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Title: **Modelling and Simulation considerations for an End-to-End Supply Chain System**

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Abstract: The efforts of this review paper are twofold: to provide an insightful examination of various contributions to knowledge surrounding simulation methods within an end-to-end supply chain and to guide research agenda by indicating generic elements required to model such systems using simulation. The authors examined 255 publications from 21 peer-reviewed journals in the field of an end-to-end supply chain and simulation using a systematic literature review approach. Each publication was thoroughly reviewed to capture best practices and key characteristics relative to simulation modelling techniques used in the context of complex end-to-end supply chain systems. This allowed for identification of generic elements required to model such systems, which were grouped into Structural, Computational and System Organization pillars. This research contributes to the body of knowledge by defining generic aspects of simulation modelling techniques used to study properties and attributes of complex end-to-end supply chains. The paper advances the theoretical understanding of the simulation methods used and applicability of simulation methodology in modelling end-to-end supply chain systems. The research presents the key findings from the use of simulation in modelling end-to-end supply chains and the main ways in which this modelling technique has informed research and practise.

Title Page including Author details

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"***Modelling and Simulation considerations for an End-to-End Supply Chain System***"

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1. Introduction

A supply chain (SC) system is a network of businesses, which are engaged in various activities and processes required to deliver goods and/or services on time and in full to the end customer (Handfield & Nichols, 2002). In an end-to-end supply chain (E2E-SC) system, the number of business entities linked to each other can be very large and often difficult to know their exact number. It has been acknowledged that despite working on a common goal, businesses have disjoined or contradicting objectives and various constraints (Handfield & Nichols, 2002). This research argues that E2E-SCs exhibit systemic properties and complexity attributes, which have a considerable impact on the management of these systems. Therefore, this study is set to establish the challenges and limitations of using simulation methodology within the constraints of E2E-SC systems.

Although, current studies considered the state of the art of simulation in supply chain context (Oliveira, Lima, & Montevechi, 2016), this paper contributes by providing a systematic review of simulation modelling in the context of E2E-SC, where challenges relative to development of complex simulation models are highlighted.

Modelling techniques can be used to support decision makers in managing E2E-SC systems and to gain a better understanding of their properties and attributes. This can be achieved by developing and analysing an array of modelling examples integrating concepts from several fields without the need to modify the actual system or network. The current range of SC models can be further enhanced by a set of generic rules, elements and processes that can be considered for modelling and simulation of these complex E2E-SC structures. The ambition of this paper is to outline these considerations and provide guidance to SC modellers, managers, data analysts and experts on how simulation projects considering E2E-SC structures can be approached, designed and used to enhance their decision-making process and results implementation. Simulation is considered to be one of the most suitable methods for modelling complex systems (Terzi & Cavalieri, 2004). Some examples within the extant literature highlight the benefits of using various simulation techniques, which due to their inherent capabilities allow to:

- consider more elements or characteristics of a complex system within models (Chatfield, Hayya, & Harrison, 2007);
- analyse dynamic behaviour of a complex SC system (Labarthe, Espinasse, Ferrarini, & Montreuil, 2007);
- combine aspects relative to SC systems as well as Supply Chain Management (SCM) within the models (Caridi, Cigolini, & De Marco, 2005);
- integrate multidisciplinary knowledge from various fields such as: computer science, engineering (Petersen, Aase, & Heiser, 2011), biology (Surana, Kumara, Greaves, & Raghavan, 2005) and behavioural sciences (Govindu & Chinnam, 2010).

Albeit the efforts in developing advanced and powerful modelling techniques are quite immense and accredited to many, further insights can be gained by advancing theoretical understanding of the simulation methods used and applicability of simulation methodology in modelling end-to-end supply chain systems. This study contributes to the body of knowledge by providing an overview of the literature on modelling E2E-SC systems using simulation. This is achieved by reviewing simulation modelling techniques used to study properties and attributes of complex E2E-SCs. These considerations can serve as fundamental building blocks when developing sophisticated and powerful simulation models of any E2E-SC. This paper presents key findings on the use of simulation in E2E-SC systems and discusses how simulation modelling has informed research and practise within an E2E-SC.

The paper is structured as follows. After the introductory section, an overview of the system thinking, and the complexity theory is presented. The importance of both theories to simulation modelling of an E2E-SC is also explained in Section 2. In Section 3, a systematic literature review (SLR) strategy used in this paper is presented and a review protocol is defined. The findings of the SLR are presented in

Section 4, which opens with a classification of the identified themes and generic processes relative to E2E-SC systems. The SLR findings continue with an overview of the simulation modelling techniques and specification of their generic elements. The research is based on the ontology that integrates the systems thinking philosophy, complexity theory and simulation methodology. A review of the main aspects relative to these ontologies within selected studies, culminated in defining considerations for modelling E2E-SC systems. A summary of the research findings and areas for further work concludes the paper.

2. System thinking and complexity

E2E-SCs are complex systems and this part of the paper is set to elaborate on the importance of system thinking philosophy and complexity theory in the E2E-SC system simulation modelling. The paper is sought to review literature on simulation modelling of complex E2E-SC system structures and to this extent is deemed relevant to highlight the importance of the complexity theory and system thinking.

The elements or parts of an E2E-SC system, for instance a set of suppliers, manufacturers, distributors and customers forming an E2E-SC, interact between each other not in absolute terms but in a relative sense. Normally, each element (i.e. suppliers) can be treated as a fundamental building block of an E2E-SC or if viewed from another perspective, the same element can be decomposed into smaller, autonomous parts (i.e. considering critical processes performed at supplier level). Interactions and relations between suppliers, manufacturers, distributors and customers instigate modifications in the E2E-SC system behaviour compared to when those elements are not a part of the system. Viewing this more generally, Morin (1992) appreciated that the paradigmatic view of the system can be multidimensional. This is attributed to the existing varying levels of confluence between the two important ontological derivatives: (1) a system is a physical construct based on the fundamentals of realism, where the perception of the observer depicts the system description, and (2) a system is a perception of an ideal, heuristic and pragmatic model in nature designed with the aim to evaluate, improve, control or model a phenomenon. Following Morin's (1992) views, this research deliberates on the difference between an E2E-SC system structure and its system organization, where the former is derived from simplicity and reductionism of the system to the structural whole (all elements/parts i.e. echelons), also referred to as holism. On the other hand, system organization (SO) considers the knowledge on elements/parts and whole of the system beyond its structure, which takes an account of the recursive influence of the emergent phenomena created by such structure. This implies that E2E-SC system elements/parts can evolve over time leading to changes within the SO and interactions between parts and systems. Understanding the complexity of these interactions, whether related to the system structure or SO is fundamental to the research as well as for rationalization and knowledge development about systems in addition to characteristics of their organizational interactions. This is important for E2E-SC systems, which are complex systems and simulation methodology is often used to study their systemic properties.

Various studies examined the following aspects of the system theory and complexity within SC systems:

- Simplified yet holistic view of a SC systems structure, for instance, as observed in Ertem et al. (Ertem, Buyurgan, & Rossetti, 2010) where consideration was given to a procurement process of a particular product within E2E-SC.
- The emerging nature of system organization, where SCs have been studied using complex adaptive system tools and techniques to better understand the complexity of SCs and how it occurs (Surana et al., 2005) or emergent architecture of system levels (Shang, Li, & Tadikamalla, 2004).
- The hierarchical nature of system organization where the system is regarded as a set of sub-systems that form complex interactions, and the system as a whole outperforms the sum of its parts (Pundoor & Herrmann, 2007) or hierarchical linkages of the SC elements modelled using Petri nets as a way to detect conflicts between entities/parts (Blackhurst, Wu, & Craighead, 2008).

- Entropy methodology that compares the different types/levels of information sharing approaches in the SC, where the organization produces entropy due to the uncertainty of information that leads to system degradation and on the other hand, with the help of auto-corrective information sharing mechanism, regeneration of system (negentropy) occurs (Martínez-Olvera, 2008).

These studies regard SCs as complex systems, which is also a viewpoint sustained by this research. These compel the present work to similarly ascertain the complexity factors. Thought is given to system principles from the paradigm level, observing E2E-SC as a simplified structure or as an emerging organization, through SC phenomenal level, up to the level of principal explanations in order to understand the source of complexities (Morin, 1992) and considering the impact that complexity has on the simulation modelling efforts.

The challenge in modelling E2E-SCs as systems emanates not only from SC dynamics, but also from the complexities that originate at structural and operational levels. These exist within the organizational aspects of systems (Temponi, Bryant, & Fernandez, 2009) and require a clear and comprehensive framework that could serve as a blueprint to provide focus while developing E2E-SC system oriented simulation models. The efforts of this paper are directed towards identification of simulation modelling considerations within complex E2E-SC systems, which cogitate on principles of system thinking and complexity theory as found in Morin (1992) and on the simulation modelling aspects gathered throughout the process of the SLR. This is to provide a guide for an E2E-SC system modelling, emphasizing on the system structure, organization and the impact that properties of such systems can have on simulation model development and systems modelling. Consequently, this research gathered generic elements required for modelling an E2E-SC system using simulation and grouped them under structural, systemic organizational and computational pillars. These will be discussed in the following sections alongside other findings from the systematic literature review.

3. Systematic Literature Review

In order to dichotomize the existing research on modelling E2E-SC, the authors applied the SLR strategy that provides rigor by building upon the existing work within the area. This section provides a deep dive into a systematic review of the literature published in highly ranked journals on the use of simulation modelling in E2E-SC systems and follows a three steps approach namely: plan, review and report, in line with defined research boundaries (Rousseau, Manning, & Denyer, 2008). This approach offers a full transparency regarding studies selection and review steps. Moreover, it is a thorough, fair and rigorous search strategy hence deemed the most appropriate approach to answer the research questions (Kitchenham et al., 2009; Tranfield, Denyer, & Smart, 2003).

Simulation is a well-recognized methodology to study SCs, particularly for studying complex issues within these systems. Although widely used by SC managers/decision makers and researchers, the existing modelling techniques are not fully embedded to model E2E-SC systems. Various researchers dedicated their efforts to review simulation and supply chain related literature in search for trends, new developments and future prospects (Barbati, Bruno, & Genovese, 2012; Bellamy & Basole, 2013; Jahangirian, Eldabi, Naseer, Stergioulas, & Young, 2010; Oliveira et al., 2016; Santa-Eulalia, Halladjian, D'Amours, & Frayret, 2011).

Nevertheless, we could not name any earlier reviews that systematically reviewed literature in attempt to identify generic considerations for simulation modelling of E2E-SC systems.

The challenge with applying SLR methodologies for studies on simulation modelling of E2E-SC systems is compelled by the broad-range of heterogeneous studies within the area. In conducting the SLR (Fig.1.), this research adopts a three phased approach: planning, conducting the review and reporting (Hohenstein, Feise, Hartmann, & Giunipero, 2015), (Pashaei & Olhager, 2015), (Ashby et al., 2012), (Colicchia & Strozzi, 2012), (Pilbeam, Alvarez, & Wilson, 2012). In the planning stage of the SLR, the research needs were identified as well as the research aim and objectives were formulated. Moreover, both authors have formed a review panel to help direct the SLR process through regular meetings, discussions and aligning on the inclusion and exclusion of studies. The first author carried out the initial search and the second author independently checked and confirmed the search at every stage (Tranfield et al., 2003). The planning stage was finalised by creation of the SLR protocol, which captured all aspects of the SLR process as shown in phase 2 of the SLR in Figure 1 below.

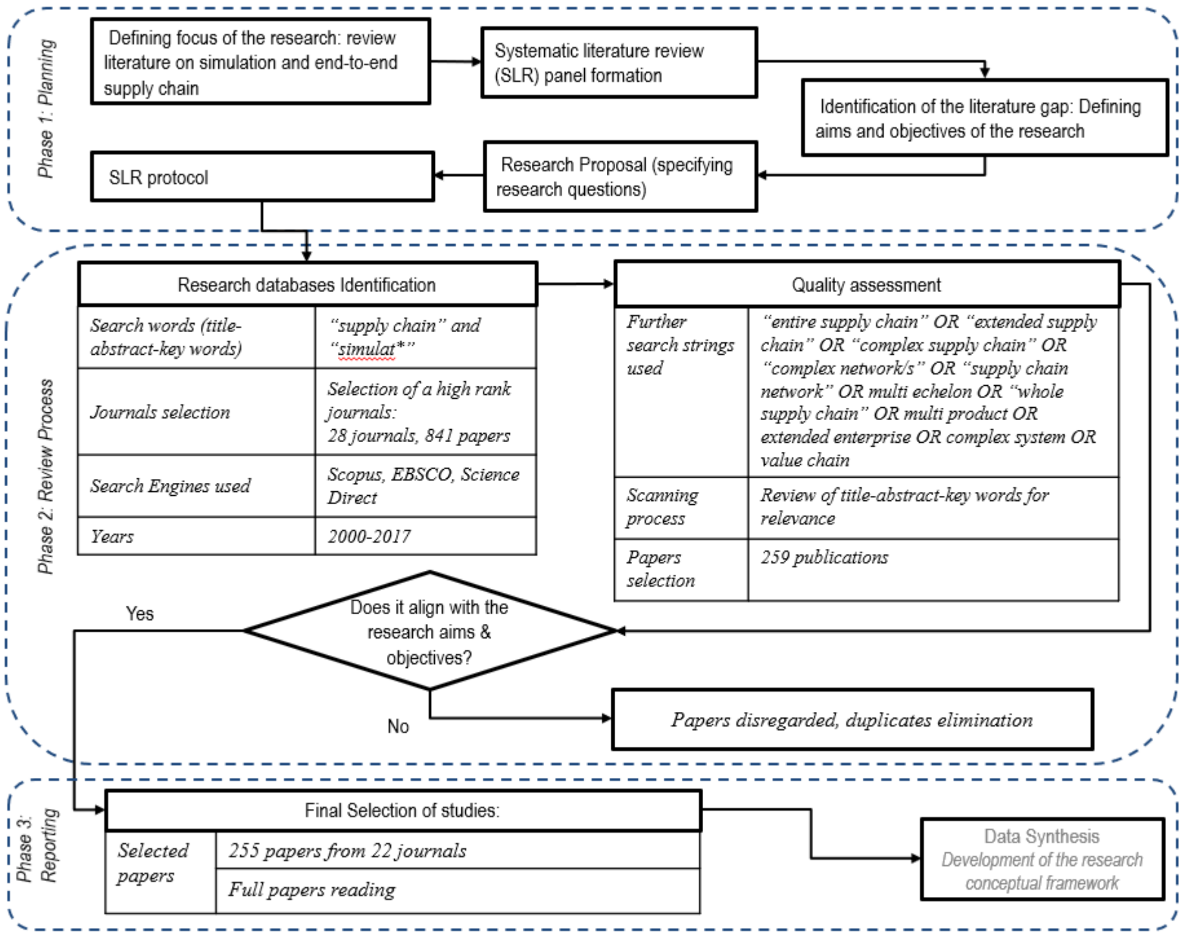

Fig. 1. Systematic Literature Review process.

Source: Chilmon (2018)

The overall perspective deliberated within this study is to focus on commonly used elements, processes and the system characteristics when modelling E2E-SCs using simulation. The researchers developed the following primary research question to guide the SLR process:

RQ. How can simulation method be used to support modelling of an E2E-SC system?

The review process step of the SLR focused on searching for the relevant literature by using a well-established key words/search strings: “supply chain” AND “Simulat*” (Shafer & Smunt, 2004). A Scopus Science Direct and Business Source Complete (Hohenstein et al., 2015; Pashaei & Olhager, 2015) search engines were used for this purpose, which returned a large number of studies within the scope of the research hence deemed a sufficient source to use. Thereafter, a multiple screening approach was undertaken (Pilbeam et al., 2012). One screening filter was to apply a time frame between 2000 and 2017. Another screening activity was to devise more focus to the search criteria by selecting journals that deemed applicable to this research considering two distinct aspects of an E2E-SC grounded upon the concepts of supply chain and operations management and referring:

- To the cumulative efforts of multiple organizations directed towards product or service delivery to the end user/customer and
- To the entire chain of processes/ activities undertaken in order to deliver the product/ service to the final user/customer (Handfield & Nichols, 2002).

The authors achieved this by focusing on a selected number of high rank journals within the field of supply chain and simulation, building further on the grounding work of Shafer and Smunt (Shafer & Smunt, 2004), whose efforts focused on simulation studies within the Operations Management (OM) field. This research spans beyond the boundaries of OM in search for generic elements to be included in an E2E-SC simulation model.

Table 1 List of surveyed journals and papers selected for evaluation.

No.	Journal Title	Abbr.	Research Domain	Search string: "supply chain "AND "simulat*"	Selected Studies on E2E-SC ^^
1	International Journal of Production Research (3)	IJPR	OM; OPS&TECH	197	65
2	International Journal of Production Economics (3)	IJPE	OM; OPS&TECH	160	50
3	European Journal of Operational Research (4)	EJOR	OR&MS	82	28
4	Computers and Industrial Engineering (2)	CAIE	IE/ENG; OPS&TECH	74	25
5	*International Journal of Simulation and Process Modelling (N/A)*	IJSPM	SPM	45	8
6	*International Journal of Physical Distribution and Logistics Management (2)*	IJPDLM	OPS&TECH	23	6
7	Journal of the Operational Research Society (3)	JORS	OR&MS	23	8
8	*International Journal of Simulation Modelling (N/A)*	IJSIMM	CS	25	6
9	Computers and Operations Research (3)	COR	OR&MS	21	8
10	*Simulation Modelling Practice and Theory (2)*	SMPT	SSM; OR&MS	23	12
11	Production and Operations Management (4)	POM	OM; OPS&TECH	17	5
12	Omega: The International Journal of Management Science (3)	OME	OR&MS	18	7
13	*Supply Chain Management: An International (3)*	SCM: IJ	OR&MS; OPS&TECH	21	2
14	Decision Sciences (3)	DS	OR&MS	12	1
15	IIE Transactions (3)	IIE	IE/ENG; OR&MS	12	0
16	Interfaces (2)	INFCS	OR&MS	13	5
17	*Annals of Operations Research (3)*	AOR	OR&MS	15	3
18	Journal of Operations Management (4*)	JOM	OM; OPS&TECH	10	5
19	*Journal of Simulation (1)*	JOS	OR&MS	12	1
20	International Journal of Operations and Production Management (4)	IJOPM	OM; OPS&TECH	8	3
21	Operations Research (4*)	OR	OR&MS	9	2
22	IEEE Transactions on Engineering Management (3)	IEEE-TEM	IE/ENG; OPS&TECH	7	2
23	*International Journal of Modelling and Simulation (N/A)*	IJMS	CS/ENG/M	6	3
24	Management Science (4*)	MS	OR&MS	3	0
25	Naval Research Logistics (3)	NRL	OR&MS	3	0
26	Journal of Supply Chain Management (3)	JSCM	OPS&TECH	2	0
27	Harvard Business review (3)	HBR	ETHICS-CSR-MAN	0	0
28	Production and Inventory Management Journal (N/A)	PIM	IE/ENG	0	0
^^The final number of papers identified through screening activities. In *italics* journals added by this research.				841	255^^

Source: Chilmon (2018)

With the aim to address the research questions, a further seven journals were added to Shafer and Smunt's list to integrate elements from the field of E2E-SC and simulation modelling. A similar approach was observed in Ashby et al. (2012), where additional journals were considered as relevant due to the interdisciplinary nature of the subject of inquiry. The list of selected journals is presented in the Table 1 (added journals are in italicized text).

Shafer and Smunt (2004) investigation into empirical simulation studies in Operations Management is believed to be having an angle of relevance to the scope of this research and was considered for identification of thematic categories and trends in the E2E-SC literature past the year of 2000. A "supply chain" search string was used as well as wildcard characters to search for variations of the word simulation (search string: "simulat*") in the selected 28 journals, covering years between 2000 and 2017. The selection of articles was based on the appearance of the above search strings within the title, abstract, or key words of a paper. The search was performed in 3 databases: Scopus, EBSCO and Science Direct. This resulted in a total of 841 peer-reviewed journal publications, which were considered as a satisfactorily large number of studies for investigating the use of simulation modelling in E2E-SC.

Continuing on the quality assessment criteria and to provide more focus, a further review of the title, abstract and key words was conducted to ensure that all papers were adhering to the further search criteria, which were: "*entire supply chain" OR "extended supply chain" OR "complex supply chain" OR complex network/s OR "supply chain network" OR multi echelon OR "whole supply chain" OR "multi product" OR "multi-product" OR "extended enterprise" OR "complex system" OR "value chain"*. This resulted in elimination of 582 publication that were deemed outside of the research scope and a remainder was 259 papers. There were also 4 duplicates that were identified with the help of the End Note software, leaving the final number of 255 papers for review. The full list of the 255 journal papers chosen for data synthesis and evaluation is provided in Appendix 1. All selected articles were extracted to Microsoft Excel with the support of the Reuters Bibliographic Software End Note and then all selected journal papers were read, interrogated and classified into thematic and methodological categories. The use of Excel facilitated creation of supportive tables with thematic categories and the analysis of the collected data.

4. Review findings

This section provides an overview of the SLR findings and presents the classified themes and categories that embrace the system thinking and complexity theory, with the view of underlining the relevance and application of complexity elements into generic modelling aspects when using simulation.

4.1. Journals

This section provides an overview of the distribution of the selected papers by journal, thematic categories identified and most often used simulation modelling techniques. The review revealed that the majority (66%) of selected studies were published in four journals: International Journal of Production Research (IJPR), International Journal of Production Economics (IJPE), European Journal of Operational Research (EJOR) as well as Computers and Industrial Engineering (CIE) as highlighted in Figure 2. This indicates the most often researched areas are related to production and manufacturing, as per journals' aims and scope (Taylor and Francis 2013, Elsevier 2014). The selected journal papers covered the following research domains spanning from OM, OR&MS through Industrial Engineering/Engineering (IE/E), Computer Science (CS), Mathematics (M) to Simulation Process Modelling (SPM) and System Simulation and Modelling (SSM). OM prevailed in research on modelling E2E-SC systems using simulation. Shafer and Smunt's (Shafer & Smunt, 2004) categorisation of studies, which focused on empirical simulation in OM was used as a starting point.

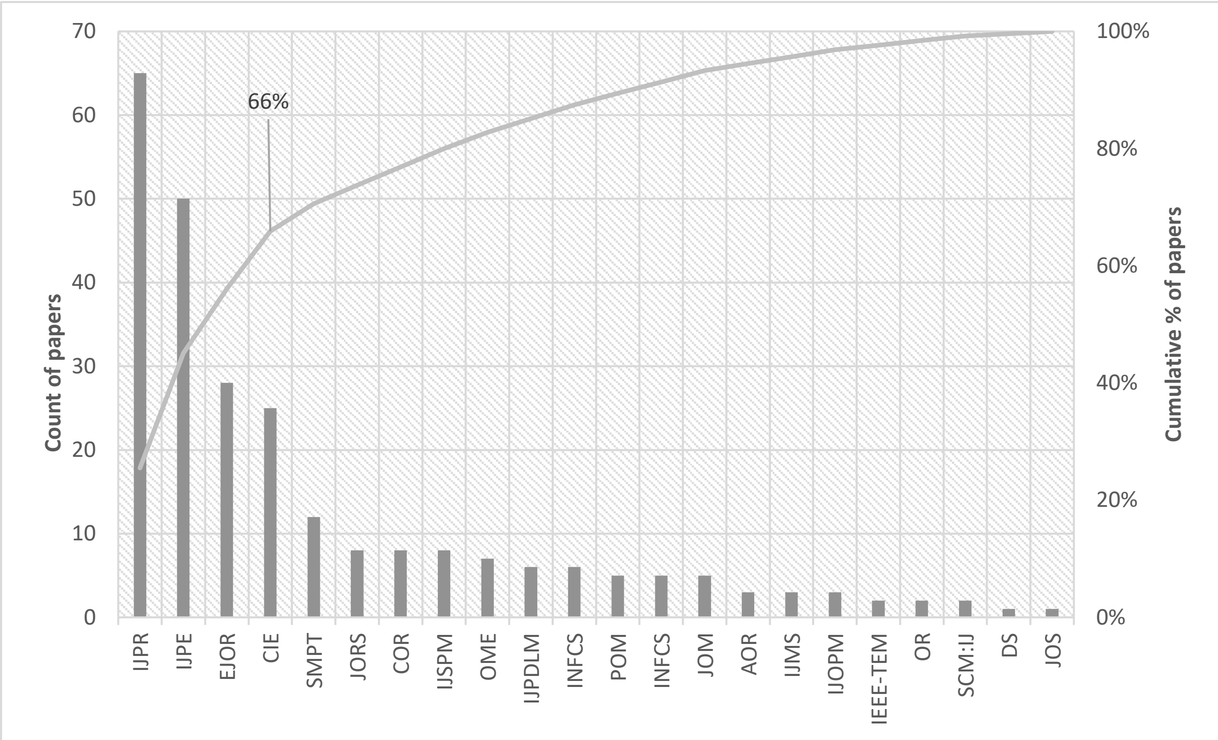

Fig. 2. Distribution of selected studies by journal

Source: Chilmon (2018)

The summary provided by Shafer and Smunt's (Shafer & Smunt, 2004) identified scheduling as the matter of inquiry that was the most recurrent. This was followed by capacity planning and the cellular manufacturing categories. Although, this paper considered thematic categories highlighted by Shafer and Smunt (Shafer & Smunt, 2004), these were viewed from an E2E-SC system perspective. This study identified a set of new categories, which are going to be discussed in the following section.

4.2. Thematic categories

The review of the 255 studies determined that most frequent subjects of inquiry for simulation modelling in E2E-SC systems are SCM and inventory management (categories also identified by Shafer and Smunt (2004)). The current research also established 22 supplementary themes that have not been featured within the classification presented by Shafer and Smunt (Shafer & Smunt, 2004) (presented in italics in Table 2).

Table 2 Classification of papers based on common themes and simulation modelling techniques

	Simulation Method Used										
Model Theme	**Antcl (smltS)**	**DES**	**SD**	**ABS**	**Hbrd**	**MC/QS**	**Literature review**	**OOS**	**MAS**	**simulation game**	**PDS**
SCM	36	10	7	8	7	4	3	1	1	1	1
Inventory management	36	12	1	2	2	3	1	1	1		
SC dynamics (Bullwhip)	21	4	14	4	4	5	3	1	1	1	
SC network	20	9	1	1	2	3		1			
Information sharing/ uncertainty	11	8	1	5		3					
SC performance	9	7	3	2	3	1	2				
Production planning and inventory control	15	3	1		2		2		1		
Collaboration (co-ordination)	7	3		8	1	1	1				
SC Design/ redesign	8	7	1	1	2	2					
Manufacturing / remanufacturing	7	3	3	1	2	1	1				1
Modelling	6	4		2	2		3				
Production- Distribution	10	1	1	1	1					1	
Strategy	9		2	2	1	1					
Production Planning & Scheduling	4	2	1		3	3	1				
Transport & Logistics	9	3			1		1				
Reverse SC (Logistics)	4	3	2			1					
Closed Loop SC	4	1	4		1						
SC risk	4	3		1	1		1				
Process management	4	2	1	1	1						
Order Fulfilment	4	1	1		2						
Capacity planning / management	2	1	3			1					
SC Planning & Control	4			1		1	1				
Purchasing	2			3				1			
DSF (Decision Support framework)	2	2	1								1
NPDiv (new product development)	2	1			1	1	1				
IT	4	1	1								
Forecasting	1	2	2								
Outsourcing	5										
SC resilience	2	2				1					
SC integration/ synchronisation	3	1									
SC Config	3	1									
SC Process (SCP) design	3										
Mass customisation	1	1		1							
System Re-engineering	1	2									
Physical Internet (PI)	3										
Resource allocation/sharing	2										
Batching / Batch processing		1	1								
NPDiff (new product diffusion)			1	1							
Manpower Planning			1								
Exogenous shock		1									
Behavioural operations										1	
Machine learning	1										
Extended Producer Responsibility (EPR)	1										

The newly identified themes presented in italics in Table 2 highlight that the highest number of studies focused on SC dynamics (Bullwhip Effect), with high significance also devised to SC network, information sharing/uncertainty, SC performance, SC collaboration (co-ordination), SC design, modelling moving onto production distribution and transport and logistics. This extends beyond Shafer and Smunt's (2004) selection of themes into categories that not only cover features of entire E2E-SC systems, but also highlight the heterogeneity of the SCM doctrine and how it impacts on modelling E2E-SC. In fact, many of the additional themes have proved to have a noteworthy impact on SCs behaviour, dynamics or structure and were considered in order to enrich the knowledge on E2E-SCs and its properties i.e. the study of Cannella et al. (2008), which investigated the impact of SC dynamics on inventory management and the entire system performance.

It can be observed that in the past years, the research efforts in modelling E2E-SCs have veered towards SCM adopting varied frameworks or classifications. The SCM is one the most frequently used categories predominantly featured in research studies adopting analytical method supported by simulation study modelling technique. These have not only emerged from quantitative aspects and modelling techniques, but persist to be derivatives of various epistemological dimensions (Soni & Kodali, 2013). These epistemological dimensions are reflected in the thematic categories identified in Table 2 where the knowledge is developed by studying various structural elements of an E2E-SC such as policies, flows, processes, products, strategies. Furthermore, the complex nature of E2E-SC systems goes beyond structure into the organisational and behavioural aspects with more sophisticated modelling techniques being used. This has culminated in the shift of the OM philosophy towards a more radical approach and appreciation of a wider range of disciplines thus embracing their contribution to the generic SC field and knowledge development. The next section will focus on discussing the simulation modelling techniques used to model the heterogeneity of the research on E2E-SC systems.

4.3. Simulation methods

Simulation modelling techniques have been explicitly used within research on topics that consider the interface between various cross-disciplinary areas within complex systems. The following aspects should be considered before choosing simulation as an appropriate modelling technique (Shannon, 1975):

- No mathematical formulation could solve the problem in hand, or a mathematical problem has no analytical resolution methods,
- Simulation is the most applicable and less costly tool,
- The requirement is to observe the SC performance over time.

Modelling complex E2E-SCs is not a trivial exercise and all the above-mentioned points would almost certainly apply to a higher or lesser extent within studies on such systems, hence the use of a simulation method is quite often observed. For that reason, this method is of an interest within this paper, with the aim to comprehend how and why simulation is used in studies on complex systems as well as how such methodology would apply to modelling E2E-SCs.

The literature shows multiple attempts by Min and Zhou (2002) and Lee and Kim (2002) to classify SC models into either static, dynamic, analytical, deterministic, simulation or hybrid models. The existing classifications appear to have focused on characteristics or particulars of the system to be modelled and/or a specific SC research agenda. Studies that seem to have addressed matters such as SC coordination and system dynamics (Chan & Chan, 2010) often build upon the existing models classifications to further the knowledge on certain SC system aspects or areas. In addition, others focused on definite modelling techniques and looked into the broader application of such modelling methods (Hwarng et al. 2005; Chatfield et al., 2007). This research evaluates whether these classifications could apply to modelling E2E-SCs, attempting to gather the elements within simulation methodology that should be regarded as a common 'denominator' in modelling studies' classifications.

The literature reviewed shows the following simulation modelling techniques used to study E2E-SC systems:

- Agent based simulation (ABS) - an approach to modelling systems as autonomous and intelligent entities often incorporating existing decision modelling techniques (i.e., optimization or heuristics) and knowledge from diverse disciplines (game theory, biology, computational intelligence) (Govindu & Chinnam, 2010);
- Discrete-event simulation (DES) - an approach that models the system as activities and queues that change at discrete points of time (Tako & Robinson, 2009);
- System dynamics (SD) - an approach that studies the dynamic behaviour of systems that incorporates a feedback concept into the system model and uses visual representation which is then translated into mathematical formulas by computer software (Poles, 2013);
- Monte Carlo/Queuing simulation (MCQS) - a modelling approach that simulates a system by varying its parameters according to pre-determined distributions in order to obtain statistical inferences (Pezeshki, Baboli, Cheikhrouhou, Modarres, & Akbari Jokar, 2013);
- Analytical Model/ Simulation Study (AM/SS) - a modelling approach that is based on developing complex analytical techniques supported by simulation;
- Hybrid simulation (Hbrd) - a modelling approach based on developing a platform or architecture that combines/mixes two or more modelling techniques (Y. J. Son & Venkateswaran, 2005), (Venkateswaran & Son, 2009);
- Parallel and Distributed Simulation (PDS) - an approach that simulates system as multiple models developed on various computers but run in a co-ordinated manner (Iannone, 2007);
- Object-oriented Simulation (OOS) - a design methodology based on objects and classes, where the objects define a structure of the model and classes comprise of generalisations of certain objects which share the same data structure of behaviour.

These modelling techniques have been used to address a specific aspect/s within selected thematic categories. The review presents the most significant modelling approaches starting from purely simulation techniques such as ABS, DES and SD through MC/QS and closes the classification with mixed or combined modelling approaches, where simulation has been used alongside other modelling technique/s. The classification presented also considers object-oriented modelling or parallel and distributed simulation, however, it was observed that these modelling approaches were often derived from one of the other categories presented above. A summary of all simulation methods used is presented in Table 3. This includes 8 papers that provided literature reviews and two papers which discussed the benefits of developing a simulation game to provide a practical explanation of theories surrounding SCM or bullwhip effect. These papers did not discuss the modelling approach taken hence were kept as separate categories.

The review found that majority of the selected papers seemed to have focused on analytical models as a primary research approach and a simulation study was conducted to address computational difficulties or to enlarge the scope of the model. Moreover, it has been observed that a simulation technique has been often used within E2E-SC as a facilitator, helping to solve otherwise difficult mathematical problems, i.e. solution to intractable mathematical calculations or as a search engine for the optimal or near optimal input/output parameters that are to be considered in the mathematical formulation (Chiu & Huang, 2003).

It has been noticed that more often research combined different methodologies with simulation such as in Rabelo et al. (2007), where neural networks were used to build on the knowledge gained from developed SD simulation model to learn and identify the impacts as well as consequences of changes in key parameters on SC system behaviour. In that case a sequential use of simulation and artificial intelligence methods has been observed.

Table 3 Count of Simulation methods used per journal

Count of Title	Simulation method used										
Source title	**ABS**	**Antcl (smltS)**	**DES**	**Hbrd**	**Literature review***	**MAS**	**MC/QS**	**OOS**	**PDS**	**SD**	**simulation game**	**Grand Total**
AOR		3										3
CIE	2	13	5	2	1		1			1		25
COR	1	4		1						2		8
DS		1										1
EJOR	2	19	2	1			2			2		28
IEEE-TEM			1	1								2
INFCS		4								1		5
IJMS	1			1				1				3
IJOPM		2					1					3
IJPDLM			3	1	1					1		6
IJPE	5	24	10	4	1		5			2		51
IJPR	8	31	13	5	2		4			4		67
IJSPM		1	4	1			1				1	8
IJSIMM		5								1		6
IJ:SCM			1		1							2
JOM		3					1			1		5
JOS		1										1
JORS	1	2		1	1			1	1	1		8
OME		4	1	1		1						7
OR		2										2
POM		2					1			1	1	5
SMPT	2	1	3	1	1			1	1	2		12
Grand Total	22	122	43	20	8	1	16	3	2	19	2	255

Parallel and distributed simulation models simulate system as multiple models developed on various computers but run in a coordinated manner often interconnected via a local or wide network (Iannone, Miranda, & Riemma, 2007). Such simulation models can be based on existing simulation technique as observed in Roy and Arunachalam (2004), where DES was utilized and large scale simulation models developed on multiple processors. This method has been considered as a part or characteristic of one of the above identified simulation modelling techniques. Research in modelling SC systems provides a wide range of detailed and often dedicated simulation models, which are difficult to replicate to other business types or SCs. Nevertheless, there is a lack of a generic modelling framework that brings a holistic, yet simple to follow and understand view of an E2E-SC system to allow decision makers to adopt, change, manipulate and perform desired scenario analysis.

The identified simulation modelling techniques were further summarised in Table 4. The main research findings are described for each of the modelling techniques within selected studies as well as the potential challenges and issues in applying such methodology to modelling E2E-SC systems.

Table 4 Review of end-to-end supply chain modelling techniques

Modelling Method	Summary of research findings / challenges and issues	Authors
Agent Based Simulation (ABS)	Multi-agent (MA) approach allows modelling SC as a network or a system of intelligent business units with hierarchical and autonomous characteristics. ABS method used to model SCs behaviour capturing non-linear decisions making and impact of various operational and strategic policies. Agents' techniques allow incorporating knowledge from other disciplines i.e. social science aspects and incorporating them into the model. Multiple, complex and interacting components of an E2E-SC system studied as complex adaptive system; agent software engineering approach is capable to capture emergent behaviour of agents in the complex system. Considers interactions between decision maker and quantitative model equations by creating artificial intelligence developed as a computer program. Intelligent agent technology permits to model vertical and horizontal processes within SC structures, where multi-agents replicate SC partners, who exchange information, collaborate, negotiate or make operational or strategic decisions. Agents possess normative characteristics allowing for regulation of SC system behaviour during simulation run.	(Albino, Carbonara, & Giannoccaro, 2007; Allwood & Lee, 2005; Amini, Wakolbinger, Racer, & Nejad, 2012; Caridi, Cigolini, & De Marco, 2005; Chong, Wang, Yue Tan, & Cheong, 2014; H. Dai, Lin, & Long, 2014; Datta & Christopher, 2011; Roberto Dominguez, Cannella, & Framinan, 2014; Ferreira & Borenstein, 2011; Govindu & Chinnam, 2010; Kaihara, 2001; Labarthe, Espinasse, Ferrarini, & Montreuil, 2007; J. S. K. Lau, Huang, & Mak, 2004; G. Li, Yang, Sun, Ji, & Feng, 2010; J. Li & Sheng, 2011; J. Li, Sheng, & Liu, 2010; Meng, Li, Liu, & Chen, 2017; K. J. Mizgier, Wagner, & Holyst, 2012; Ponte, Sierra, de la Fuente, & Lozano, 2017; C. Yu, Wong, & Li, 2017; D. Z. Zhang, Anosike, Lim, & Akanle, 2006; W. G. Zhang, Zhang, Mizgier, & Zhang, 2017)
	Requires skilled programmer to develop agents and apply changes as models often developed to handle specific problem or context. Research work focused on focal company or on solving/addressing particular problem. Lack of studies/models representing E2E-SC. ABS or MA simulation models may be difficult to validate, and analysis of results may be difficult to explain.	
Discrete Event Simulation (DES) Object Oriented Simulation (OOS)	DES used to examine different aspects relative to E2E-SC systems, for instance SC configurations considering given set of operational parameters, in terms of number of SC levels, echelons, policies and linkages Design of Experiment (DoE) is often used to evaluate various simulation scenarios SC boundaries are set depending on the criticality of the processes and flow of materials and information DES often used for modelling operational aspects of SCs; incorporating OM/MS and OR techniques within simulation model, for example integrating Excel	(Alqahtani & Gupta, 2017; E. Bottani & Montanari, 2010; Byrne & Heavey, 2006; Carvalho, Barroso, MacHado, Azevedo, & Cruz-Machado, 2012; Cigolini, Pero, Rossi, & Sianesi, 2014; Francesco Costantino, Gravio, Shaban, & Tronci, 2015; Dev, Shankar, Dey, & Gunasekaran, 2014; Duarte, Fowler, Knutson, Gel, & Shunk, 2007; Elia & Gnoni, 2015; Fridgen, Stepanek, & Wolf, 2015; Gumrukcu, Rossetti, & Buyurgan, 2008; Gupta, Ko, & Min, 2002; Hwarng, Chong, Xie,

	spreadsheet with Arena simulation software through Visual Basic for Applications (VBA). Uses hierarchical approach to modelling, which provides a ground for varying level of simulation details i.e. relative to SC processes. Optimization is featured in Arena simulation software allowing for quick change of input parameters and search for the best combination of those parameters so as to achieve optimal output performance through set of simulation runs. This allows for greater level of experimentation. Existing Simulation Software Packages like eM-Plant, Anylogic, Arena etc. can be further advanced through programming efforts to incorporate analytical relations to simulation inputs and outputs. DES can be used to create meta-models involving user interface with databases, software application written in general purpose programming and ad hoc library of objects written in the simulation language	& Burgess, 2005; Ivanov, 2017; Jammernegg & Reiner, 2007; Long, 2014; Francesco Longo, 2014; F. Longo & Mirabelli, 2008; Lyu, Ding, & Chen, 2010; Martínez-Olvera, 2008; Mishra & Chan, 2012; Kamil J. Mizgier, 2017; Pan, Nigrelli, Ballot, Sarraj, & Yang, 2015; F. Persson, 2011; F. Persson & Araldi, 2009; Fredrik Persson, Olhager, Tekniska, Linköpings, & Institutionen för, 2002; Pirard, Iassinovski, & Riane, 2011; Pundoor & Herrmann, 2007; Sari, 2007; A. J. Schmitt & Singh, 2012; T. G. Schmitt, Kumar, Stecke, Glover, & Ehlen, 2017; Stefanovic, Stefanovic, & Radenkovic, 2009; Tannock, Cao, Farr, & Byrne, 2007; Thron, Nagy, & Wassan, 2006; Van Der Vorst, Beulens, & Van Beek, 2000; Van Der Vorst, Tromp, & Van Der Zee, 2009; J. Venkateswaran & Son, 2004; Verma, 2006; Wadhwa, Mishra, Chan, & Ducq, 2010; Wikner, Naim, & Rudberg, 2007; Xudong, Kumar, & Tan, 2008; C. Zhang & Zhang, 2007; Hung, Kucherenko, Samsatli, & Shah, 2004; Rossetti & Thomas, 2006; Xiang & Rossetti, 2014)
	Simulation usually limited in scope; considering one or limited number of products and processes; focusing on deterministic assumptions, focusing on objectives of focal company. Further work required to allow integration of existing information technology developments (i.e. EDI) into simulation model.	
System Dynamics (SD)	SD method used to simulate dynamic movements in SCs. This modelling technique is derived from control theory and causal loop diagrams, which allow defining SC structure and its flows as well as feedback loops. The method is based on mathematical formulation consisting of system of differential equations, which is solved via simulation. Focused on system thinking and is not data driven. This modelling method is primarily used to study aspects relative to Bullwhip Effects in the SCs considering the impacts of various SCM techniques such as products returns, remanufacturing or recycling within forward or closed loop SCs on the entire SC performance. Used to study hybrid business models i.e. considering combination of two different strategies make-to-order (MTO) and make-to-stock (MTS). Control parameters used within the model which affect the forward and feedback loops particularly when stochastic parameters are considered. Often used to model dynamics in automobile SCs.	(Anderson Jr, Fine, & Parker, 2000; Barlas & Gunduz, 2011; Das & Dutta, 2013; Georgiadis & Athanasiou, 2013; Helo, 2000; Higuchi & Troutt, 2004; Hofmann, 2017; Holweg, Disney, Hines, & Naim, 2005; Hussain & Drake, 2011; Martínez-Olvera, 2009; Moreno, Mula, & Campuzano-Bolarin, 2015; Özbayrak, Papadopoulou, & Akgun, 2007; Pierreval, Bruniaux, & Caux, 2007; Poles, 2013; Rabelo, Helal, Lertpattarapong, Moraga, & Sarmiento, 2008; Spengler & Schröter, 2003; Springer & Kim, 2010; Vlachos, Georgiadis, & Iakovou, 2007; Wangphanich, Kara, & Kayis, 2010)

	Powerful simulation packages such as Vensim, iThink, Powersim or Stella are used to enhance model functionality, capacity and performance. Although, the advancement in these tools capabilities allow for optimization and are geared more towards business managers, there is still lack of E2E-SC system models and guidance on how to develop such models.	
Analytical Model/ Simulation Study (AM/SS)	Simulation often used to facilitate development of analytical models that combine multiple mathematical techniques and various SCM strategies to better understand the effects of interactions amongst factors in complex E2E-SC systems, allowing to: • Perform multiple scenario analysis so as to capture different SC strategies, policies, configurations, designs or uncertain parameters. • Search for optimal or near optimal solutions in combinatorial optimization of large-scale problems with stochastic parameters. • Gain further insides into SC designs by incorporating complex OR techniques into the model scope so more echelons, layers, products, processes etc. can be considered. Results of analytic models can be incorporated into a simulation model to study SC related problems over a period of time (also to consider statistical distribution in the place of various stochastic parameters). Simulation aids experimentation on complex analytical models so the knowledge from various cross-disciplinary fields such as natural sciences, physics or biology can be incorporated and the further impact on E2E-SC system performance can be analysed and evaluated. Models are usually derived from well-established and known mathematical formulation relative to modelling SC systems such as inventory management methods (particularly surrounding SC dynamics and bullwhip effect), production planning and control, SCM strategic decisions, production and distribution. Simulation provides an arena for manipulating parameters within complex analytical models so as to aid decision maker with the most suitable operational, tactical or strategic solutions or trade-offs. Analytical models and analytics can add value to holistic SCM by considering information and data, which are cross-functional, spanning multiple system levels and focusing on historic and future time dimensions.	(Abdel-Malek, Kullpattaranirun, & Nanthavanij, 2005; Yavuz Acar & Atadeniz, 2015; Y. Acar, Kadipasaoglu, & Schipperijn, 2010; Ahire, Gorman, Dwiggins, & Mudry, 2007; Ali & Boylan, 2011; Altiparmak, Gen, Lin, & Karaoglan, 2009; Arora & Kumar, 2000; Banerjee, Banerjee, Burton, & Bistline, 2001; Bayraktar, Lenny Koh, Gunasekaran, Sari, & Tatoglu, 2008; Beamon & Chen, 2001; Ben-Tal, Golany, & Shtern, 2009; Biehl, Prater, & Realff, 2007; Eleonora Bottani, Montanari, Rinaldi, & Vignali, 2015; Boulaksil & Fransoo, 2009; Brabazon & MacCarthy, 2017; Caggiano, Jackson, Muckstadt, & Rappold, 2009; Salvatore Cannella, Bruccoleri, & Framinan, 2016; Chaharsooghi & Heydari, 2010; Chebolu-Subramanian & Gaukler, 2015; Chen & Huang, 2006; Chern, Chen, & Huang, 2014; Chiu & Huang, 2003; Ciancimino, Cannella, Bruccoleri, & Framinan, 2012; Çimen & Kirkbride, 2017; F. Costantino, Di Gravio, Shaban, & Tronci, 2014; Daganzo, 2004; Daultani, Kumar, Vaidya, & Tiwari, 2015; De Sensi, Longo, & Mirabelli, 2008; Diabat, 2014; Disney & Towill, 2002; Dixit, Seshadrinath, & Tiwari, 2016; R. Dominguez, Framinan, & Cannella, 2014; Fan, Schwartz, & Voß, 2017; Fleischhacker, Ninh, & Zhao, 2015; Fleischmann, Van Nunen, & Gräve, 2003; Fröhling, Schwaderer, Bartusch, & Rentz, 2010; Fu, Ionescu, Aghezzaf, & De Keyser, 2015; Ganeshan, Boone, & Stenger, 2001; Garvey, Carnovale, & Yeniyurt, 2014; Gaukler, Ketzenberg, & Salin, 2017; Giannoccaro & Pontrandolfo, 2002; Gill, 2009; Gomez Padilla & Mishina, 2009; Gong, Liu, & Lu, 2015; Govindan & Fattahi, 2017; Güller, Uygun, & Noche, 2015; Haines, Hough, & Haines, 2017; Ho, 2007; Hsu & Liu, 2009; Karaman & Altiok, 2009; Kauremaa, Småros, & Holmström, 2009; Khilwani, Tiwari, & Sabuncuoglu, 2011; Klassen &

However, analytic models are limited in scope as the computational calculation tractability is too difficult when consideration is given to complex E2E-SC systems; hence simulation is often used as a facilitator. Research is required to progress the knowledge on various ways to mix or combine analytics with simulation to address more complex issues within E2E-SC systems.	Menor, 2007; Kull & Closs, 2008; Lai, Wu, Shi, Wang, & Kong, 2015; R. S. M. Lau, Xie, & Zhao, 2008; C. Li & Liu, 2012; M. Li, Wu, Zhang, & You, 2015; Y. Li, Niu, Zhao, & Wang, 2017; C. W. R. Lin & Chen, 2003; G. Lin et al., 2000; Liu & Nagurney, 2011, 2013; Ma & Ma, 2017; Mahnam, Yadollahpour, Famil-Dardashti, & Hejazi, 2009; Manuel, Al-Hamadi, & Qureshi, 2015; Marquez, Bianchi, & Gupta, 2004; Martinez-Olvera, 2010; Mateen, Chatterjee, & Mitra, 2015; Meijboom & Obel, 2007; Meixell & Wu, 2005; Mohebbi & Choobineh, 2005; Mousavi, Alikar, Niaki, & Bahreininejad, 2015; Munoz & Dunbar, 2015; Nativi & Lee, 2012; Nekooghadirli, Tavakkoli-Moghaddam, Ghezavati, & Javanmard, 2014; Niranjan & Ciarallo, 2011; Ovalle & Marquez, 2003; Özdemir, Yücesan, & Herer, 2006; Petrovic, 2001; Pezeshki, Baboli, Cheikhrouhou, Modarres, & Akbari Jokar, 2013; Poojari, Lucas, & Mitra, 2008; Qazi, Quigley, Dickson, & Ekici, 2017; Rao, Scheller-Wolf, & Tayur, 2000; Riddalls & Bennett, 2002; Sagawa & Nagano, 2015; Sahin & Robinson Jr, 2005; Salehi, Mahootchi, & Husseini, 2017; Salem & Elomri, 2017; Sarrafha, Rahmati, Niaki, & Zaretalab, 2015; Shu & Barton, 2012; Shu & Karimi, 2009; Shukla, Shukla, Tiwari, & Chan, 2009; Solis, Longo, Nicoletti, Caruso, & Fazzari, 2014; J. Y. Son & Sheu, 2008; Spiegler & Naim, 2017; Surana, Kumara, Greaves, & Raghavan, 2005; Swenseth & Olson, 2016; Temponi, Bryant, & Fernandez, 2009; Tiacci & Saetta, 2011; Tiwari, Raghavendra, Agrawal, & Goyal, 2010; Truong & Azadivar, 2005; Tsadikovich, Levner, Tell, & Werner, 2016; Van Landeghem & Vanmaele, 2002; Viswanathan, Widiarta, & Piplani, 2007; Wadhwa, Saxena, & Chan, 2008; Wang, Wang, & Ouyang, 2015; Warburton, Disney, Towill, & Hodgson, 2004; Yadav, Mishra, Kumar, & Tiwari, 2011; Yan, Robb, & Silver, 2009; Yang, Pan, & Ballot, 2017; F. Yu, Kaihara, Fujii, Sun, & Yang, 2015; B. Zeng & Yen, 2017; Y. Zeng & Xiao, 2014; J. Zhang, Liu, Zhang, & Bai, 2015; L. Zhang, 2015; X. Zhang & Huang, 2010)

Monte Carlo/ Queuing Simulation (MC/Q)	The method allows for continuous review of SCs performance. Samplings from statistical distribution are used in place of uncertain parameters. Based on analytical model or mathematical assumptions. Although this method allows for evaluating different control structures and/or varying level of approximation for E2E-SC systems in continuous manner, some technological advancement within this method are required. This method could be developed further to incorporate intelligent features such as learning during simulation runs, whereby through alteration of simulation parameters or simulated policies an intelligent control of inventory, production or distribution could be performed and evaluated.	(Adenso-Díaz, Moreno, Gutiérrez, & Lozano, 2012; Ayanso, Diaby, & Nair, 2006; S. Cannella, Ciancimino, & Márquez, 2008; Cattani, Jacobs, & Schoenfelder, 2011; Celik & Son, 2012; Croson & Donohue, 2003; Z. Dai & Zheng, 2015; Diaz & Marsillac, 2017; Holweg & Bicheno, 2002; Hovelaque, Duvaleix-Tréguer, & Cordier, 2009; Mendoza, Mula, & Campuzano-Bolarin, 2014; Kamil J. Mizgier, Wagner, & Jüttner, 2015; Sanei Bajgiran, Kazemi Zanjani, & Nourelfath, 2017; Sari, 2008; Wu & Olson, 2008)
Hybrid Simulation (Hbrd) Parallel and Distributed Simulation (PDS)	This category considers models that combine simulation with analytical models, other simulation methods, other research methodologies (i.e. case study) or with artificial intelligence. There is varying level of interactions between the techniques, whereby some models present sequential use or combined use of two or more modelling techniques and others more sophisticated architectures, where model runs and connects between methods automatically. The attempts made to use local versus global optimization in hybrid mixed integer linear programming model combined with simulation with the economic benefits being only confirmed in reference to the case study. Further work is required to develop/enhance iterative procedures for combining simulation with various modelling techniques. Hybrid models provide scope for developing and building upon all of the above presented techniques, yet require clear framework to ensure validity, tractability and replicability.	(Arns, Fischer, Kemper, & Tepper, 2002; Brandenburg, 2017; Chatfield, Hayya, & Harrison, 2007; Cigolini, Pero, & Rossi, 2011; Hlioui, Gharbi, & Hajji, 2015; Iannone, Miranda, & Riemma, 2007; Lee, Cho, Kim, & Kim, 2002; Lee & Kim, 2002; Moghaddam, 2015; Pathak, Dilts, & Biswas, 2007; Rabelo, Eskandari, Shaalan, & Helal, 2007; Reiner, 2005; Rijpkema, Rossi, & G.A.J. van der Vorst, 2014; Roy & Arunachalam, 2004; Shang, Li, & Tadikamalla, 2004; Shi, Liu, Shang, & Cui, 2013; Y. J. Son & Venkateswaran, 2007; Vahdani, Zandieh, & Roshanaei, 2011; Vamanan, Wang, Batta, & Szczerba, 2004; J. Venkateswaran & Son, 2009; J Venkateswaran & Son*, 2005)

Source: Chilmon (2018)

The research in modelling E2E-SC systems requires more simplistic yet flexible and ingenious models that are easy to implement and reuse. Cattani et al. (2011) pointed out that one way to do so is by developing an approach that could use intelligent heuristics that are embedded into simulation methodology and are able to learn in time and utilize the acquired knowledge during a simulation run. To address this need and to guide the research agenda, the next section will investigate which generic elements are required to model E2E-SC systems using simulation. This is to appreciate the theoretical perspective, concepts and aspects or issues relative to the research topic.

5. Modelling consideration for an E2E-SC using simulation

Modelling an E2E-SC system using simulation topic is an area worth investigating and so is broadening the knowledge and understanding of generic elements of an E2E-SC simulation model. This research applies a paradigmatic view on modelling activity, where the modelling concepts are built upon fundamentals of complexity theory, systems thinking and simulation methodology. This has been achieved by reviewing SLR selected studies that exclusively incorporated complexity within the title, abstract or key words with the aim to capture generic modelling principles relative to E2E-SCs (Table 5). These were viewed through paradigmatic lenses (Morin, 1992) and were classified under structural, computational and system organization artefacts as depicted in Figure 3.

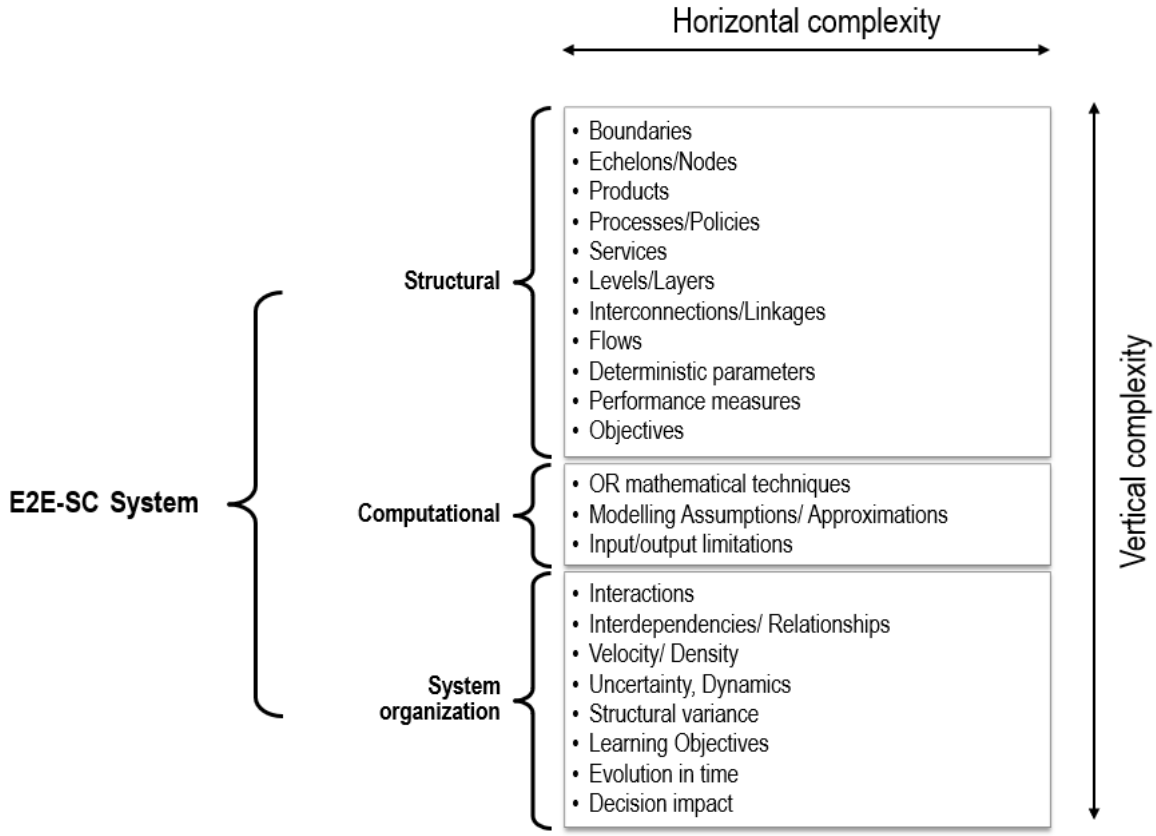

Fig. 3. Generic elements for modelling E2E-SC system using simulation

Source: Chilmon (2018)

Complexity in an E2E-SC system refers to the structural, computational and systemic organizational differentiation or variety that may exist in an organization or any E2E-SC system under consideration (Choi & Hong, 2002). The complexity of the model can arise from the number of sub models used to depict the level of differentiation in the structure and organization as well as the number of mathematical techniques applied. Horizontal complexity refers to the number of elements/components, for instance the number of products or the number of modelling objectives. Various elements such as number of products, policies or echelons/nodes are often spanning across multiple levels with parts belonging to the same echelon, but having different characteristics (Hwarng et al., 2005), hence requiring different mathematical (OR) techniques to depict interactions/relationships within an E2E-SC system. This can be referred to as a vertical complexity (Choi & Hong, 2002).

Table 5 Complexity factors relative to E2E-SC

No	Author	Journal	Key elements	Complexity drivers	S	C	SO
1	Abdel-Malek, Kullpattaranirun, and Nanthavanij (2005)	IJPE	Purchasing, Outsourcing, DSF	• parent company and 4 supply layers with different order arrival rates and service rates (Levels) • queuing model- Markovian assumption of sojourn times of orders in process at various levels in SC; considering SS, LT (computational- simulation experiments used to compare the Markovian analytical results to non-Markovian ones, OR mathematical technique)	✓	✓	
2	Arora and Kumar (2000)	INFCS	SC (enterprise) re-engineering	• dynamics of SC system environment that creates challenges is setting SC system model boundaries (dynamics, boundaries), capturing and selecting all relevant interactions between system and the environment i.e. system, subsystem components (interactions, levels) • challenge in categorization of system and environment variables (input/output limitations)	✓	✓	✓
3	Ayanso, Diaby, and Nair (2006)	EJOR	Inventory system, SCM	• complexity of decision-making environment affected by LT, demand uncertainty; cost and distribution variability in the multi-channel distribution SC (uncertainty, structural variance); • computer simulation used to understand interaction effects of the variables on the proposed rationing policy (interaction, decision impact, OR mathematical technique)	✓	✓	✓
4	Byrne and Heavey (2006)	IJPE	SC Visibility	• multiple product with differing demand pattern flow through multi-echelon SC, capacity constraints (products, echelons, flows, structural variance) • the following independent parameters: forecasting methods; Simple moving average (SMA) and double exponential smoothing (DES) as well as demand pattern, information sharing, capacity, LT, transportation, order processing, production set up, inventory cost and backorder policies. (OR mathematical techniques, modelling assumptions, input/output assumptions)	✓	✓	✓
5	Carvalho, Barroso, MacHado, Azevedo, and Cruz-Machado (2012)	CIE	SC design	• SC interconnecting links, relations e.g. number of nodes, facilities within each node, policies, processes (interconnections/linkages, echelons/nodes, policies, processes, SC performance measure) • simulation model inputs comprised of demand data, product (vehicle) subset material tree, inventory data, resource data, costs data and transportation data (modelling assumptions, input/output limitations)	✓	✓	✓
6	Dai, Lin, and Long (2014)	IJPR	SCM	• SC complexity enhanced due to multiple actors, units with conflicting objectives, dynamic, stochastic, uncertain and evolving nature, fractal approximate self-similarity of SC systems structure and organisation (SC structure, evolution in time, uncertainty, dynamics, relationships, interactions, modelling approximations)	✓	✓	✓
7	Dominguez, Cannella, and Framinan (2014)	CIE	Bullwhip Effect, SC network	• Multiple stages in the SC (horizontal complexity) and multiple nodes per stage (vertical complexity) • divergent SC network structure impact on the computational results versus those achieved in serial SC	✓	✓	
8	Dominguez, Framinan, and Cannella (2014)	IJPR	Bullwhip Effect, SC network	• computational technique (Smoothing replenishment rule) used to improve SC performance (OR mathematical techniques, performance measures)	✓	✓	

9	Hwarng, Chong, Xie, and Burgess (2005)	IJPR	SC integration, SCM	• multiple levels (echelons) • oversimplified assumptions that is assumed distributions rather than distributional parameters based on real data (modelling assumptions)	✓	✓	
10	Iannone, Miranda, and Riemma (2007)	SMPT	SCM, performance evaluation	• technological obstacles to integration of distributed SC simulation models across geographical locations, complex interdependencies between SC participants (input/output limitations, interdependencies)		✓	✓
11	Khilwani, Tiwari, and Sabuncuoglu (2011)	IJPR	SC network design	• discrete event timings interactions in the model relative to customer arrival, manufacturing of products (interactions, products, processes) • generalizability and simplifications but including all production processes requiring hierarchical simplification (modelling assumptions/approximations)	✓	✓	✓
12	C. Li and Liu (2012)	SMPT	Order Management	• dynamic behaviour as a result of interactions between players/actors causing order amplification in multi-stage SC system (dynamics, interactions, echelons/nodes)	✓		✓
13	G. Li, Yang, Sun, Ji, and Feng (2010)	IJPE	SCM, SC network	• evolving organisational SC structures and functions (evolution in time) • diversity of interconnections and relations, collaboration that changes/evolves subject to various factors and changes in the environment (interconnections, learning objectives) • dynamics of the model entities (dynamics)	✓		✓
14	Long (2014)	IJPR	SCN	• hierarchical framework based on SCOR- structure modelling and ABS – function modelling		✓	
15	Mishra and Chan (2012)	IJPR	Manufacturing	• computational difficulty in process planning of distributed manufacturing SC		✓	
16	Mizgier, Wagner, and Holyst (2012)	IJPE	SCM, production	• SC network structure affected by interconnection channels • logistical system interconnection density • production dynamics due to number of stages, products, periods and economic environment	✓	✓	✓
17	Özbayrak, Papadopoulou, and Akgun (2007)	SMPT	Manufacturing	• SC structure with many variables and linkages	✓		
18	Surana, Kumara, Greaves, and Raghavan (2005)	IJPR	SC coordination	• interactions and interdependencies between entities, processes and resources (interdependencies, processes, resources) • SC structure spanning several levels, which evolves and self-organizes over time (evolution in time) • highly structured hierarchical robust SC system prone to disturbances	✓		✓
19	Tannock, Cao, Farr, and Byrne (2007)	IJPE	Manufacturing	• SC interconnections and variability in performance affected by those connections (Interconnections) • product, process complex structure attributable to the SC type (aerospace)	✓		✓
20	Temponi, Bryant, and Fernandez (2009)	EJOR	Strategy	• aggregated enterprise model that considers multiple business functions with interacting elements (structural variance) • various business functions modelled as sub-models and described with differential equations (OR mathematical techniques)		✓	✓
21	Venkateswaran and Son (2004)	IJPR	SC modelling	• level of model details and approximations used to model the SC (model assumptions/ approximations)	✓	✓	

22	Vlachos, Georgiadis, and Iakovou (2007)	COR	Capacity Planning, Reverse SC	• variability in return flows impact on the capacity planning for remanufacturing process (flows)	✓		
23	Wikner, Naim, and Rudberg (2007)	IEEE-TEM	Mass customization, manufacturing,	• dynamics (uncertainty) of the environment (customer demand)			✓
24	Wu, Frizelle, and Efstathiou (2007)	IJPE	SCM	• SC structure defined by the expected amount of information (entropy) to describe the state of planned system and operational complexity determined by amount of information required to describe system deviation from the plan (deterministic parameters, input/output limitation, learning objectives)	✓	✓	✓
25	Zeng and Xiao (2014)	IJPR	SCN	• modelling used to address cascading failure spread in cluster SCN (layers)	✓		

S-structural complexity, C- computational complexity, SO- systemic organisational complexity, LT-lead time, SS- safety stock, SP-stockout probability, MTO- make to order

Source: Chilmon (2018)

The number of products, flows, processes and/or services offered could amplify the complexity in modelling E2E-SCs together with the type and characteristics of each of these elements (Adenso-Diaz et al., 2012; Byrne & Heavey, 2006; Min, 2009; Carvalho et al., 2012). Likewise, the modelling process would require setting clear objectives and performance measures as those would determine the boundaries of the considered system, number of elements as well as links between them. These were also included under the structural part, which focused on the holistic elements of an E2E-SC, where parts and the whole of a simplified system could be recognized and represented in one model. These referred to varied structural complexity factors such as number of echelons, players or parties within each echelon, SC layers, number of products or processes as well as system boundaries.

The second group emerged as concepts relative to simulation modelling and the inherent computational complexity. For instance in Abdel-Malek et al. (2005), a structural dimension of the multi-level SC was modelled as a series of tandem queues to account stochastic parameters and provide relevant assumptions. Multiple computational factors need to be considered when modelling E2E-SC system. These are often used to allow for greater representation of any E2E-SC system, particularly because modelling more often involves multi-disciplinary aspects relative to any of those identified under SLR theme/s.

The study isolates the complexity factors as embedded within multi-dimensional aspects that derive from three categories: Structural, Computational and a further complexity element being linked with the SO aspects. These factors are often interrelated hence present a distinctive approach towards modelling issues relative to complex E2E-SCs. This is corroborated in various studies; for instance, Arns et al. (2002) provide a hybrid model that adopts a hierarchical modelling approach to reduce the computational complexity, allowing the aggregation of various sub-models through different approaches (i.e., Queuing Network and Petri nets).

Supply Chain Operations Reference (SCOR) model has also been incorporated within many studies as a way to define and/or map SC processes given its standard functionality (Long, 2014; Carvalho et al., 2012; Petersen et al., 2011; Persson & Araldi, 2009; Pundoor & Herrmann, 2007; Rabelo et al., 2007). Pundoor and Herrmann (2004) proposed a SC simulation model based on Discrete Event Simulation (DES) and SCOR model to study the dynamic nature of the SC incorporating multiple level elements that permit the addition of extra features. Dynamic behaviour of the SC system instigated by supply, demand or lead time uncertainties has similarly been modelled by Pirard et al. (2011), where the work presented by the authors evaluates various SC design scenarios under different control policies that were applied to inventory management, scheduling and production activities. Within their study, the decision maker was involved in optimizing the selected elements (rules) in the model to improve the SC system performance.

Simulation capabilities have also been employed in detailed process modelling to support decision-making procedures as in Fröhling et al. (2010), where consideration was given to the integration of complex SC planning processes. The authors presented an innovative application of OR techniques to closed-loop SC and designed a recycling process model that allocated residues from different sources to recycling sites. Simulation methodology further supplements the computational constructs by elucidating its importance and complex relation with other elements.

Moreover, representation of such complex SC system may require multiple models due to the scale of changes and interactions between elements within system. This can be observed in many of the selected papers, where a singular model was not capable to capture or reflect all aspects of the modelled system or to fully fit with the purpose of a system model. This often determines the use of multidisciplinary modelling techniques where simulation methodology is combined with other OR&MS models/techniques. Computational factors considered in Table 6 are relative to modelling techniques that were used in the selected studies and deemed particularly relevant in simulation modelling of an E2E-SC system.

Table 6 OR/MS mathematical techniques

OR/MS mathematical techniques	
Category	*Specification*
Optimization, mathematical programming	Multi-echelon, multi-objective optimization
	Multi-echelon inventory allocation problem (4 allocation schemes: lexicographic with priority to intermediate demand, lexicographic with priority to downstream demand, predetermined proportional allocation, and proportional allocation) to search for the best base-stock level (Niranjan & Ciarallo, 2011)
	Integer programming (IP) model with Taguchi technique and Artificial Immune System (AIS) to search for a near optimal solution to the distribution problem (Shang et al., 2004)
	Taguchi technique and Response Surface Methodology (RSM) (Tiwari et al., 2010)
	Stochastic optimization problem solved using an Infinitesimal Perturbation Analysis procedure (Total Cost minimization) (Özdemir et al., 2006)
	2-stage stochastic IP (Liu & Nagurney, 2013); (Poojari et al., 2008)
	Chance Constrained Programming for SC risk evaluation (D. Wu & Olson, 2008)
	Mixed-integer Quadratic model to address SC co-ordination (Pezeshki et al., 2013)
	Mixed-integer linear programming (MILP) model with decomposition technique (Profit maximization) (Meijboom & Obel, 2007)
	Dynamic Allocation Problem with uncertain supply (DAP-US) addressed by developing a two-stage extended Genetic Algorithm (eGA) (C. W. R. Lin & Chen, 2003)
	Automatic Pipeline, Inventory and Order Based Production Control System (APIOBPCS) algorithm (transfer function model of the system developed using causal diagrams, block diagrams, difference equations and z-transform) (Disney & Towill, 2002a)
	Robust optimization to control serial multi-echelon, multi-period SC (Ben-Tal et al., 2009)
	Minimum Flow Time Variation (MFV) rule for customer order scheduling (Hsu & Liu, 2009)
Heuristics	Heuristics for inventory balancing and transhipment policy to minimize the overall cost (Tiacci & Saetta, 2011)
	Metaheuristics optimization; Inventory model that incorporates fuzzy sets and multi-objective Particle Swarm Optimization (Cost minimization) (Mahnam et al., 2009)
	Heuristics of Capacity utilization, variability and inventory (CVI) in complex SC operations (Klassen & Menor, 2007)
	Heuristic algorithms for strategic safety stock placement problem that use simulation to compare results for iterative LP and MIP approximation of (Shu & Karimi, 2009)
	Evolutionary algorithm (EA) –AIS used for batch sequencing in multi-stage SC, Fuzzy Set Numbers combined with Program Evaluation and Review Technique to analyse Supply chain network (SCN) (Vahdani et al., 2011)
Forecasting	Moving average (MA), Exponential Smoothing ES (DES, SES, TES), regression (multiple-regression) (Anderson Jr et al., 2000); (Bayraktar et al., 2008)
Intelligence	Petri nets (PN)- hybrid, generalized, stochastic, deterministic and stochastic (Arns et al., 2002)
	Steady State Genetic Algorithm (ssGA) for SCN design (Altiparmak, Gen, Lin, & Karaoglan, 2009)
	Queuing Network (QN) (Arns et al., 2002)
	Markov decision process supported by Reinforced Learning (RL) to control inventory policies between multiple actors in SC (Giannoccaro & Pontrandolfo, 2002)
	Neural Nets (NN); Eigenvalue Analysis to evaluate SD model outputs (Rabelo et al., 2008)
	Complex Adaptive System (CAS) (Surana et al., 2005)
	SCN modelled as CAS and Fitness Landscape Theory to highlight evolutionary complexities of such SC systems (G. Li et al., 2010)

Source: Chilmon (2018)

It has been observed that the computational complexity is relative to OR&MS mathematical techniques used to model an E2E-SC system. Those techniques consider such fields of modelling as optimization, mathematical programming, heuristics, forecasting, project management and intelligent state-of-art methods. Some of the specificities of such techniques are presented in Table 6 together with the reason for use.

It has been noted that the computational complexity is derived from developments as well as a technological shift in modelling where a new era of combining modelling approaches prevails, particularly observed in hybrid and AM/SS models. Hierarchical approach to simulation modelling allows incorporating different levels of detail where each sub-model can be supported by different simulation modelling technique/s. Interestingly, such models often feature Artificial Intelligence algorithms (i.e., GA, NN, AIS, and RL etc.) and the researcher continuously seeks to test capabilities of such algorithms as well as their applicability to model complex E2E-SC systems.

6. Review Summary and Research Impact

Complexity is an attribute of many systems and it can be clearly observed in E2E-SCs. This paper presents findings from the systematic literature review of the supply chain and simulation field, by adopting an integrated and holistic assessment of an E2E-SC, from market-demand scenarios through order management and planning processes, and on to manufacturing and physical distribution. Thus, by providing significant advances in understanding of the theory, methods used and applicability of supply chain simulation, this paper further develops the body of knowledge within this subject of inquiry. Modelling an E2E-SC system using simulation requires a comprehensive level of understanding of the SCM, modelling and interferences between these two and other disciplines. The development of an E2E-SC model using simulation requires three crucial components that need to be considered during the model design stage: structural, computational and systemic organizational that are vital elements of complex systems like E2E-SCs, each with their subcategories as indicated in Figure 3. The SLR exhibited various issues and practical decisions relative to E2E-SC simulation modelling that are influenced by the complex computational techniques and methods that often span across multiple dimensions and disciplines such as mathematics, computer engineering, software design, biology, education and many others. Conclusively the SLR underlined the following points regarding modelling E2E-SC systems using simulation:

- The most frequently researched themes relative to an E2E-SC system simulation modelling are: SCM, Inventory management, SC dynamics, Production planning and Inventory control. These are vital to drive a high performing E2E-SC system. These themes are usually part of multi-disciplinary and cross-sectional studies, where multiple aspects, issues and processes are considered.
- The complexity in E2E-SC system models is derived from structural, computational and systemic organizational factors, which need to be considered during the modelling process.
- An advanced and extended version of existing OR/MS mathematical modelling techniques are often used to facilitate development of E2E-SC simulation models.
- There is an observed shift in simulation modelling towards combining (hybrid) models that are characterised by the amalgamation of multiple modelling techniques and research methodologies.
- Simulation model outputs are often reinforced by application of artificial intelligence algorithms to support the decision maker in providing a better understanding of the system behaviour and system evolution.
- E2E-SC system models are often hierarchical, where multiple decisions are made at various levels that have an ultimate impact on the entire E2E-SC system performance.

This paper contributes to knowledge and understanding of the characteristics of E2E-SC systems as well as the requirements for simulation modelling. The next step would be to develop an experimental model and test the proposed generic E2E-SC simulation elements in real E2E-SC systems to underline its applicability and practicality.

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