of epidemiology [20,21], where the spread of viruses and diseases among the individuals could be monitored and controlled to reduce the impacts of disease break-outs. Recently, the SNA is employed in organizational behavior studies [9,22] and in construction management to analyze communications and information flow between the participants for improved management of projects and better integration of multi-disciplinary teams [14–16].

1.4. Background of building information modeling (BIM) and lean principles

A building information model is a parametric n-dimensional model that compiles, links, and computes building information. Although the model is a very powerful tool for project development, BIM goes beyond the notion of a model or tool. Building information modeling is a project life cycle process using the provided model and parametric building information to simulate virtually the physical, functional, and task-related attributes of a project. It helps stakeholders make educated decisions and execute the project with reduced costs, schedules, rework, and better quality.

Lean practice is concerned with the overall, simultaneous, and continuous improvement of all phases of a project. The core principles of lean target fundamental issues of collaboration, value creation, transparent communication, reduced rework, avoidance of cost and schedule overruns, as well as eliminating waste of all kinds, of which errors constitute a major waste. In his book "The Toyota Way", Liker discusses 14

Table 1
Social network quantitative metrics.

Type	Metric	Definition (this metric describes)
Node	Degree centrality	How many other nodes a node is connected to (undirected) [15]
	Betweenness	How many pairs of individuals are connected through a node with least number of steps; brokerage role [16]
	Closeness	How close a node is to other nodes; depends on shortest average length [17]
Network	Density	How many actual links exist between nodes divided by the number of total possible links in the network [15]
	Clustering	How clustered groups of people are compared to the rest of the network, existence of closed triads and small communities [16]
	Average path length	How many steps, on average, nodes require to reach each other [17]
	Modularity	How dense the connections between nodes within groups as compared to nodes with other groups [18]

lean management principles that drove away inefficiencies from Toyota's practices [23]. One of these principles that can help identify and mitigate design defects is building a culture of stopping and fixing problems so that quality can be attained early and from the first time. Another lean principle emphasizes the importance of slow decision making by consensus after considering all options, which can be reflected in the process of design error management by having designers avoid uninformed assumptions and hasty decisions without coordinating with others. Using reliable and well tested technology can be considered as highly important for designers as machine-based operations should be guaranteed to provide error-free solutions to designer's inputs. Most importantly, the lean principles stress on learning so companies and individuals can continuously improve and diminish defects and inefficiencies in their processes.

It has become commonly realized that planning and managing the design process can enhance project productivity and client satisfaction. In this regard, the strength of BIM lies in enabling collaboration between the participants throughout the project's life cycle [24], and adding value by reducing the design defects and minimizing the resulting rework, costs, and time delays. In fact, BIM and lean are synergistic practices as BIM embraces lean principles at the core of its process. BIM and lean streamline information exchange, enable real time management, and improve decision making among project teams.

By understanding the benefits of BIM and lean interactions, the design errors can be better tackled in an attempt to reduce both their incidence and their dissemination. However, applying BIM alone as a tool and failing to employ it as a lean process does not bring about the desired benefits. Therefore, the effects of BIM and lean should be seen from a social network theory to assess their potential as defense strategies against the occurrence of design defects and their diffusion.

2. Research methodology

To achieve the research objectives mentioned earlier, a research methodology is developed and summarized in Fig. 1 below. After clarifying how information flow patterns play a role in the emergence of the design errors, a proactive framework for managing the design defects is first proposed to highlight the role of social network analysis and simulation for better understanding the dynamics of the design errors and the impacts of BIM and lean practice for error management.

The proposed framework suggests several steps for better managing design errors. Among these steps, two fundamental ones are selected to be studied in detail throughout the paper: step (1) mapping the networks and interaction behavior for each environment, and step (2) simulating the diffusion of the design errors within each network. First, social network theory is used to construct the networks under each project type and analyze their structures. Gephi [25], a network analysis and visualization software, was used to map the interaction and information exchange networks and calculate the respective metrics. The resulting structures and metrics for the traditional and BIM/lean setup are compared against each other to help understand the underlying differences in their communication environments. The structures present a static understanding of the governing relationships at one point in time. Second, to map the dynamic nature of error generation and propagation, agent-based modeling performed through NetLogo software, is used to simulate the diffusion of the design errors in these structures under different conditions. The resulting configurations of both structures from Gephi are used as input for the NetLogo simulation. NetLogo is an agent-based simulation tool for modeling the actions and interactions of agents (in this case the agents are project players) and to evaluate their impact on the system [26]. The values of parameters used in the simulation models are based on theoretical assumptions in order to better represent a generic range of different possibilities and scenarios. Agent-based simulation also allows tracing design errors throughout the network. It is a convenient tool for multiple experimentation and testing the hypothesis introduced in this study that “BIM and lean practice can provide effective defense and reduction mechanisms against design errors”. The dynamics of this procedure help measure the severity of outbreaks of errors and assess the impacts of the proposed design error management strategy. In order to compare the impacts of traditional and BIM/lean practice on the reduction and mitigation of design errors, agent-based simulation is used to model four theoretical scenarios of error transmission between the individuals under each environment, measure the time it takes for errors to disperse and be remedied, as well as the percentage of the individuals receiving these errors and learning from them. The scenarios represent combinations of different theoretical ranges of parameters used in the simulation model. The simulation results for each scenario are plotted and analyzed to highlight the impact of BIM and lean practices on design error management. Afterwards, an international panel of experts in the fields of lean, BIM, and social network analysis was consulted to seek their feedback on the inputs and the results of the experiments performed in this study in order to validate their theoretical basis and rationale.

2.1. Research limitations

The framework developed and experiments performed are based on hypothetical values and theoretical assumptions representing generic projects. Therefore, the results obtained are derived based on the given input and do not reflect any specific project. These results and experimental setups need to be further validated by applying them on several case studies to obtain specific ranges of values that reflect real life practices.

3. Framework development

3.1. Model for information flow and interactions of design errors

Research so far has answered the questions of “How” and “Why” defects occur, but they ignored two fundamental contributors to errors: improper information flow, and the relations between the influencing factors and contributors. Unless the information exchange channel

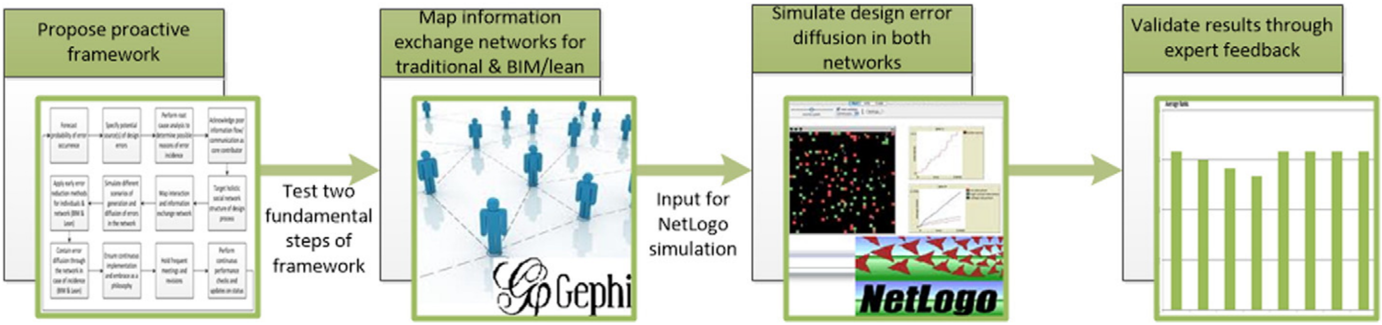


Fig. 1. Research methodology.

and its relation to the interactions of design errors are examined, the required interventions to improve the performance of the design process are difficult to attain.

Fig. 2 proposes a way to connect the "How" and "Why" and incorporate the role of information flow into what has been studied earlier. The squares represent the factors ("Why") and the failures ("How"), and the circles represent sub-categories or different types of these factors and failures. The idea behind the model is to combine what previous researchers have studied separately into linked factors and failures. The model shows how information flow influencing factors are connected to workplace and organizational factors. These factors are related to coordination, culture, social, cognitive, and informational aspects of the design process. If the individuals fail to communicate or exchange the right data needed to perform their design adequately, errors are more likely to be generated and dispersed among the teams. On the other hand information flow failures are the core of the contributing factors and are tightly linked to direct (mistakes appearing directly in design) and latent failures (hidden errors that propagate and result in failures). Such failures are manifested, for instance, when designers are not being aware of the needs of other project participants or all the requirements of design. The lack of proper information exchange and shared cognition creates a medium for the incidence of failures. However, the design data are traditionally piled in silos before they are exchanged between the design teams [27]. The reasons behind the design failures and the ways in which they occur are highly intertwined. In fact, classifying factors or manifestations into discrete categories independent of each other conceals the actual continuum that links causes with effects, and hides the synergistic product of the interacting factors and interacting contributors, at which improper information flow is the core. Therefore, the reasons and effects of underlying problems should not be examined separately, but should be analyzed as a whole interconnected chain as suggested by the model in Fig. 2.

3.2. Framework for proactive design error management through SNA, BIM, and lean

A first step to effective reduction and containment of design errors is to understand the drawbacks of the traditional reactive ways for managing design defects. Fig. 3 presents a framework of the reactive design error management strategy and the respective consequences of a passive way of handling defects. The rectangles present how managers handle issues under a reactive mindset and the circles represent the ways in which errors behave.

A reactive method is not effective because it responds late to the aftermath of a problem, resolves it by superficial remedies, and does not prevent its future occurrence. This approach takes action once a defect is detected, which is usually a manifestation of more profound reasons as discussed in the model in Fig. 2. However, managerial boards tend to guess apparent causes of such incidences and adopt a blame/punitive policy towards the individuals of direct fault. Although defense schemes are implemented against these failures, they target the superficial and obvious causes, which fail to reduce the underlying causes. Therefore, the errors continue to occur, pass downstream, and even multiply if not detected early because the designs for various disciplines are interdependent.

A proper approach for reducing design errors is to adopt a proactive strategy by taking action before error incidence, focusing on the whole network of individuals, exploring the dynamics of the design process, and embracing BIM and lean as the fundamental corrective measures

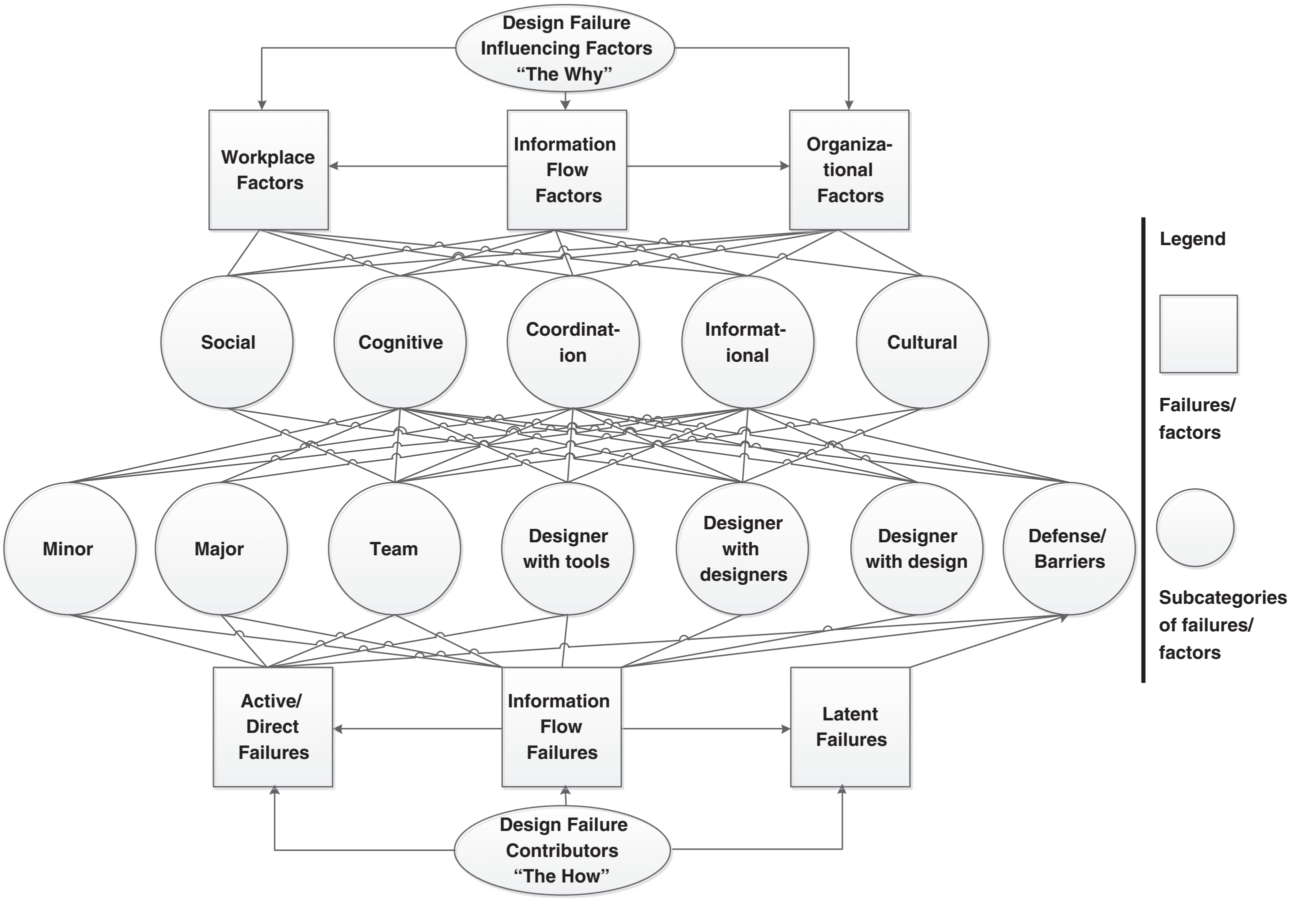


Fig. 2. Interactions of information flow and design errors.

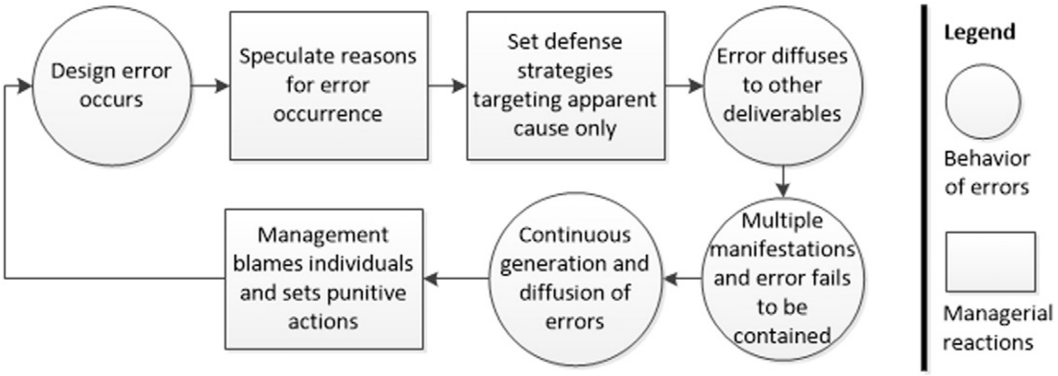


Fig. 3. Reactive design error management and consequences.

to the reactive policies traditionally followed. The framework in Fig. 4 presents one possible way of managing errors. The framework is a potential attempt to bridge the gaps and drawbacks of the reactive approach. It is a combination of suggested steps that build from general proactive management principles tailored to preemptively manage defects in the design phase.

The proposed procedure starts by forecasting the potential of error incidence to assess risks and examine thoroughly any possible causes that might induce defects, without waiting for failures to happen. By performing root cause analysis, which is a basic principle in lean philosophy, the underlying reasons will be revealed. As discussed earlier, improper information flow and poor communication is the basis for most errors. The framework highlights the need to target the entire network of the individuals, not single individuals only, by mapping the structure of interaction and information exchange networks.

Then, to set early defenses and barriers to defects, it is first important to understand and simulate the dynamics of errors and their diffusion patterns along the network. The applications of BIM tools and lean practices during designing process allow the reduction of mistakes and contain their diffusion. These steps, supported by holding frequent meetings, carrying out regular revisions, and performing continuous performance checks, are key elements in setting up a proactive framework.

This approach is more efficient in managing errors as opposed to a reactive method because it not only provides defense schemes but targets the founding causes of errors. The effectiveness of this framework should be assessed on case-by-case basis and modified according to the satisfaction level of the concerned parties by the outcomes of its application. It can be customized as deemed suitable by individuals, managerial, or directive boards of the firm according to the organizational setup and management policies.

4. Experimental design

The aim of the experiments is to assess the use of social network theory and agent-based simulation to show the potential benefits of BIM/lean networks in detecting and resolving design errors faster. The values provided in the experiments would vary from project to project and are not hard values. They provide a basis to perform the experiments and test the hypotheses introduced in this research.

4.1. Setup for experiment 1: design social network structures

The suggested social network theory approach can serve as a means for the mitigation of the design errors by examining a broad diversity of interaction channels, which was limited previously to separate the individuals and the small groups of designers. Since many errors are manifestations of wrong and improper exchange of information or lack of transparent communication, studying information and interaction networks form the basis for understanding and managing errors. Gephi was used to map the interaction and information exchange networks for both traditional, and the BIM and lean (integrated) network. Gephi allows one to visualize, manipulate, and analyze the networks by providing graphs and quantitative metrics to form a thorough

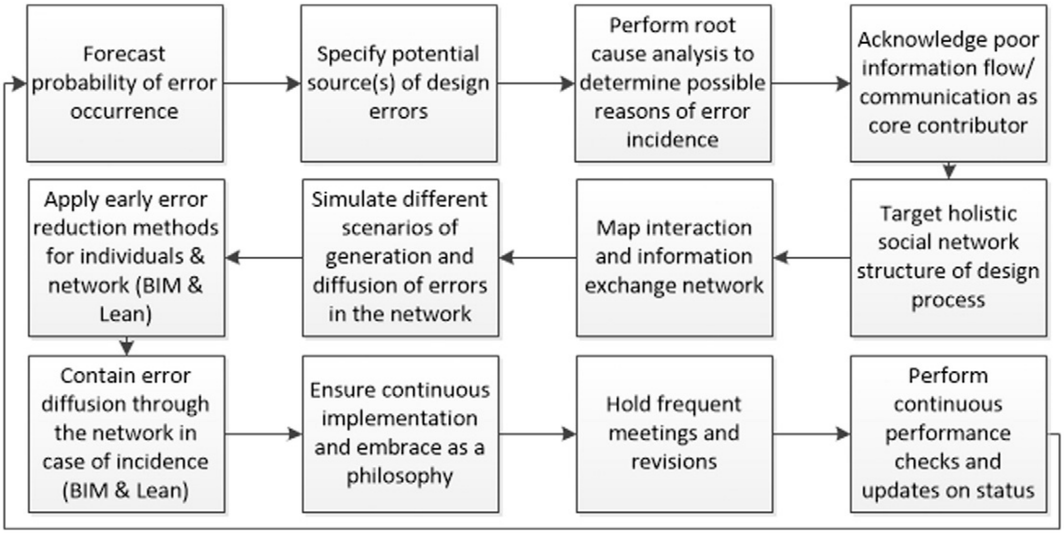


Fig. 4. Proactive framework for design error management.

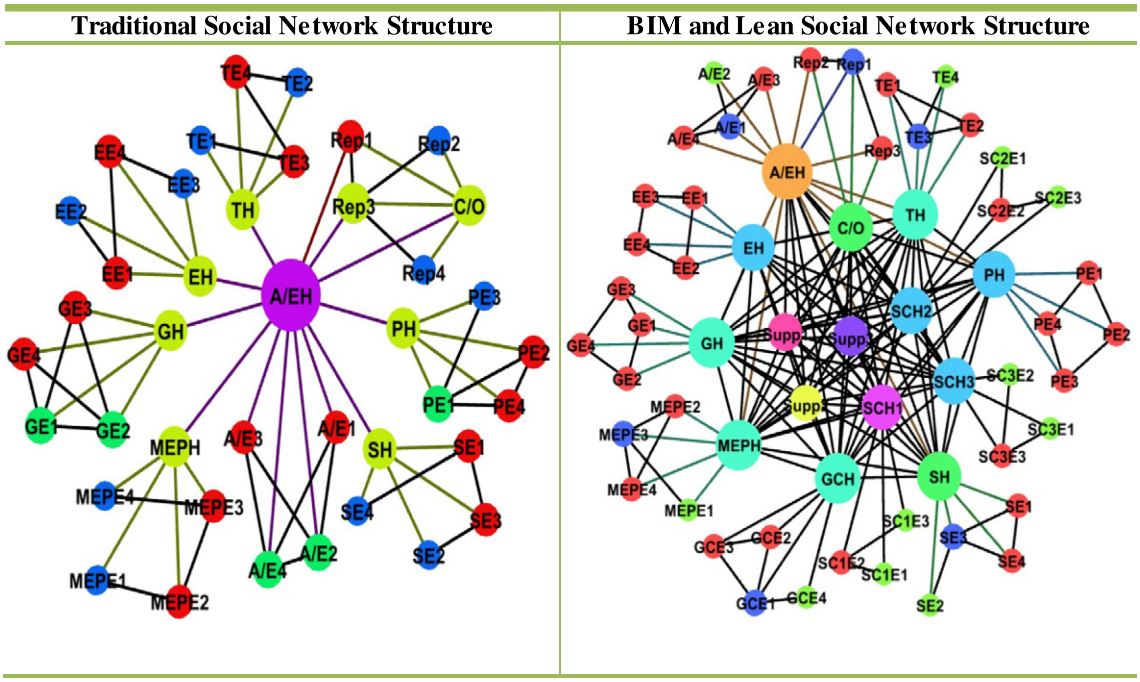


Fig. 5. Hypothetical structures of traditional and BIM/ lean social networks.

understanding of the structures. Fig. 5 and Table 2 present generic structures of each network and the list of abbreviations/annotations of the nodes.

The construction industry under traditional systems is highly fragmented, where each team strives to increase their own benefit and profit at the expense of other teams. This situation reflects a lack of awareness among project participants of the needs of each other, what is required to add value to the project, in addition to poor information exchange and transparency [28].

The design phase in traditional project delivery is mainly driven by the Client/Owner (C/O) and the A/E. The involved disciplines depend on the scope of the project, and traditionally consist of the architectural, structural, mechanical/electrical/plumbing (MEP), conveying systems, environmental, geotechnical, and planning disciplines, where each discipline team is usually formed of the head/ manager and the team engineers. For this study, a suggested example of a small/medium sized design firm (the left network in Fig. 5) was assumed for mapping a generic structure based on interviews with design professionals with 20 years of experience working at major architectural/engineering firms, observations of authors of behaviors within these firms, and previous research [14,15,29]. The provided structure example consists of 8 groups, each including the head/manager, and 4 team individuals (engineers or representatives). The lines are links between nodes (individuals), which represent existing interaction patterns and information exchange paths. It is also assumed here that the individuals within separate teams work closely, but there is no interaction between teams, and contractors or builders are not involved earlier in the design phase. The A/E normally plays the role of the coordinator and the link between the C/O and the rest of the project participants. Therefore, the A/E is the central and largest node given that he has most connections with the rest of the teams. The other players are clustered within their own isolated teams as seen in the structure as separate webs.

Under a BIM and lean configuration, early involvement of contractors, sub-contractors, and suppliers allows the integration of construction experience early on. This reaps benefits such as providing constructability analysis, performing value engineering, and providing accurate manufacturing details with least errors and assumptions. The proposed structure presented (the right network in Fig. 5) builds on principles of integration and information exchange, as well as the early involvement of key project participants [30]. The structure shows the addition of new nodes, representing the general contractor, sub-contractors, and suppliers, with their engineering teams. More importantly, the different teams are integrated, where there are more ties between the different teams, and the A/E is no longer the sole coordinator between the disciplines and the C/O. The two suggested structures are hypothetical examples out of many other possibilities as they would differ according to each project, country/location, culture, work environment, etc.

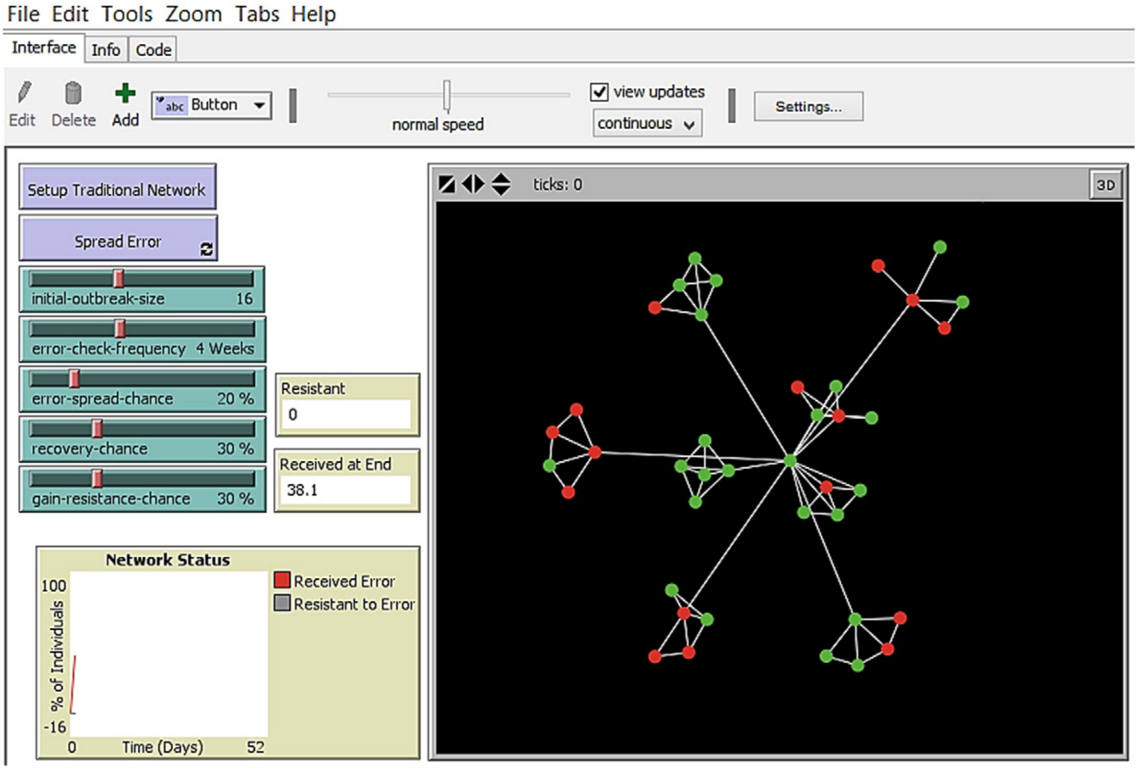
4.2. Setup for experiment 2: simulation of design error diffusion

The limitation of the static structures generated by Gephi is that they fail to provide the required means to determine which of the traditional or BIM/lean structure is favorable for error dissemination or error containment. This matter is supported by a dynamic simulation tool,

Table 2
List of abbreviations for design social network structures.

List of abbreviations

A/EH: Architect/Engineer Head
A/E: Architect/Engineer
C/O: Client/Owner
Rep: Client Representative
SH: Structural Head
SE: Structural Engineer
Supp: Supplier/Manufacturer
MEPE: MEP Engineer
GH: Geotechnical Head
GE: Geotechnical Engineer
EH: Environmental Head
EE: Environmental Engineer
PH: Planning Head
TH: Transportation Head
TE: Transportation Engineer
GCH: General Contractor Head
GCE: General Contractor Eng.
GCH: General Contractor Head
SCH: Sub-contractor Head
SCE: Sub-contractor Engineer



☑ view updates

initial-outbreak-size 16

error-check-frequency 4 Weeks

error-spread-chance 20 %

recovery-chance 30 %

gain-resistance-chance 30 %

Resistant 0

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Fig. 6. Sample of a NetLogo traditional structure interface.

NetLogo. For the purpose of this study, a NetLogo model, Virus on a Network [31] is modified and customized to be used to simulate different scenarios for the diffusion of design errors generated by designers under both structures. The aim of the simulations is to observe the dynamics of error transmission between the individuals based on each structure, measure the time it takes for errors to disperse and be remedied, as well as the percentage of the individuals receiving these errors and recovering from them. Fig. 6 shows a sample of the NetLogo interface.

Table 3 defines and specifies the values of parameters used in NetLogo for traditional and BIM/lean structures. At each step, and given a specified error spread chance, an error generated by an individual (colored red) attempts to spread to all connected individuals. However, the individuals receiving an error or generating an error are not immediately aware that they have done so. Only when the design checks are conducted would individuals become aware of having errors in their design. In addition, the individuals receiving an error have the tendency to fix it, representing a sort of error healing energy, which is defined through the "recovery-chance" parameter. Also, the individuals have the ability to learn from the design error they have detected and prevent its future occurrence. This is translated as the "gain-resistance-chance". Gaining resistance resembles a shield and defense mechanism against errors, and reduces the chance of generating a similar design error or allowing it to diffuse into the network.

For traditional structures, the design checks are not frequently conducted as opposed to regular checks under a BIM and lean environment. Moreover, since the individuals under traditional networks are not closely connected to each other and their interactions are limited to a few number of individuals within their teams, the probability for an error to propagate is lower than that in BIM and lean social networks. As for resistance and recovery chance, BIM and lean networks are assumed to maintain a higher rate given several defense schemes to be discussed in later sections. A 10% difference is assumed between the ranges of recovery and resistance chance of each structure as specified in Table 3. The input values are hypothetically selected and do not reflect any specific project. Further research and applications on real case studies are required to provide exact values or ranges of values.

5. Results

5.1. Experiment 1: design social network structures

The quantitative social metrics defined in Table 1 are calculated for both traditional and BIM/lean structures. The results were calculated by Gephi software and are summarized in Table 4 below. They are divided into structure, node, and network specific metrics.

Table 3
NetLogo parameters used for both structures.

Parameter	Definition and Purpose	Values for Traditional	Values for BIM/ Lean
Initial-outbreak-size	Number of individuals generating design errors	40% of individuals	40% of individuals
Error-check-frequency	Frequency of design checks to detect an error	4–5 weeks	1 week
Error-spread-chance	Probability for error to diffuse to linked individuals	20%	50%
Recovery-chance	Probability that an individual fixes a design error before or after it diffuses (healing energy)	10% to 40% (in 10% increments)	20% to 50% (in 10% increments)
Gain-resistance-chance (resistivity)	Probability that an individual does not commit an error due to learning effect (shield)	10% to 40% (in 10% increments)	20% to 50% (in 10% increments)

Table 4
Metrics of traditional and BIM/lean integrated social networks.

Type	Metric	Traditional	BIM/lean
Structure	Number of nodes	40	59
	Number of edges	70	183
	Graph type	Undirected	Undirected
Node (averaged)	Degree centrality	3.51	6.21
	Betweenness	39.85	41.83
	Closeness	3.04	1.79
Network	Density	0.09	0.11
	Avg. clustering coefficient	0.76	0.79
	Average path length	3.04	2.44
	Diameter	4	4
	Modularity	0.74	0.40
	Number of groups	8	11

For the structure metrics, the graph type is selected to be "undirected" for both networks, where information exchange can happen both ways between the individuals and does not follow a specific direction. Under the traditional structure, less players (nodes) are involved during the design phase as opposed to a more integrated BIM/lean project environment early in the design phase. Nonetheless, the number of existing edges (existing connections between individuals who interact and exchange information) is higher for the BIM/lean network as there is more collaboration and team work between and within the involved teams as opposed to traditional projects. The node metrics are averaged over the total number of nodes for each network. They represent average characteristic pertaining to every individual node such as their closeness to the rest of the nodes or their centrality (or importance) within a network. On average, the degree centrality and betweenness for nodes in the traditional structure mark lower values as compared to the BIM/lean based networks (3.51, and 39.85 vs. 6.21 and 41.83 respectively). This indicates that the individuals in a BIM/lean environment are more equally connected to each other and can more easily reach others within their network. While the closeness metric has a higher value for traditional (3.04) compared to (1.79) in a BIM/lean structure, but this value does not mean that the individuals are closer, but instead, the higher the "closeness" metric is, the more edges or hops are required to reach the rest of the nodes. The network metrics are related to the overall structure composition.

For the traditional structure, the average path length and modularity values (3.04 and 0.74 respectively) are higher than those for the BIM/lean network (2.44 and 0.40 respectively). This indicates that, on average, an individual requires more edges and connections to reach to another individual in a traditional network, and that there are more connections within a team than there are between teams.

On the other hand, the BIM/lean structure ranks higher on density, average clustering coefficient, and number of existing groups than the traditional structure. This relates to the existence of more nodes and more connections between the project players in a BIM/lean network as compared to a traditional network. As for the diameter metric, the value is the same for both structures as the size of the networks is not drastically different to be notable in the results.

5.2. Experiment 2: design error diffusion simulation

Agent-based models that simulate the diffusion of design errors are prepared and run for both structures. To compare the error dispersion and containment between both networks, the simulations are conducted as per the parametric setup shown in Table 3. Four different combinations were performed for each structure, hence a total of eight scenarios were conducted for both networks. For each scenario, the initial-outbreak-size, error-check-frequency, and error-spread-chance (defined in Table 3) were fixed. The variation was performed over the recovery-chance and gain-resistance-chance under each scenario as shown in Table 5 below. For example, when the traditional structure has a recovery chance and gain resistance chance of 10%, it is compared to four BIM/lean setups respectively having 20%, 30%, 40%, and 50% for both parameters (Fig. 8). The minimum difference of recovery and resistance chance is suggested to be 10% for both structures, with BIM/lean having the higher values in all scenarios. For each scenario, thirty five manual iterations were performed, averaged, and plotted. Table 6 summarizes the results obtained from the plots graphed in Figs. 8, 9, 10, and 11.

Each iteration presents different sources of errors and different diffusion paths. The results of interest are the percentage of individuals that the errors spread to and who are able to gain resistance and recover thus avoiding repeating similar errors. The results also show the time (in weeks) it takes for the errors to diffuse and to be contained. The comparisons were arranged accordingly to allow mapping several combinations of each traditional error diffusion scenario under the given parametric range versus all possible BIM/lean ranges. The plots represent the overall diffusion of errors and not only the initial outbreak. The results show that it takes more time for errors to diffuse and peak under a traditional environment (represented by solid lines), but the percent of individuals who receive the error is always higher than those under the BIM/lean configuration. Although the errors spread and peak at a slower rate under the traditional structure, the time for recovery and gaining resistance (represented by dotted lines) is slower than the BIM/lean network.

Additionally, the plots within the BIM and lean structure show that the higher the recovery and resistance chances are, the faster the error spreads and dies out, and the faster the recovery and resistance processes are. Note that not all individuals are able to become resistant and recover in both structures, since the learning process and human capabilities vary from individual to another and from an organization to another. Thus, aiming for 100% error containment is an ideal to be pursued.

An international panel of experts in the fields of the lean, BIM, and social network analyses was consulted to seek their feedback on how well the models represent the characteristics of each environment and the validity of the results of the experiments performed. The experts were asked to rank 8 aspects on a scale of 1 to 5, where 1 indicates

Table 5
Parameters for design error diffusion scenarios.

Scenario	1 (Fig. 8)	2 (Fig. 9)	3 (Fig. 10)	4 (Fig. 11)
BIM/lean	Traditional			
	10% recovery-chance 10% gain-resistance-chance	20% recovery-chance 20% gain-resistance-chance	30% recovery-chance 30% gain-resistance-chance	40% recovery-chance 40% gain-resistance-chance
20% recovery-chance 20% gain-resistance-chance	✓	–	–	–
30% recovery-chance 30% gain-resistance-chance	✓	✓	–	–
40% recovery-chance 40% gain-resistance-chance	✓	✓	✓	–
50% recovery-chance 50% gain-resistance-chance	✓	✓	✓	✓

Table 6
Summary of simulation results of error diffusion scenarios.

	Scenario results	Peak time and % of individuals receiving errors	Peak % individuals gaining resistance	Time for error to be resolved and individuals to gain resistance
1	Traditional 10% recovery; 10% gain resistance	84% after 16 weeks	70%	204 weeks
	BIM/lean 20% recovery; 20% gain resistance	69% after 4 weeks	80%	82 weeks
	BIM/lean 30% recovery; 30% gain resistance	56% after 3 weeks	80%	43 weeks
	BIM/lean 40% recovery; 40% gain resistance	47% after 2 weeks	76%	26 weeks
	BIM/lean 50% recovery; 50% gain resistance	41% after 1 week	76%	18 weeks
2	Traditional 20% recovery; 20% gain resistance	63% after 12 weeks	70%	65 weeks
	BIM/lean 30% recovery; 30% gain resistance	56% after 3 weeks	80%	43 weeks
	BIM/lean 40% recovery; 40% gain resistance	47% after 2 weeks	76%	26 weeks
	BIM/lean 50% recovery; 50% gain resistance	41% after 1 week	76%	18 weeks
3	Traditional 30% recovery; 30% gain resistance	51% after 8 weeks	77.5%	45 weeks
	BIM/lean 40% recovery; 40% gain resistance	47% after 2 weeks	76%	26 weeks
	BIM/lean 50% recovery; 50% gain resistance	41% after 1 week	76%	18 weeks
4	Traditional 40% recovery; 40% gain resistance	42% after 7 weeks	82.5%	28 weeks
	BIM/lean 50% recovery; 50% gain resistance	41% after 1 week	76%	18 weeks

the aspect being unreasonable and 5 being very reasonable. The aspects pertain to the inputs and outputs of the Gephi and NetLogo models. The responses are averaged and summarized in Fig. 7. The averaged ranks for all aspects indicate that the inputs and outputs are fairly to highly reasonable, thus providing theoretical validity to the assumptions and the results.

6. Discussion and recommendations

Early design collaboration and integration of construction expertise enabled by the BIM and lean principles are the main reasons for the different compositions between both networks. For a traditional project structure that does not adopt the BIM or lean principles, only the architect and engineers are present during the design phase, where teams usually collaborate within their internal department. This explains the lower number of individuals present, the lower number of edges (lower connection across teams), and the higher network modularity as connections are only denser within teams but not between them. Within a BIM and lean environment, contractors, suppliers, sub-contractors, and other specialty engineers are involved earlier in the design phase, which helps merge the input and requirements of downstream players with those of the upstream in an information pull strategy. Not only that more participants are present, but also the lean philosophy of sharing information and collaboration, with the help of BIM to enable and facilitate this process, allows teams to connect to players external to their discipline and to decentralize the exchange of information and decision making. This justifies the higher network density and number of groups in the BIM/lean structure. As opposed to the centralized control through the A/E on a traditional project, the process becomes decentralized when implementing BIM and lean, which helps remove bottlenecks, stream-line data exchange, and increase the autonomous work of teams and individuals.

The resulting node metrics show that the participants in a BIM/lean-based structure are more equally central on average as they are almost connected to everyone else without one central player. In addition, the betweenness and closeness metrics show that in a BIM/lean network, individuals are closer to each other and can reach the rest of the players

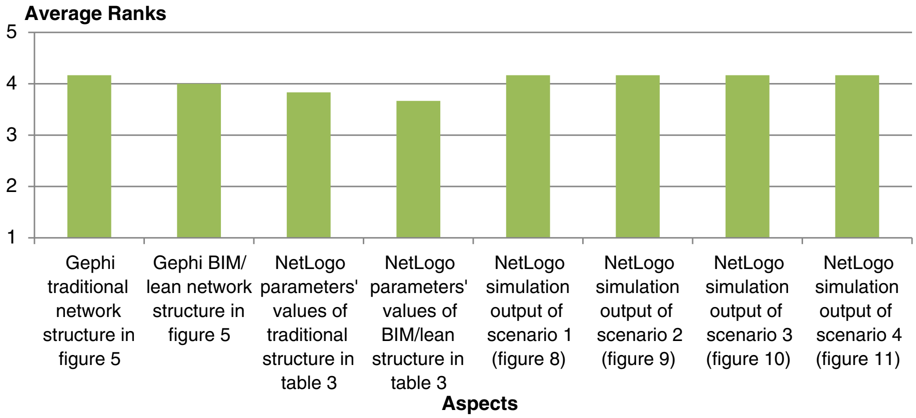

Fig. 7. Responses of expert.

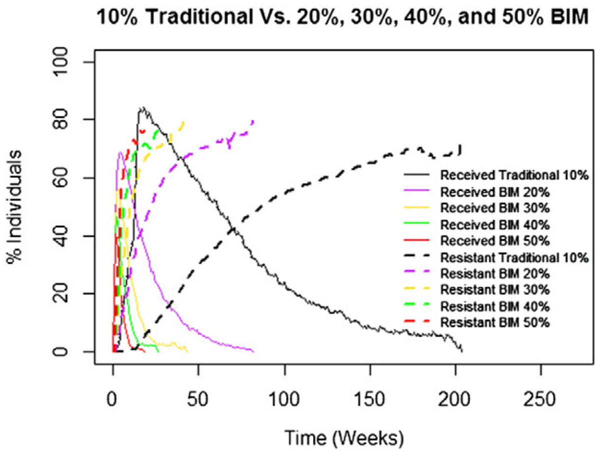

Fig. 8. NetLogo scenario 1 plots.

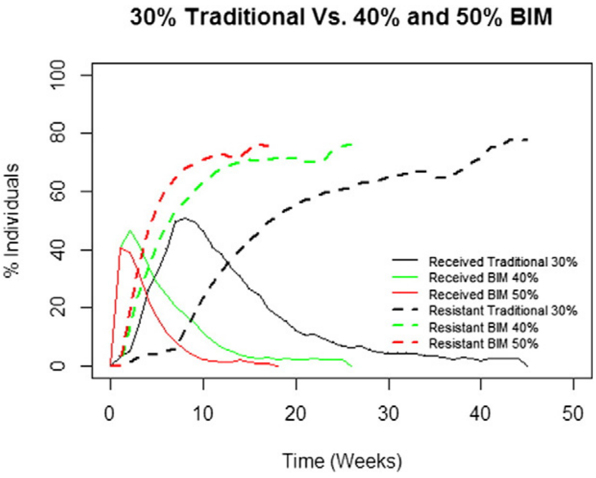

Fig. 10. NetLogo scenario 3 plots.

in a shorter path, as opposed to the traditional network where an individual requires to pass through several connections to get to the person they need. This justifies why the average path length of the network, similar to the closeness metric, is higher for a traditional network. The comparison of both structures indicates that a BIM/lean network is favorable for the exchange of information, with a faster ability to reach a larger number of individuals due to enhanced communication and collaboration. While the BIM/lean structure is an adequate environment for the diffusion of useful information, the question of concern is how would design errors spread in a similar environment. One would assume that this structure would similarly allow the design errors to disperse quickly and reach many individuals, which is not a favorable condition. This assumption is justified by the results of experiment 2 where Figs. 8, 9, 10, and 11 show that for a BIM/lean structure, the errors spread to the maximum number of individuals at a much faster rate as compared to the traditional network behavior. However, by examining the plots, we find out that the errors die out at a faster rate in a BIM/lean network as individuals detect and resolve errors by frequent checking and communication. On the other hand, when comparing traditional and BIM/lean structures at the same value of the recovery-chance and gain-resistance-chance (i.e. 20% for both parameters of traditional structure versus 20% for both parameters of BIM/lean structure; 30% for both parameters of traditional structure versus 30% for both parameters of BIM/lean structure), the BIM/lean simulation results show poor performance in design error management as summarized in Table 6. This shows that if the communication and information exchange patterns in a BIM/lean network are the same interactions as in a traditional environment, the system resembles a virus or disease spreading quickly in an environment of well-connected and interactive individuals with weak defensive mechanisms, as opposed to a less connected and interactive cluster of individuals where the virus slowly spreads and infects less people until it fails to find a host to multiply and spread. Therefore, the lesson learned from these results is that the BIM and lean should not be used under a traditional mindset of poor communication and fewer design-checks but instead exploit the several functionalities of the BIM and inherent collaboration of a lean environment that can reduce the design errors.

The techniques enabled by BIM such as clash detection and automated code checking can serve as possible defense lines against the diffusion of the design defects. By conducting regular design reviews, more accurate and faster approach of conflict detection, and code compliance checking, errors that could have easily passed undetected in the traditional approach would more probably be discovered through proper team work and high levels of BIM utilization.

Big-room meetings, design charrettes, and collaborative design under a lean environment, real-time visualization, and decision making enabled through BIM [13,32] might be potential reasons for a faster and smoother resolution of errors and mending information deficiencies between the teams. This is in contrast to the traditional structures, where individuals and teams do not perform continuous checking and design communications, thus allowing more defects to pass unseen and manifest in several deliverables. In addition, several human errors

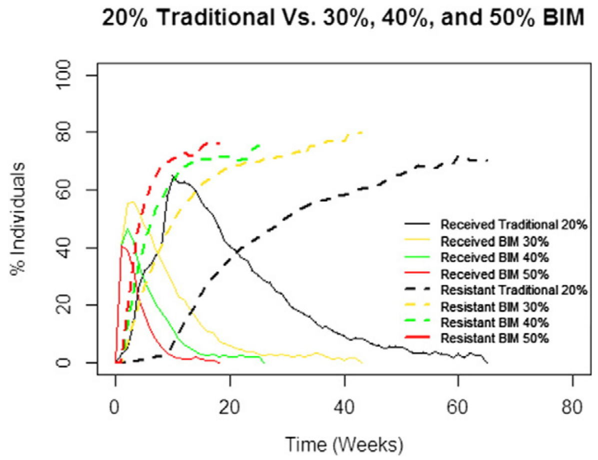

Fig. 9. NetLogo scenario 2 plots.

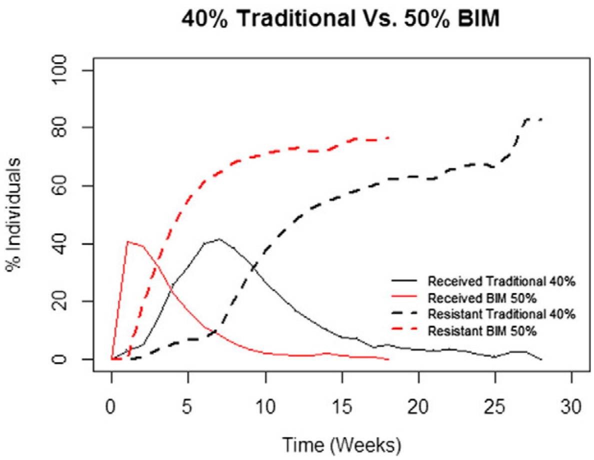

Fig. 11. NetLogo scenario 4 plots.

remain concealed and pass downstream unchecked. Hence, the individuals assume that the design is valid and pass it on to others who build the rest of their design on deficient inputs.

A long-term solution to design defects requires addressing the root causes, which are human-based errors. Even if BIM technology enables automated checking procedures, the individuals and teams need to develop and improve the defense mechanisms within them. When a defect is detected, the root cause analysis should be performed to find the fundamental causes, a solution should be developed to remove these causes or mitigate their consequences, learn from these errors, and prevent their future occurrence. The resistance to errors as a recourse action emerges from a continuous learning attitude and instilling a quality-at-bay principle where each individual is made responsible for ensuring his/her design to be error free. Therefore, the use of the BIM and lean justifies the results of the simulation where resistance is gained faster.

7. Conclusions and future research

Current strategies for design error management neglect the role of proper information flow and communication between the project players. Previous studies also ignore the importance of error diffusion dynamics, the structure of design teams, and the mechanics of interaction between and within teams. This paper assesses the role of social network theory and simulation in comparing design error management strategies between the traditional and the BIM/lean based environments to show the potential benefits of the BIM and lean in reducing the design errors and containing their diffusion.

This research proposes an effective design management perspective that adopts a wider view for studying the design errors and emphasizes the need for a proactive approach to counteract the current reactive measures that are ineffective in combating the occurrence of the design defects. A social network theory approach is adopted to analyze and compare two hypothetical project types, the traditional and the BIM/lean-based projects. It focuses on their social network structures, interactions and information exchange patterns among the project players, and the dynamics of error propagation. Using Gephi to model the structures of each project design network, and based on the theoretical assumptions, the resulting metrics indicate that using the BIM and lean principles favors the exchange of information and creates a more cohesive social network with more collaboration and connections within and between the different teams. In addition, agent-based modeling was employed to model the diffusion of the design errors under each hypothetical structure type. Based on the theoretical setup, the results from the different diffusion scenarios show that a BIM/lean network is more effective in reducing and containing errors. The employment of several defense mechanisms such as continuous and real time communication, clash detection, automated code checking [13,32], design charrettes, and continuous learning can be a likely reason for the reduction of defects. These mechanisms need to observed and analyzed on projects to determine their potential effectiveness. Further research is required to test the theoretical experiments presented in this research through several real case studies. These case studies can help test how the theoretical models apply under different structures of the BIM/lean and traditional projects. The results from such studies can also help justify the findings of this paper.

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