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A comparative evaluation of the effectiveness of virtual reality, 3D visualization and 2D visual interactive simulation: an exploratory meta-analysis

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Abstract
Research on the application of 3D visualization and virtual reality (VR) in discrete-event simulation (DES) has received increased attention in the past two decades. The increasing popularity of the 3D display in DES is mainly due to superior display capabilities and the associated benefits that it offers. However, the 2D display also continues to enjoy active use to date, thus provoking some fierce debates questioning the need for the 3D and VR if the 2D interface suffices. Several studies comparing the effectiveness of the different visualization methods also produce different conclusions. This paper undertakes a meta-analysis of the different positions and synthesizes the findings from 162 studies on the impacts of the 2D display *versus* 3D/VR on user performance on various DES tasks. The results highlight four key findings. First, the perception that the 2D display is more effective for model development is misleading as 3D/VR offers overall better performance and quality of models. Second, 3D/VR enables more effective performance than 2D display for model verification and validation. Third, 3D/VR decreases the time taken for verification, validation, experimentation, and analysis of results, but can increase model development time. Finally, the latent variables such as the application domains and nature of the problems tackled have no direct or indirect influence on the efficacy of the 3D display/VR *versus* 2D on DES task performance.

Keywords
3D visualization, discrete-event simulation, virtual reality, visual interactive simulation

1. Introduction

Visualization in discrete-event simulation (DES) has continued to evolve since the introduction of visual interactive simulation (VIS) and visual interactive modeling (VIM) in the early 1980s.[1,2] As predicted by Hurrion[3] and Jain,[4] virtual reality (VR) and the three-dimensional (3D) display are the most recent developments in the advancement of DES practice as a decision-support system.[5,6] This 3D/VR has enjoyed a steady growth in popularity and adoption by DES researchers and practitioners in academia and industry in the past 17 years.[2] In DES, the transformation in the nature and sophistication of the visual display from the VIS/VIM based on two-dimensional (2D) graphics to 3D/VR results from the tremendous advances in computer hardware and software,[7] and the adoption of these technologies in other fields. Some of the popular areas of application of 3D/VR include computer games,[8] architecture,[9] and archaeology.[10] Similarly, developers of computer models and simulation professionals, and users of these systems to aid business decisions, tend to prefer 3D visualization and VR,[11,12] a trend that has continued since the 1980s when the 3D maintenance aids, computer modeling, and design tools such as "Crew Chief," "Combiman," "Cyberman," etc. were preferred as good fit for the tasks at hand.[13] The proponents of 3D/VR espouse the view that the higher the dimension of the visual display, the better the clarity and understanding of the model.[6,11]

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Despite the popularity of VR/3D visualization, traditional VIS/VIM continues to enjoy active use.[6,11] Unlike during the advent of VIS/VIM, which quickly replaced the non-visual interface,[14] the same is not the case with 3D/VR. Some model developers sometimes use both versions (2D and 3D/VR) concurrently, indicating that both display techniques still offer some notable benefits. Rohrer[15] found that visualization generally (2D and 3D displays) improves people's understanding of simulation, although 3D visualization possesses the vital attribute of realism more than does 2D. Practitioners in academia and industry also have different opinions about the realized benefits of 3D visualization and VR compared to traditional VIS/VIM.[2] For example, some authors posit that the 2D display offers better performance in model development[16,17] and knowledge elicitation for decision-making[18,19] compared to 3D/VR visualization, while others[11,20,21] offer a positive and glowing appraisal in favor of 3D visualization and VR for model verification and validation tasks. However, simulation software vendors continue to create both 3D/VR and 2D versions (e.g., WITNESS/WITNESSVR,[22,12] AUTOMOD/AUTOMOD 3D,[23] COSMO WORLD/COSMO WORLD 3D.[11] A few simulation softwares offer the 3D/VR version alone (e.g., FLEXSIM[24]).

The 2D version "uses icons and display techniques that confine its scope to a mostly flat 2D surface," while 3D visualization "contains real binocular stereographic depth effects."[11] In the broader computer science field, the term "VR" applies in different contexts and often refers to graphics and equipment that provide a sense of immersion (e.g., by using specialized equipment, such as a head-mounted display to interact with the virtual environment[7]). In DES the 3D display is usually referred to as VR by simulation vendors and users.[12,25] Most DES software provides a 3D display rather than immersive VR, although this will likely change in the future as the use of VR equipment becomes more affordable and popular in DES practice[26–29]. This paper uses the terms "3D" and "VR" interchangeably.

The rest of the paper is organized as follows: Section 2 examines the existing literature, explains the scope of this research and presents the theoretical framework. Section 3 discusses the research methodology. Section 4 presents the results, synthesizes the conclusions from the literature, and discusses the realized value of 2D display vs. 3D/VR in DES. Section 5 discusses the main findings. Section 6 concludes the paper and shows areas for future work.

2. Theoretical background

2.1 Existing literature surveys on visualization techniques in DES

Information visualization as a multidisciplinary field is an active area of research and practice, both in mainstream computer science and in simulation applications. In separate articles published in 1987 and 1991, Bell and colleagues[30,31] analyzed the various developments in VIM/VIS for the period covering the 1980s and early 1990s. Similarly, Otamendi and colleagues[32] reviewed the general advances in DES and the visual display for the remaining parts of the 1990s, with a brief mention of 3D/VR as the current trend in the early 2000s. This paper, therefore, offers the first comprehensive review since the introduction of 3D/VR in DES, covering the period 2000–2016.

In the past 17 years, the adoption of 3D and VR as a DES modeling methodology by practitioners and researchers in the industry and academia has grown tremendously.[2,11,27] Almost all simulation software vendors now implement 3D/VR animation,[17] while actively maintaining the 2D display. Some journals have also devoted special editions to addressing the impacts of 3D visualization in DES (e.g., *Simulation* 77(3–4)[33]). However, most of these studies led to different conclusions and caused endless debates, hence the need to synthesize these views. This paper fills this gap through a comprehensive and comparative review evaluating the performance effectiveness of 2D vs. 3D/VR display on the various DES tasks in the context of cognitive fit theory,[12,34–37] as explained in Section 2.2. The results of this study will be beneficial to simulation practitioners and researchers in academia and industry, and any simulation project team attempting to determine the model development tasks and when to use either 3D/VR or 2D displays, or both.

2.2 Theoretical framework

This review utilizes cognitive fit theory to guide the evaluation of the effectiveness of 2D display versus 3D/VR on the performance of various DES tasks and activities. The theory examines the fit of a chosen technology to specific tasks.[35,38] The significance of this theory is that it provides the guidance to choosing appropriate tools or methods that match specific tasks and activities in order to enhance performance.[35] Further details about this theory are available elsewhere.[35]

Cognitive theory is appropriate for this study for several reasons. First, any DES activity revolves around the performance of several tasks and activities, ranging from problem formulation through verification and validation, and the presentation and implementation of the results.[11,39] Second, this paper evaluates visualization techniques in DES (2D display, 3D visualization/VR), and examines the techniques that suit the specific tasks to enhance performance.[40] For example, while 2D display or 3D/VR can improve the performance of some DES functions (e.g., model validation and verification[6,11,41]), it may not be very useful for other tasks, (e.g., problem definition[11]).

Previous studies on usability engineering and information visualization employed cognitive fit theory successfully. Vessey[35] surveyed the literature on "graph vs.

tables" and concluded that the cognitive fit between the task and its representation affect performance. Dennis and Carte[42] extended the application of cognitive fit theory to user performance on geographically based tasks, concluding that the use of geographical information systems is more effective when using map-based presentations versus tabular data. Wickens and Carswell[43] emphasized the importance of "display proximity," and the extent to which the display matches a given task and the visualization format (e.g., 2D versus 3D). Further, Vessey[35] and Dennis and Carte[42] identified several forms of tasks and presentation styles including "spatial versus symbolic," and explained the effects on performance. Thus, the nature of the activities informs the display choices, which in turn affects performance effectiveness and efficiency.[44] Spatial tasks involve the acquisition of information or comparing alternatives for decision-making, while symbolic functions utilize numeric data.[35,42]

While cognitive fit theory originated from different disciplines such as psychology and ergonomics,[43,45] it is also applicable to the study of information visualization techniques. For example, in an experimental study, Akpan and Brooks[6] examined the learning style of users and the possible effects on performance using 2D versus 3D for model validation and verification, and decision-making tasks. The study highlighted that both the visual and non-visual learners who carried out the tasks on the 3D display performed significantly better than those who used 2D. Dennis and Carte[42] present the two forms of tasks as mutually exclusive, while Akpan and Brooks[6] show circumstances in which the spatial and symbolic values can complement each other in the task performance.

2.3 Research questions (RQs)

The use of both 3D and 2D displays to perform the same or different DES tasks and activities has raised several questions. First, what DES tasks or activities can be performed better using 3D or 2D display? Second, why use 3D modeling and simulation platforms/tools if 2D displays can serve the purpose and *vice versa*? Table 1 presents the five hypotheses formulated to answer these and several other questions. The first question (RQ1) seeks to determine the effectiveness of 3D vs. 2D displays on the performance of eight primary DES tasks (RQ1(i) to RQ1(viii) in Table 1). The second research question (RQ2) examines another major issue of contention about the comparative impacts of 3D vs. 2D on time taken to complete the modeling and simulation tasks. The third and fourth questions (RQ3 and RQ4) examine the comparative impacts of 2D vs. 3D/VR on problem formulation and conceptual modeling. Finally, RQ5 examines the possible co-effects of any latent variables and the type of display (3D/VR vs. 2D) on task performance. These latent variables are explained in Section 2.4.

2.4 Latent variables

The fifth research question (RQ5) examines any possible influence of some latent variables on the conclusions reached by the reviewed articles. The latent variables examined include:

- Problems tackled: Does the nature of the problem tackled influence the outcomes of the studies conducted by the reviewed articles?
- Application domains: Computer simulation and modeling is a multidisciplinary subject that guides decision-making in diverse fields of application, e.g., healthcare, manufacturing or aerospace.
- Research methods: The purpose is to identify any possible effects of the approach adopted by the reviewed articles on the outcomes, such as case study, survey, or scientific experiments.
- Period of study: In this era of rapid transformation in technology, the graphical displays of simulation elements and components improved over time. This study intends to observe any possible effects of the time dimension on the results, given an extended period covered in this study (2000–2016).

3. Research methodology

This literature review is structured according to the guidelines offered by the "Preferred Reporting Items for Systematic Reviews and Meta-Analyses – PRISMA."[46] PRISMA defines the steps and the processes in identifying, interpreting, and evaluating articles' data; Moher and colleagues[46] offer further details. This paper follows the PRISMA guidelines[46] in collecting the data that help to answer the RQs that were identified in Section 2.3.

3.1 Literature search, screening, and selection criteria

The literature search covered the period 2000–2016. The multidisciplinary nature and broad applications of DES and information visualization means articles in the field are published in several journals over various disciplines. Figure 1 shows the filtering, screening, and selection process based on the PRISMA guidelines.[46] Employing the search, filtering, and querying functionalities of Endnotes, duplicate entries were removed, while a further filtering process reduced the initially retrieved articles from 1929 to 453, using eligibility screening.

The selection criteria were as follows. Any selected articles must: address the effects of information visualization in 3D/VR or 2D displays; evaluate the impacts of visual display in DES (2D, 3D/VR, + DES), which helped to answer the RQs listed in Table 1; must be a peer-reviewed article published in journals or reputable conference

Table 1. Research questions (RQs).

RQ1	Does 3D visualization/VR or 2D display offer more effective performance on the following model development and simulation tasks? i. Model development ii. Experimentation iii. Model run iv. Model verification v. Model validation vi. Analysis of results vii. Presentation of results vii. Implementation
RQ2	Does it take longer to perform the DES tasks using 3D visualization compared to 2D display? i. Model development ii. Verification iii. Validation iv. Analysis of results
RQ3	i. Does 3D visualization improve problem definition performance more than 2D display? ii. Does it take less time to undertake problem definition with 3D visualization compared to 2D display?
RQ4	Does 3D visualization improve conceptual modeling performance more than 2D display?
RQ5	What are the impacts of other latent variables (application domains, research methods, problems tackled) on performance other than the two types of display (3D vs. 2D)?

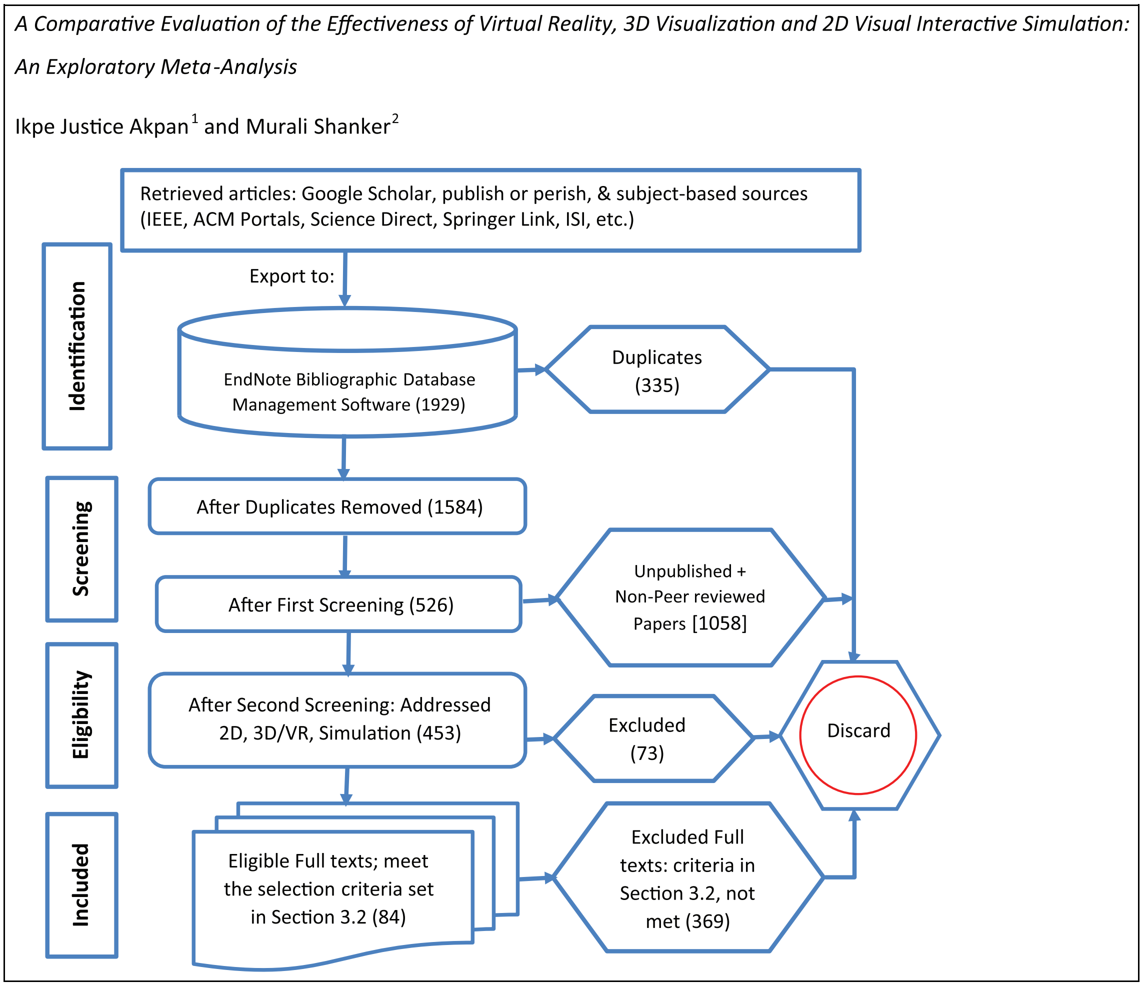

Figure 1. Screening and selection process for the articles based on PRISMA guidelines.[46]

proceedings between 2000 and 2016 (print/online sources); and the articles must be written in English or have been translated into English. Articles that examined the general benefits of visualization in DES without specifying the display types (e.g., Jain[7]) were removed.

The filtered vs. selected papers follow a similar trend throughout the 17-year period, except in 2012 and 2016, when there was a surge in publications on 3D and VR research in DES. This trend highlights the importance of visualization in DES, and a sustained development in the display techniques as a way of advancing DES practices since the early 2000s.

Out of the 453 publications screened, 84 papers (about 19%) met the selection criteria as stated in Section 3.2, while 369 papers were discarded.

4. Research data, results, and analyses

4.1 The research data

The data used for the analysis were extracted from the reviewed articles to help answer the RQs (RQ1–RQ5) listed in Table 1. The problems tackled by each reviewed publication and the DES tasks performed (e.g., model development, verification, validation, etc.) are listed in Table 2.

The reviewed papers employed one of the five research methods listed in Table 3, with more than 62% of the articles using the case study method, while over 30% utilized the experimental study approach. The remaining 8% of the reviewed papers used either the survey method or a combination of survey and case study or experiment and case study (Table 3). None of the selected publications used other research methodologies such as an interview method. The case study method involved either an implementation of a simulation solution or using the platform to model a system of interest in 3D/VR, 2D display, or both, and evaluating the impacts of visualization on some DES activities/tasks (e.g., Kamsu-Foguem and colleagues[9] and Kamat and Martinez[21]). Others used off-the-shelf simulation software to do so (e.g., Akpan and Brooks[6]; Runeson and Höst[111]). Table 3 also presents the 24 different application domains in which the selected/reviewed publications tackled problems.

Table 4 shows the list of selected articles and the related publication outlets. Over 50% of the 84 selected papers appeared in 10 major journals and conference proceedings in the fields of information systems and information technology (IS/IT), operations research/management science (OR/MS), and decision sciences (DS) journals. *Simulation* and *Automation in Construction* had the highest count of seven each, or 8%, of the papers. *Expert Systems with Applications* and *Simulation Modelling Practice & Theory* each had six, or 7%, of the selected papers. Others are *Decision Support Systems, Journal of Operations Research Society, ACM Transactions on Modeling & Computer Simulation, Winter Simulation conference proceedings*, and *MIS Quarterly* with 3–4 articles each. Also, one article each came from *Systems Analysis Modelling Simulation, Computers and Industrial Engineering*, and 27 other journals in IS/IT, OR/MS, and the general computing fields. Civil engineering and construction had the highest number of articles in terms of the application domains.

The research data compares the effectiveness of 3D/VR vs. 2D display techniques on the performance of DES tasks. On average, each paper investigated 2–3 DES tasks. For example, Akpan and Brooks[6] and Kamat and Martinez[72] examined the impacts of 2D and 3D/VR displays on model verification, validation, and credibility. All the papers included in the review contributed to the overall conclusions of this paper. However, some authors covered more DES tasks, e.g., Akpan and Brooks,[11] Dangelmaier et al.,[59] Petti et al.[49] Out of the 162 investigations by the 84 reviewed articles, the studies that evaluated the impacts of the 3D/VR and 2D display techniques on presentation had the highest number (32), followed by analysis of results (28). The DES activities with the fewest number of research articles were on problem definition (5), while the conceptual modeling and implementation of the simulation outcomes had 4 each (Table 3). It is not surprising that the studies on problem definition and conceptual modeling had fewer studies based on a common perception that visualization does not influence these DES tasks.[2,11]

In the application domains, the 84 articles tackled problems in over 33 application areas, some of which includes aerospace, production, manufacturing, construction, and medical services operations. Others were road and air traffic controls, real estate services, and emergency and crisis management (Table 3). Some of the reviewed papers tackled problems in more than one application area. For example, Akpan and Brooks[6] examined problems in the automotive industry and bank customer services operations. Table 3 shows the complete list.

4.2 Results and analyses

The objective of this review is to evaluate the efficacy of the visualization techniques (2D vs. 3D/VR) on the performance of DES tasks (as discussed in Section 2). The conclusions from the 84 reviewed articles and the investigations on 162 DES tasks showed three possible outcomes (3D/VR better, 2D better or same performance). We utilize the exploratory technique to analyze and synthesize the conclusions from the reviewed articles while comparing the efficacy of 3D/VR vs. 2D display in the performance of modeling and simulation tasks. The exploratory analysis technique also helps to probe further into the non-quantitative rationale for the preference of one visualization method over the other. Previous studies evaluating the visual interactive simulation[11,112] adopted a similar approach for similar reasons.

4.3 RQ1: does 3D visualization enhance better performance on DES tasks than 2D display?

The answers to the first research question covers seven DES activities (RQ1(i) to RQ1(viii) in Table 1).

Table 2. The problems tackled and the DES tasks performed.

Reference	Problems tackled	Problem definition	Conceptual modeling	Model development	Model run	Experimentation	Verification	Validation	Analysis	Presentation	Implementation
Akpan and Brooks[11]	Surveyed simulation practitioners and users on diverse DES projects	X		X	X	X	X		X	X	X
Mueller-Wittig et al.[47]	Virtual factory: improving electronics assembly processes					X	X				
Rohrer[15]	Using visualization to improve the simulation processes of a manufacturing system			X			X	X	X	X	
Hutabarat et al.[48]	VR-DES as a method to visualize the complexity of shop floor behavior					X					
Petti et al.[49]	Shop floor facility layout design	X		X		X	X	X		X	
Fishwick et al.[50]	Modeling methodology			X							
Akpan and Brooks[6]	Auto assembly and banking customer service						X	X			
Alberts et al.[51]	Diagnoses of inflammatory response syndrome							X	X		
Al-Hussein et al.[52]	Tower crane operations on construction sites			X			X	X			
Whyte[53]	Construction management									X	
Waly and Thabet[29]	Engineering construction process planning and design				X						
Bruzzone et al.[54]	Process management for large-scale retail stores								X	X	
Chan[55]	Process design					X	X	X			
Wenzel and **Jessen**[56]	Process planning									X	
Chen and Huang[57]	Problem formulation (2D vs. 3D)		X	X						X	
Choi et al.[58]	Automated manufacturing systems design			X				X			
Dangelmaier et al.[59]	Simulated digital factory			X	X	X	X	X	X	X	
Den Hengst et al.[60]	Collaborative modeling: airport construction/operations			X		X					
Dorozhkin et al.[61]	Coupling interactive flexible manufacturing operations				X	X			X		
Bailey et al.[62]	Evaluating display types							X			
Fabritius et al.[63]	Determining best visualization method									X	
Farooq et al.[64]	Implementation process simulation of mobile wireless network	X			X	X	X	X	X		
Fishwick[65]	Modeling systems using 2D vs. 3D			X		X				X	
Fishwick et al.[66]	Visualization in 2D vs. 3D			X							

(continued)

Table 2. Continued

Reference	Problems tackled	Problem definition	Conceptual modeling	Model development	Model run	Experimentation	Verification	Validation	Analysis	Presentation	Implementation
Talmaki et al.[67]	Monitoring visibility-constrained construction				X				X	X	
Su et al.[68]	Smart building planning			X			X				
Suh et al.[69]	Products display									X	
Huang et al.[26]	System implementation			X	X						
Sun et al.[34]	Container terminal management			X							
Tory et al.[40]	Performing tasks on 2D vs. 3D									X	
John et al.[45]	Relative positioning in air traffic control using 2D and 3D									X	
Kamat and Martinez[70]	Creating and evaluating software for construction management			X			X	X			
Kamat et al.[71]	Evaluating speed detection in 2D vs. 3D						X	X			
Kamat[20]	Construction process-level planning						X	X			
Kamat and Martinez[41]	Visualization of construction equipment						X	X		X	
Kamat and Martinez[72]	Validating complex earth-moving construction activities						X	X		X	
Kamat and Martinez[21]	Construction planning							X	X		
Kamsu-Foguem et al.[9]	Detection of issues in intensive care patient								X	X	
Khoury et al.[73]	Airside airport construction and operation						X	X			
Kim et al.[74]	Web-based simulation									X	
Kim and Chung[75]	Modeling of human 3D anatomical model								X		
Van Orden and Broyles[76]	Altitude and speed judgment (air traffic control)									X	
Aigner et al.[77]	Visual analytics								X	X	
Kumar and Benbasat[78]	Evaluation of 2D vs 3D line graphs								X	X	
Li et al.[79]	Virtual construction					X			X		
Lindskog et al.[80]	Systems re-design			X						X	
Moon et al.[81]	Simulated body shop design in auto assembly						X				
Mujber et al.[82]	Flexible manufacturing process analysis						X	X			
Murphy and Perera[83]	Process planning		X								
Nah et al.[84]	Compare 2D vs. 3D									X	

(continued)

Table 2. Continued

Reference	Problems tackled	Problem definition	Conceptual modeling	Model development	Model run	Experimentation	Verification	Validation	Analysis	Presentation	Implementation
Wainer and Liu[36]	Systems evaluation								X	X	
Okulicz et al.[85]	Process planning								X		
Otamendi et al.[32]	Software evaluation and selection for airport construction and operations			X							
Quarles et al.[86]	Analyze interaction among components			X							
Rekapalli and Martinez[23]	Process evaluation							X			
Waisel et al.[37]	Model formulation by experts	X	X								
Robinson et al.[22]	Knowledge elicitation and decision-making in auto engine production				X	X					
Rodriguez et al.[87]	Industrial plants and traffic flow, speed, rate, etc.								X	X	
Ahlberg et al.[88]	Diagnoses and case detection during surgery									X	
Qu et al.[18]	Teleonomic modeling of eggplant								X	X	
Rua and Alvito[10]	Reconstruction of heritage					X			X	X	
Rubio et al.[89]	Flexible manufacturing								X		
Smallman et al.[90]	Evaluation of 2D vs. 3D in air traffic control								X		
Son and Kim[91]	Visualization of underwater vehicle and effective maneuvering control								X		
Oerter et al.[92]	VR platform for collaborative modeling and simulation			X	X	X					
Hurrion[3]	3D modeling as DES methodology					X			X		
Dialami et al.[93]	Material transport and flow in a friction stir welding							X			
Vasudevan and Son[94]	Evacuation performance using different layouts in crowd safety management									X	
Lu et al.[95]	Assembly facility planning operation							X			
Korošec et al.[96]	Production scheduling and optimization	X									
Khosravi et al.[97]	Metamodeling and simulation of baggage handling			X							
Hartmann and Fischer[98]	Reviewing facility with 3D visualization										
Chen et al.[99]	Maintenance and management of building facilities			X							

(continued)

Table 2. Continued

Reference	Problems tackled	Problem definition	Conceptual modeling	Model development	Model run	Experimentation	Verification	Validation	Analysis	Presentation	Implementation
Shen et al.[100]	Safety and security in emergency and crisis management									X	
Hajdas[101]	Creating an intelligent support system and simulating construction process dynamics					X			X		
Somasundaram and Kalaiselvi[102]	Surgical experiment					X		X			
Calabrese et al.[103]	Shipboard damage control							X			
Li et al.[104]	Construction planning								X		
Hong et al.[105]	Construction process planning			X			X	X			
Moghadam et al.[106]	Building construction scheduling								X		
Nandan et al.[107]	Material transport and flow in a friction stir welding process							X	X		
Zhang et al.[108]	Evaluateing the use of 2D and 3D simulation visualization in planning and performing hepatectomy operations									X	
Patel et al.[109]	Disaster, emergency, and crisis management									X	
Zhou et al.[110]	Manufacturing process optimization							X	X		
		5	3	22	9	17	19	26	28	32	1

Table 3. The research methods and application domains covered by the reviewed papers.

Application domains	Case study	Experiment	Survey	Case study and survey	Case study and experiment
Advertising		Suh et al.[69]			
Aerospace	Khoury et al.[73] Otamendi et al.[32]	Van Orden and Broyles[76] Den Hengst et al.[60] Smallman et al.[90] Khosravi et al.[97] John et al.[45]			
Agriculture (virtual plantation)		Qu et al.[18]			
Archaeology		Rua and Alvito[10]			
Automotive		Akpan and Brooks[6] Robinson et al.[22]			
Banking – customer service		Akpan and Brooks[6]			
Business analysis			Akpan and Brooks[11]		
Construction (Civil Eng.)	Kamat and Martinez[21] Kamsu-Foguem et al.[9] Waly and Thabet[29] Talmaki et al.[67] Rekapalli and Martinez[23] Kamat and Martinez[21] Kamat and Martinez[41]	Kamat et al.[71] Chen and Huang[57] Li et al.[79]			
Facility layout planning/design		Petti et al.[49]	Akpan and Brooks[11]		
Finance			Akpan and Brooks[11]		
Healthcare	Kamsu-Foguem et al.[9] Alberts et al.[51] Zhang et al.[108] Kim and Chung[75]		Akpan and Brooks[11]		
Logistics operations	Wenzel Jessen[56]				
Manufacturing	Lu et al.[95] Dorozhkin et al.[61] Lindskog et al.[80] Rubio et al.[89] Mujber et al.[82] Chan et al.[55] Zhou et al.[110] Murphy and Perera[83] Hutabarat et al.[48] Rohrer[15] Mueller-Wittig et al.[47]		Akpan and Brooks[11]		
Marine – seaport	Sun et al.[34]				
Modeling methodology	Hong et al.[105] Farooq et al.[64] Kim et al.[74] Wainer and Liu[36] Fishwick et al.[50]			Fishwick et al.[66]	Fishwick[65]
Not specified		Waisel et al.[37]			
Ontology	Fabritius et al.[63]				
Production operation	Okulicz et al.[85]				
Real estate construction	Moghadam et al.[106] Whyte[53] Li et al.[104] Hartmann and Fischer[98] Hajdas[101] Chen et al.[99] Su et al.[68] Al-Hussein et al.[52]				
Repairs and maintenance (auto)	Moon et al.[81]				

(continued)

Table 3. Continued

Application domains	Case study	Experiment	Survey	Case study and survey	Case study and experiment
Retail	Bruzzone et al.[54]				
Safety and security	Patel et al.[109]	Vasudevan and Son[94] Shen et al.[100]			
Systems implementation and evaluation	Choi et al.[58] Kamat and Martinez[70] Bailey et al.[62] Rodriguez et al.[87] Calabrese et al.[103] Son and Kim[91] Oerter et al.[92]	Nah et al.[84] Kumar and Benbasat[78] Tory et al.[40]		Huang et al.[26]	
Visual analytics	Aigner et al.[77]				
Welding		Dialami et al.[93] Nandan et al.[107]			

4.3.1 RQ1(i): model development. Model development involves the implementation of a conceptualized problem via a computer program or using off-the-shelf modeling software or specialized applications such as WITNESS, FLEXSIM,[6,11,12,24] or customized modeling and simulation tools like VITASCOPE[70] or RUBE.[50] Examining the impacts of the visual display on performance during modeling activities, 59% (13 out of 22) of the studies concluded that 3D display offers better performance, while 32% (7 out of 22) of the studies considered 2D display as better, and 9% (2 out of 22) viewed both displays as offering the same performance effectiveness.

The combined frequencies of the ''2D better'' or ''no difference'' in performance effectiveness is 41% compared to 59% for 3D visualization (Table 5), indicating a higher preference for 3D/VR. Also, most of the authors preferring the 2D display agreed that the 3D display offers an overall better performance, but preferred the 2D because 3D/VR is more difficult and it takes a longer time to build a model. Table 6 provides the bases for the conclusions and further explanations.

4.3.2 RQ1(ii): Experimentation. Experimentation is another activity in which the visual display plays a key role. The activity involves an evaluation of the alternative courses of actions, such as undertaking a what-if analysis toward arriving at a preferred decision to improve the system under study.[79,113]

Out of the 17 studies that examined the performance effectiveness of 3D visualization vs. 2D display on model experimentation, 16 (or 94%) concluded that 3D visualization offers better and faster performance. Table 7 presents further explanations for the conclusions provided by the reviewed articles.

4.3.3 RQ1(iii): Model run. Studies on the impacts of 3D vs. 2D display on performance effectiveness during model runs attracted only nine articles investigating the activity. The purpose of running a model is often to perform other tasks such as experimentation, validation, and verification, or to examine the behavior of the system modeled. Out of the nine articles that investigated the impacts of the 3D display vs. 2D on model runs, 78% concluded that 3D visualization offers better performance, while 22% considered 2D as more effective. Table 7 offers further explanations/reasons.

4.3.4 RQ1(iv): Model verification. Model verification is another DES activity that benefits significantly from the use of visual displays.[3,6,11,15,31] The verification activity involves determining whether the conceptual model and assumptions are translated correctly into a DES model.[41,72] Nineteen articles investigated the impacts of 3D display vs. 2D on verification tasks. Eighteen out of 19, or 95%, of the studies concluded that 3D visualization makes it easier to verify the DES model than does 2D (Table 5). As demonstrated by Kamat and Martinez,[72] even the domain experts with limited expertise in simulation were able to understand the model easily and detect severe errors caused by the model developers' incorrect use of data. These were errors that the simulation experts may not detect. Table 6 presents the reasons for these conclusions.

4.3.5 RQ1(v): Model validation. Model validation is the process of determining whether a simulation model is an accurate representation of the system based on the particular objectives of study.[6,72] The activities include checking and correcting errors in the model, such as logic, routing, incorrect components combination, or systems errors.[6,41]

Table 4. List of reviewed articles and the publication outlets (2000–2016).

Journals	References	*n*	Journals	References	*n*
Simulation	Akpan and Brooks[11] Alberts et al.[51] Wenzel Jessen[56] Choi et al.[58] Fishwick[65] Khoury et al.[73] Wainer and Liu[36]	7	*Automation in Construction*	Hong et al.[105] Waly and Thabet[29] Chen and Huang[57] Al-Hussein et al.[52] Huang et al.[26] Li et al.[104]	7
Simulation Modelling Practice & Theory	Bruzzone et al.[54] Farooq et al.[64] Murphy and Perera[83] Otamendi et al.[32] Rodriguez et al.[87] Qu et al.[18]	6	*Expert Systems with Applications*	Robinson et al.[22] Son and Kim[91] Korošec et al.[96] Chen et al.[99] Khosravi et al.[97] Calabrese et al.[103]	6
Proceedings of the Winter Simulation Conference	Hutabarat et al.[48] Rohrer[15] Mueller-Wittig et al.[47] Fishwick et al.[50]	4	*Journal of the Operational Research Society*	Den Hengst et al.[60] Fabritius et al.[63] Waisel et al.[37] Hurrion[3]	4
ACM Transaction on Modelling & Computer Simulation	Fishwick et al.[66] Kim et al.[74] Oerter et al.[92]	3	*MIS Quarterly*	Suh et al.[69] Kumar and Benbasat[78] Nah et al.[84]	3
Decision Support Systems	Akpan and Brooks[6] Kamsu-Foguem et al.[9] Shen et al.[100]	3	*Advances in Engineering Software*	Kamat and Martinez[70] Kamat[20]	2
Journal of Computing in Civil Engineering	Kamat and Martinez[21] Kamat and Martinez[41]	2	*International Journal of Production Research*	Moon et al.[81] Okulicz et al.[85]	2
Computers and Industrial Engineering	Lu et al.[95] Vasudevan and Son[94]	2	*Multimedia Tools and Applications*	Kim and Chung[75]	1
Proceedings of the Operational Research Society Simulation Workshop	Petti et al.[49]	1	*Science and Technology of Welding and Joining*	Nandan et al.[107]	1
Engineering with Computers	Talmaki et al.[67]	1	*Computers in Industry*	Dangelmaier et al.[59]	1
Systems Analysis Modelling Simulation	Kamat and Martinez	1	*Journal of Archaeological Science*	Rua and Alvito[10]	1
Journal of Construction, Engineering & Management	Rekapalli and Martinez[23]	1	*Journal of Information Technology in Construction*	Kamat et al.[71]	1
Computers in Biology and Medicine	Somasundaram and Kalaiselvi[102]	1	*Computers & Graphics*	Aigner et al.[77]	1
International Journal of Computer Integrated Manufacturing	Rubio et al.[89]	1	*IEEE Transactions on Visualization & Computer Graphics*	Tory et al.[40]	1

(continued)

Table 4. Continued

Journals	References	*n*	Journals	References	*n*
Human Factors: The Journal of the Human Factors & Ergonomics Society	John et al.[45]	1	*Technological and Economic Development of Economy*	Hajdas[101]	1
The American *Journal* ***of*** *Surgery*	Ahlberg et al.[88]	1	*Virtual Reality*	Dorozhkin et al.[61]	1
Journal of Materials Processing Technology	Mujber et al.[82]	1	*IEEE Computer Graphics and Applications*	Smallman et al.[90]	1
Advanced Engineering Informatics	Sun et al.[34]	1	*Procedia CIRP*	Lindskog et al.[80]	1
Computer Standards & Interfaces.	Su et al.[68]	1	*Displays*	Van Orden and Broyles[76]	1
Journal of Defense Modeling & Simulation: Applications, Methodology, Technology	Oerter et al.[92]	1	*Canadian Journal of Civil Engineering*	Moghadam et al.[106]	1
International Journal of Material Forming	Dialami et al.[93]	1	*Organization Science*	Bailey et al.[62]	1
Building Research and Information	Hartmann and Fischer[98]	1	*Assembly Automation*	Chan et al.[55]	1
Construction Management and Economics	Whyte[53]	1	*Surgical Oncology*	Zhang et al.[108]	1
Geomatics, Natural Hazards and Risk	Patel et al.[109]	1	*JOM Design and Manufacturing*	Zhou et al.[110]	1

Table 5. Summary of the conclusions from the reviewed articles on the impacts of 3D vs. 2D displays on DES tasks.

DES activities	Which display better enhances performance?				Performance time			
	n	3D better	2D better	Same	*n*	Shorter time with 3D	Shorter time with 2D	Same time
Model development	22	13	6	3	10	1	9	–
Experimentation	17	16	1	–	–	–	–	–
Model run	9	7	2	–	–	–	–	–
Verification	19	18	–	1	5	5	–	–
Validation	26	24	–	2	6	6	–	–
Analysis	28	28	–	–	4	2	1	1
Presentation	32	32	–	–	–	–	–	–
Problem definition	5	3	1	1	1	1	–	–
Conceptual modeling	4	–	2	2	–	–	–	–
Implementation	1	–	–	1	–	–	–	–
n = 162								

Investigating the efficacy of 3D vs. 2D visual display on model validation, 92% (24 out of 26) of the reviewed articles concluded that 3D display is more effective when performing model validation. The remaining 8% of the reviewed articles found that both 2D and 3D displays offer the same level of performance effectiveness, while no study identified 2D display only as a better option when checking for errors in the model (Table 5). This shows a significant positive outcome in favor of 3D visualization. According to Akpan and Brooks,[6] using a 3D display increases validation performance by over 70% when attempting to spot an error that is relatively harder to find and 65% more effective than the 2D display in finding the standard bugs in a model. Thus, the more complicated the errors, the longer it takes to find using the 2D display, if at all. Similarly, Kamat and Martinez[72] highlight that some of the errors that are easier to identify using the 3D display can take considerable effort to spot in a 2D model, if at all. Table 7 provides further details.

4.3.6 RQ1(vi): Analysis of the results. The analysis of results is another DES activity that has seen fierce debate questioning the need for 3D visualization. The analysis includes undertaking a what-if analysis or evaluating alternatives. The results show that all 28 papers that investigated the effectiveness of 3D/VR vs. 2D in enhancing results analysis in DES considered 3D/VR to be more effective than 2D display (Tables 5 and 7).

4.3.7 RQ1(vii): Presentation. This activity involves a demonstration of the model to the client or different stakeholders (e.g., managers, decision-makers[114]) involved in a given simulation project. The comparative evaluation of the impacts of 3D/VR vs. 2D on presentation of the simulation/model and the simulation results attracted the most studies (Table 5). Thirty-two articles investigated this activity, with all arriving at a similar conclusion: 3D/VR visualization is more effective than 2D in presenting and communicating simulation results to management and decision-makers. The effectiveness of 3D/VR for this purpose also encourages management buy-in to the simulation project and subsequent adoption as a decision-support system and implementation of the simulation results.[15] This conforms with practitioners' perceptions as 93% of simulation developers and decision-makers agreed with a similar conclusion in a survey of researchers and practitioners.[11] Table 7 provides further details.

4.3.8 RQ1(viii): Implementation of simulation outcomes. Studies investigating the effect of visual displays on the implementation of simulation results had the fewest publications, at only one. Akpan and Brooks[11] concluded that, although the use of visual simulation can positively influence the implementation of the simulation outcomes both in terms of its effectiveness and the time taken to complete the activity, and managers' buy-in,[15] it does not matter whether 3D/VR or 2D visual displays are used. However, more studies are required in this area before a firm conclusion can be reached.

4.4 RQ2: Comparative analysis of time taken to complete DES tasks using 3D/VR vs. 2D displays

This section presents the results of the comparative evaluation of the impacts of 3D vs. 2D displays on the time taken to perform DES tasks, as formulated in Section 2.3 (RQ2(i)–RQ2(iv) in Table 1). Relatively fewer studies investigated the time dimension in performing the DES tasks. The data extracted from the reviewed articles were summarized in three categories, "Shorter time with 3D,""Shorter time with 2D," or "Same time." These three options formed the basis for answering the RQs about the impacts of 3D/VR vs. 2D on the time taken to complete the DES tasks.

4.4.1 RQ2(i): Time taken to complete model development. Ten out of the 22 articles that examined the impacts of 3D vs. 2D displays on model development also investigated the effects of the two visualization techniques on time taken to complete model development. Nine out of the 10 articles (90%) concluded that it took a shorter time to complete model development when using a 2D display, while only one of the studies (10%) found that the 3D display took a shorter time (Tables 5 and 6). Several studies drew this conclusion irrespective of the modeling/simulation platforms and software used. Also, some of the studies that preferred 3D/VR reached the same conclusion, that 2D display does take less time to build.

4.4.2 RQ2(ii): Time taken to complete model verification. The data from the literature review on the impacts of 3D vs. 2D displays on time taken to complete model verification show a convincing position in favor of 3D visualization. The five articles that investigated this aspect of the study (time spent to undertake model verification) concluded that 3D visualization takes a significantly shorter time to complete the verification tasks.[6,11,59,72]. None of the reviewed articles considered 2D displays as offering the same level of performance or better. The reasons for these conclusions are provided in Table 7.

4.4.3 RQ2(iii): Time taken to complete model validation. Six out of the 26 articles that investigated the comparative effectiveness of 3D vs. 2D displays on model validation also examined the time taken to complete the validation task. All the reviewed papers (Table 5) concluded that it

Table 6. Model development performance evaluation using 3D/VR vs. 2D displays.

Modeling tools	2D better	3D better	Same	Modeling time	Reasons/ conclusions
AOOSS	Hong et al.[105]			2D Shorter	3D wastes time (longer to develop model)
Automod		Den Hengst et al.[60]			3D/VR helps to resolve complexities
Custom software		Dangelmaier et al.[59]			Easier for stakeholders to understand
Custom 2D with 3D CAD	Lindskog et al.[80]			2D Shorter	3D is time-consuming; over simplification
MicroPort		Sun et al.[34]			3D helps to reduce modeling effort
OLIVE		Oerter et al.[92]		2D Shorter	VR is a great learning and modeling tool
QUEST with CVP	Huang et al.[26]			2D Shorter	3D is tedious and time-consuming
QUEST3D		Khosravi et al.[97]			3D precisely represents baggage handling
RUBE RUBE			Fishwick et al. [50,66]	2D Shorter 3D Longer	3D should complement 2D, not replace “Slower speed in model creation” with 3D
SPS with 3D visualization		Al-Hussein et al.[52]			Domain experts can easily build 3D model
STROBOSCOPE, other		Chen et al.[99]			3D is precise, accurate and efficient
VITASCOPE & DCV		Kamat and Martinez[70]			3D/VR representation is accurate
VM Factory		Choi et al.[58]			Domain experts can create 3D model
Custom software			Fishwick[65]	2D Shorter	3D is appealing but time-consuming
Custom application		Chen and Huang[57]			Non-experts can interact with 3D model
VS-CaSP		Su et al.[68]		3D Shorter	Quicker to build the 3D model
WITNESS, ARENA, custom	Otamendi et al.[32]			2D Shorter	3D modeling is time-consuming
WITNESS/VR, ARENA, QUEST	Akpan and Brooks[11]			2D Shorter	3D model takes a lot longer to build

(continued)

Table 6. Continued

Modeling tools	2D better	3D better	Same	Modeling time	Reasons/ conclusions
No platform indicated	Petti et al.[49]				2D offers fast build and low cost
No platform indicated		Rohrer[15]			3D offers more realistic display
Custom software		Quarles et al.[86]			Transparent reality, accuracy, interactivity

takes less time to validate the 3D model compared to 2D displays. Table 7 offers the explanations for the conclusions.

4.4.4 RQ2(iv): Time taken to complete the analysis of results. Four articles investigated the relationship between the types of visual display (3D vs. 2D) and the time taken to complete the analysis of simulation results. A synthesis of the conclusions from the reviewed articles shows that 50% of the papers posited that using 3D/VR helps to complete the "analysis of results" in a shorter time, while 25% considered 2D displays to complete the task more quickly. One study concluded that there was no difference (Table 5). Table 7 provides further explanations and reasons for the different conclusions.

4.5 RQ3(i–ii): The impacts of 3D/VR vs. 2D display on problem definition

4.5.1 RQ3(i): Does 3D visualization improve problem definition/formulation better than 2D display?. Problem definition occurs at the early stage of a modeling and simulation project. It is during this stage that the experts formulate the problem and define the project's objectives. The general perception is that visual display is not commonly useful at this stage of a simulation process,[2,11] though a few recent studies have undertaken to employ visualization techniques at this stage of the DES process.[37,49,64,96] Practitioners also evaluated the effects of visual display at problem definition through a survey conducted by Akpan and Brooks.[11]

Five papers examined the potential impacts of 3D and 2D displays at this stage. Three out of the five studies concluded that 3D visualization can enable a better, easier, and faster problem definition compared to 2D. Petti et al.[49] observed that 3D visualization enables fast problem definition as the participants easily understood the activities performed and identified the important steps in a manufacturing process. In contrast, one paper[37] identified 2D displays as providing better performance, while another[11] concluded that there is no difference between the two options. The different reasons for the conclusions (Table 7) points to a possibility of some substantial benefits that 3D displays offer in making the problem definition task better, easier, and faster.[49,64]

Further, Waisel et al.,[37] while examining how expert model developers use sentential and 2D-based diagrammatic sketches, concluded that such modeling strategies enhances insight, leading to the creation of better models. Akpan and Brooks[11] showed that 94% of simulation professionals, users, and decision-makers did not identify any impacts of 3D or 2D displays on problem definition, and concluded that there are no additional benefits to using 3D display over 2D for this DES activity. Also, it is important to note that only one of the three articles[11] compared the impacts of 2D and 3D displays concurrently in the same study. The other two studies[37,64] focused on either 2D display or 3D visualization respectively. Since the study by Waisel et al.[37] involved only 2D sketches, further studies replicating the study using 3D drawings and diagrams is recommended to compare the outcomes.

4.5.2 RQ3(ii): Time taken to complete problem definition. Only one study evaluated the effects of the type of display and the time taken to complete the problem definition task. That paper[49] concluded that 3D allows faster problem definition. The conclusion was based on an experimental study in which the participants performing the task in 3D/VR were able to identify the important steps in a manufacturing process. However, it is important to note that this conclusion comes from a single study rather than a synthesized outcome from many papers. Further studies tackling different problems in diverse application domains are recommended before generalizing the outcomes.

4.6 RQ4: Does 3D visualization improve conceptual modeling performance better than 2D display?

The impacts of visual display on conceptual modeling is one of the three studies that received the least publications, the other two being problem definition and implementation of results. Particularly for the conceptual modeling,

Table 7. Comparative effectiveness of 3D/VR vs. 2D visualization on DES tasks.

DES tasks	Reasons/conclusions	Authors
Model experimentation		
3D/VR is better	3D best suited for real-time manipulation.	Dorozhkin et al.[61] Rua and Alvito[10]
	Enhances optimization.	Dangelmaier et al.[59]
	Easy to create new experiments and undertake what-if analyses.	Farooq et al.[64] Li et al.[79] Hajdas[101]
	Interactivity superior to 2D; shows changes in the variables, and clearly highlights collisions, violations, and near misses.	Akpan and Brooks[11] Chan et al.[55] Fishwick[65]
	Users can explore the model to carry out experimentation.	Oerter et al.[92]
	Possible to rotate model, view different angles or positions.	Hurrion[3]
	Other views (2D) misled users, while users of 3D/VR can identify exact positions to undertake brain surgery.	Somasundaram and Kalaiselvi[102]
	3D highlights model behavior.	Kamat[20] Hutabarat et al.[48] Mueller-Wittig et al.[47]
	3D/VR enables faster experimentation.	Petti et al.[49]
2D is better:	3D slower run-speed, easier to detect inaccuracies in 2D model.	Robinson et al.[22]
Model run		
3D/VR is better	Non-simulation experts can run and optimize the construction planning simulation model in 3D, and evaluate the resource utilization.	Huang et al.[26]
	Running the model in 3D was more effective for examining the model behavior, checking errors and completing the tasks faster.	Akpan and Brooks[11] Oerter et al.[92]
	Running the model in 3D offers the users the capabilities to properly visualize and explore the entire model, which reduces cost for the customer.	Oerter et al.[92]
	The 3D visualization helps to overcome the various problems associated with the 2D display such as misinterpretation and errors in the results at runtime.	Dangelmaier et al.[59]
	The immersive VR environment allows the users to interact with the model as in real life during the runtime.	Dorozhkin et al.[61] Farooq et al.[64]
	The 3D visualization system integrated with PROTOCOL platform can receive sensor input from the real world, and provide audio-visual warning feedback for accident avoidance at runtime.	Talmaki et al.[67]
2D is better	Slower run-speed of the 3D display is reducing the collection rate.	Robinson et al.[22] Waly and Thabet[29]
Model verification		
3D/VR is better	VR helps in verifying model logic and behavior	Mujber et al.[82] Mueller-Wittig et al.[47]
	With 3D/VR, domain experts who did not build the model can easily verify it.	Mujber et al.[82] Farooq et al.[64] Chan et al.[55]
	Any discrepancy in the model can be corrected easily in line with real system.	Kamat et al.[71] Dangelmaier et al.[59] Su et al.[68]
	Verification with 3D is effective and efficient; saves time and costs.	Dangelmaier et al.[59] Su et al.[68] Kamat and Martinez[72] Khoury et al.[73] Akpan and Brooks[11] Akpan and Brooks[6]
	3D makes it easier to understand construction operation and aids verification.	Al-Hussein et al.[52] Rohrer[15]
	3D/VR helps to identify bottlenecks, determine buffer sizes, throughputs, etc.	Chan et al.[55]
	Domain experts can easily identify errors that even the simulation experts may not detect.	Kamat et al.[71] Kamat[20] Kamat and Martinez[41]

(continued)

Table 7. Continued

DES tasks	Reasons/conclusions	Authors
	3D animation and the geometric details enhance verification.	Kamat[20] Kamat and Martinez[72]
	3D/VR offers significant value for model verification.	Kamat and Martinez[41] Khoury et al.[73] Petti et al.[49]
	3D/VR provides spatial and geometric details which helps in verification of automotive, construction, and other domains.	Kamat[20] Moon et al.[81]
No difference	3D can simplify verification, but it is complex to create. The 2D model is easy to create and can be equally effective in verification.	Hong et al.[105]
Model validation		
3D/VR is better	3D/VR makes it easier to detect errors in model (logic, wrong component combination, routing errors).	Akpan and Brooks[6] Akpan and Brooks[11] Kamat and Martinez[72] Kamat and Martinez[21] Bailey et al.[62] Mujber et al.[82]
	Easy to match model behavior with real world, which helps to detect any abnormalities in the model.	Al-Hussein et al.[52] Akpan and Brooks[11] Bailey et al.[62] Khoury et al.[73] Rekapalli and Martinez[23] Kamat and Martinez[70] Zhou et al.[110] Chan et al.[55] Lu et al.[95]
	3D enhances better understanding of operations and validation.	Al-Hussein et al.[52] Kamat et al.[71] Kamat[20] Rohrer[15]
	3D/VR is very effective for model validation.	Alberts et al.[51]
	3D enhances validation irrespective of the application domain.	Khoury et al.[73]
	Easier and quicker to spot errors.	Dangelmaier et al.[59] Dorozhkin et al.[61] Kamat and Martinez[72] Kamat and Martinez[70] Chan et al.[55] Petti et al.[49]
	Non-technical users and domain experts can easily validate 3D model where developers fails.	Bailey et al.[62] Choi et al.[58] Kamat and Martinez[21] Kamat and Martinez[70] Kamat[20]
	3D helps in debugging, improving the accuracy of model and system.	Dorozhkin et al.[61] Kamat et al.[71] Kamat[20] Nandan et al.[107] Somasundaram and Kalaiselvi[102]
	3D adds sufficient value in model quality by improving validation.	Kamat and Martinez[41] Zhou et al.[110] Chan et al.[55]
	3D/VR makes it easier to match simulation with real life and data.	Zhou et al.[110]
	3D/VR helps users and managers to have a clearer and more reliable picture about any changes in the system and related impacts.	Chan et al.[55] Rohrer[15]
	3D provides spatial and geometric details which helps in validation.	Kamat[20]
No difference	3D model is complex to create – OK with 2D	Hong et al.[105]
	Validation using the 2D and 3D displays were both good.	Dialami et al.[93]

(continued)

Table 7. Continued

DES tasks	Reasons/conclusions	Authors
Analysis of results		
3D/VR is better	3D is a set of low-cost and fast analysis tools and styles.	Rubio et al.[89] Moghadam et al.[106] Dangelmaier et al.[59] Akpan and Brooks[6] Kumar and Benbasat[78]
	3D is more effective in analyzing the construction methods.	Moghadam et al.[106]
	3D encodes further information that is useful for analysis.	Aigner et al.[77] Akpan and Brooks[6] Rohrer[15]
	The interactive effectiveness of 3D helps users to understand the operation, evaluate, and change the parameters of the simulation at runtime.	Dorozhkin et al.[61]
	3D offers an effective visual analysis of data, highlighting segmentation, clustering, and detection of events; also an analysis of underwater vehicles.	Kamsu-Foguem et al.[9] Son and Kim[91]
	3D/VR makes it easier to create different experiments to undertake analyses.	Rua and Alvito[10] Wainer and Liu[36]
	3D enables analysis of behaviors of the system at realistic scales on PC.	Alberts et al.[51]
	3D offers easy analysis of store layout modifications with easily understood feedback directly to domain experts and other project team's stakeholders.	Bruzzone et al.[54] Dangelmaier et al.[59] Farooq et al.[64]
	3D helps to experiment different construction methods in what-if analysis.	Li et al.[79]
	The 3D graphic and status output modules offer good interface for parameters control as well as data analysis; also enhances accuracy.	Qu et al.[18] Kim et al.[74] Nandan et al.[107]
	3D dynamic construction visualizer offers realistic feedback from simulation.	Kamat and Martinez[21]
	The 3D system allows project teams to monitor the progress of projects, and improves understanding of the processes in constructions and other domains.	Huang et al.[26] Li et al.[104] Li et al.[79]
	The 3D platform enhances workflow patterns analysis, identifying changes and the impact on construction process performance, and variant solutions.	Hajdas[101]
2D is better	The VR platform enhances behavioral analysis of the simulated system and achieving optimal solution.	Rodriguez et al.[87] Zhou et al.[110]
	Although 3D offers better analysis, it does take a longer time to perform, hence the reason for preferring the 2D.	Talmaki et al.[67]
Limitation of 3D/VR	The 2D display enhances analysis of details better than 3D.	Smallman et al.[90]
	Despite the preference for the 3D display and VR, the process of collecting input data from the system is time-consuming.	Huang et al.[26]
Presentation		
3D/VR is better	3D offers expressive presentation of certain types of data, e.g., volume data.	Aigner et al.[77] Lindskog et al.[80] Fabritius et al.[63] Tory et al.[40]
	3D/VR facilitates accurate/effective representation of information to users.	Kamsu-Foguem et al.[9] Kumar and Benbasat[78] Wainer and Liu[36]
	3D vividly mimics the appearance/shape of real grown eggplant cultivation.	Qu et al.[18]
	3D visualization helps in presenting the model to learners and stakeholders.	Fishwick[65] Petti et al.[49] Rohrer[15]
	VR provides immersion as users can move freely inside the simulation.	Rodriguez et al.[87]

(continued)

Table 7. Continued

DES tasks	Reasons/conclusions	Authors
	The 3D model enhances the exhibition to archaeological research.	Rua and Alvito[10]
	Simulating building interiors and exteriors in photo-realistic 3D display improves presentation of new apartment building units compared to using 2D.	Whyte[53]
	The real-time 3D visualization scheme provides realistic graphical views that are appealing to users that are not possible through the conventional display.	Talmaki et al.[67] Kim et al.[74] Van Orden and Broyles[76]
	The 3D realistic display enhances an elaborate presentation to decision-makers, managers, and other stakeholders not familiar with simulation.	Bruzzone et al.[54] Dangelmaier et al.[59] Kamat and Martinez[41] Kumar and Benbasat[78] Wenzel Jessen[56] Akpan and Brooks[11]
	The 3D visualized models and animations are at present still the most intuitive presentation and appealing to customers.	Chen and Huang[57] Van Orden and Broyles[76] Suh et al.[69] Nah et al.[84] John et al.[45]
	Surgeons had to transpose the 2D displays into 3D for better presentation, understanding and precise performance.	Ahlberg et al.[88] Zhang et al.[108]
	3D presents information from different angles to help users comprehend the situation and determine escape routes.	Shen et al.[100] Vasudevan and Son[94] Patel et al.[109]
Problem definition/formulation		
3D/VR is better	Easier and helps to understand the problem.	Farooq et al.[64] Korošec et al.[96]
	3D helped the participants in an experiment to identify and understand important issues and steps in a manufacturing process.	Petti et al.[49]
2D is better	Use of 2D sketch generates insight.	Waisel et al.[37]
No difference	No effect or no need of 2D or 3D at this stage	Akpan and Brooks[11]
Conceptual modeling		
2D is better	2D easier to use, especially in complex problems	Waisel et al.[37] Chen and Huang[57]
No difference	Display type is not useful at the conceptual stage	Murphy and Perera[83]
Implementation		
No difference	Implementation time is the same irrespective of display	Akpan and Brooks[11]

one can speculate about the reasons for the little interest in this area based on the perception that visual display may not bring any significant benefits to conceptual modeling activities.

Three of the reviewed articles investigated the impacts of the effects of the visual displays on conceptual modeling. The results show that two out of the three articles concluded that using the 2D display is more beneficial,[37,57] while one[83] opined that there was no difference, irrespective of using either the 2D display or 3D visualization. There is a need to be cautious in interpreting the outcomes of the studies, given the limited number of studies involved. Table 7 provides the reasons and explanations for the various conclusions.

4.7 RQ5: The impacts of other latent variables on DES tasks and activities

The purpose of this research question is primarily to observe any possible influence of other factors that can influence the performance of DES tasks and activities other than the types of displays (3D and 2D display). The potential latent variables include the application domains, research methods, problems tackled, and the time when the study was conducted between 2000 and 2016. The time dimension mirrors the different levels of technological advancement.

The data extracted from the literature survey identified 84 different problems tackled (Table 2) in 24 distinct application domains (Table 3). Some of the articles tackled problems in more than one area (e.g., Apkan and Brooks[6] tackled problems in automotive assembly and banking customer service). Table 3 also lists the five research methods adopted by the reviewed articles. For RQ1 and RQ3–RQ5, the results show that 3D visualization consistently offered better performance on the DES tasks and activities across the different application domains, problems tackled, and the research methods, irrespective of the year in which the study was conducted. Similarly, the 2D display recorded significantly higher performance on time taken to develop DES models (RQ2) irrespective of the listed possible latent variables. For example, in the analysis of the impacts of 3D/VR vs. 2D display on model development tasks (RQ1(i)), the 22 reviewed articles tackled problems in over 10 different application domains and adopted various research methods (Tables 3 and 6). According to the results, 13 studies concluded that 3D display offered better performance for model development. These studies addressed problems that spanned several application domains and research methods. This indicates that the latent variables did not exert any influence on the performance of DES tasks and activities other than the types of visual displays (3D vs. 2D). Similarly, there were no impacts from the year in which the study was conducted, hence the time dimension did not impact the outcomes. For example, Hurrion,[3] Otamendi et al.,[32] and Sun et al.[34] published in 2000, 2008, and 2012, respectively, preferred 3D/VR, and concluded that 3D can advance the potential of DES as a decision-support system, whereas Robinson and Lee,[22] published in 2012, preferred 2D display even after using the more recent 3D display. Thus, there is no impact from the date factor (and level of technology at the time the study) on the outcomes other than the visual display.

5. Discussion

The purpose of this study was to evaluate the comparative effectiveness of 2D display and 3D visualization/VR on DES activities, tasks, and user performance through a systematic literature review. The study synthesized the conclusions from 84 articles selected through a rigorous review process and exploratory meta-analysis, producing several useful highlights. The most bullish results showed that 3D/VR indeed offers significant benefits over 2D display for the presentation of models or outcomes of simulation projects to stakeholders, validation and verification, and experimentation and analysis. All 32 articles that investigated the effects of the presentation showed that 3D/VR is more useful than 2D display.

Another notable highlight of this study is synthesizing the benefits of 3D display on model development, which is a significant aspect of the DES task. The common position was that 2D display is the most effective DES and modeling technique (e.g., Wenzel and Jessen[56]). But the synthesis of the literature shows that it is indeed 3D display that provides a better model development option for DES practice in this era of advances in information visualization, not 2D display as some perceive.[15,53,56,91] Although developing a model in 2D is easier and quicker, 3D/VR offers the best overall benefits (Table 6). However, the majority of the 22 studies that examined the impact of 2D vs. 3D, (including those that favored 3D/VR) raised a concern that developing a DES model remains more difficult and takes longer. As such, we carried out a further evaluation of the time it takes to complete model development in 3D vs. 2D. The results showed an even split, with nearly half concluding that it takes longer to build a 3D model compared to a 2D model, which can be due to the diversity of the modeling techniques and tools used. For example, simulation and modeling software such as WITNESSVR offers the modeling platform in 2D with a fast-build option that translates the 2D model into a 3D visualization.[42] On the contrary, applications such as FlexSim offer model development directly in 3D from scratch.[24,115] One can speculate that the two scenarios provided by the two DES applications can lead to different conclusions, indicating an area that simulation software vendors and practitioners need to address.

Model validation and verification are other important activities in which 3D display provides clear benefits, in two main ways. First, the simulation experts and other users can easily and quickly spot errors in 3D models due to its advanced visualization features, highlighting the model behavior better than does 2D animation. Second, the stakeholders involved as part of the simulation project team are very knowledgeable in the application domains and can identify severe errors in the model. Of particular interest are situations in which the problem involves critical issues caused by the expert's use of incorrect data, followed by certification of the design as valid and verified. It is only by using a 3D model, which the domain experts can easily understand, that these experts can help to identify such mistakes as the behavior of the model appears unusual from a real-life perspective. Such problems can take simulation experts a long time to detect, if at all.[3,20, 21,72, 97,116] These results indicate that 3D visualization can bring a significant quality contribution to the DES process, and help to resolve one of the major bottlenecks that had cast doubt on DES as a decision-support system for decades.

Other areas where the benefits of 3D display/VR are significant compared to 2D include experimentation and analysis, presentation of results, and communication with clients. All but one study preferred the 3D/VR for experimentation (Tables 4 and 6). It is important to highlight the fact that the findings by the different authors largely depend on the purpose and focus of the experiment activities. The only study that preferred 2D display for experiments[22] did so because the 3D model was slower to run than the 2D model, whereas the papers that preferred 3D display for experimentation (e.g., Akpan and Brooks[11]) considered the effectiveness of the display on task performance, such as spotting errors during validation. Similarly, the outcomes for model analysis also provided strong positive results, with all 25 studies preferring the 3D/VR to provide better performance (Table 6). The results imply that the third dimension can be very helpful when evaluating model behavior and undertaking the what-if analysis.[11,77]

The central reason offered for these benefits is that 3D visualization and VR significantly enhance users' understanding of the DES model and the behavior of the systems. All 42 papers that investigated this benefit favored 3D/VR over 2D display. For example, the ability of 3D visualization to improve understanding by highlighting poor behavior of the model during runtime and experimentation (not readily evident in 2D) enhances the understating of the model, and in turn helps in the verification and validation process.[96]

6. Conclusions and future projections

This study provides strong evidence that the use of a 3D display can have considerable benefits in many aspects of the DES processes, tasks, and activities. The results show that 3D/VR offers an overall better performance on all the main DES activities and tasks, including model development, verification, and validation, and in experimentation and analysis in addition to the generally acceptable benefits of enhancing model presentation and communication. Another new finding from the study is that 3D/VR helps involved interested parties (e.g., managers and domain experts[20,21]) in the modeling process. By facilitating stakeholders' involvement in the DES process, the study shows the benefit of 3D/VR in enhancing management buy-in and the overall success of a simulation project.[15]

However, the main drawback of creating 3D models is the possibility that it can take longer to complete the model development task; the majority of the published articles identified this concern, including the studies that preferred 3D/VR display to traditional 2D display.[92] However, no studies among the reviewed articles pointed out the actual causes of the longer time required for 3D modeling. The possible causes can include the modeling platforms/tools, considering the diversity of the techniques adopted by different software and tools. Notwithstanding this limitation, the synthesized outcomes from the study indicate that 3D visualization and VR in DES is fast becoming an acceptable modeling methodology, while further work is required in research and modeling software implementation to resolve the identified drawbacks.

Further, the results of the meta-analysis presented in this study show that the application of 3D visualization and VR in discrete-event simulation, and the increased adoption of 3D visualization, and has received more attention in the past two decades, which is mainly due to its important benefits in terms of superior display capability.

Future work intends to survey the practitioners in academia and industry to establish the reasons for the concurrent use of 2D displays and 3D visualization. The research study will also investigate practitioners' perceptions about the possible use of fully immersive VR in DES. This will be followed with experimental studies on modeling and simulation with different 3D software and tools.

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