Research Article

Design of an Integrated Methodology for Analytical Design of Complex Supply Chains

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A literature review and gap analysis indentifies key limitations of industry best practice when modelling of supply chains. To address these limitations the paper reports on the conception and development of an integrated modelling methodology designed to underpin the analytical design of complex supply chains. The methodology is based upon a systematic deployment of EM, CLD, and SM techniques; the integration of which is achieved via common modelling concepts and decomposition principles. Thereby the methodology facilitates: (i) graphical representation and description of key "processing", "resourcing" and "work flow" properties of supply chain configurations; (ii) behavioural exploration of currently configured supply chains, to facilitate reasoning about uncertain demand impacts on supply, make, delivery, and return processes; (iii) predictive quantification about relative performances of alternative complex supply chain configurations, including risk assessments. Guidelines for the application of each step of the methodology are described. Also described are recommended data collection methods and expected modelling outcomes for each step. The methodology is being extensively case tested to quantify potential benefits & costs relative to current best industry practice. The paper reflects on preliminary benefits gained during industry based case study modelling and identifies areas of potential improvement.

1. Introduction

Supply chain systems are inherently complex [1]. With reference to manufacturing enterprises (MEs) and their supply chains, the term complexity has been defined in different ways. For example, Kambil [2] states that complexity is related to the amount of variety at and across processes, while Snowden [3] defines complexity in terms of visibility and order in casual relationships [4]. Also observed that supply networks are dynamically changing webs

of relationships that are becoming more complex. Wider product variety, smaller production lot sizes, more tiers, and different actors involved in coordinated supply chains also cause supply chain complexity [5]. Factors that have resulted in the need for greater variety of products realised by common sets of resources are presenting major challenges to ME managers and engineers, including production managers and engineers. Greater emphasis is often being placed on redesigning products and processes, so that the negative impacts of product variety due to product proliferation (and thence increased system complexity) can be partially overcome [6]. This kind of phenomenon has led modern organizations to implement new supply chain paradigms and adopt new techniques to support rapid design, analysis, and implementation of these new paradigms [7].

Fine [8] observed that an important core competence of an organization is its ability to design an effective supply chain. Supply chain management (SCM) techniques can be drawn from a collection, customization, and implementation of tools to that fit the environment in which they are to be used [9]. Knowledge about business processes (and their impacts on supply chains), and their supporting information technology systems, can help to underpin the reengineering, integrating, planning, and optimizing supply chains [10]. Supply chains are dynamic in the sense that they involve a changing flow of information, products, and funds, between their different operational stages; it is important to visualise information, funds, and product flows in both directions through this chain [11]. System simulations and nonlinear dynamic analysis of key outputs should be a mandatory part of any supply chain reengineering proposal [12]. Simulation can be used to study effects of uncertainty [13]. GCI [14] states that future supply chains should embrace leading supply chain practices and new ways of calculating causal impacts of such practices on supply chains [14]. With these above-stated requirements in mind, the focus of the research reported in this paper has been on developing an integrated modelling methodology which can support the analysis and design of complex supply chains.

Different state-of-the-art solutions have been reviewed with potential to support the analytical design of complex supply chains. Some of the techniques reported on include supply chain mapping [15], use of the supply chain operations reference (SCOR) model [16, 17], and the combined use of optimization, simulation, and heuristics [13]. These techniques can lend support to supply chain analysis with reference to particular focal concerns such as by modeling some structural aspects of the supply chain or by analyzing selected behavioral aspects of the supply chain.

Prior to the authors research described in this paper, little had been reported in the research literature about integrated means of deploying enterprise modelling (EM), causal loop diagramming (CLD), and simulation modelling (SM) in support of the lifecycle engineering of complex supply chains. Whereas, it was evident that when used on their own, EM techniques are suited to modele process-oriented organisational structures of complex organisations in ways that support various kinds of organisational decision making. While CLD and SM techniques have had widespread application in recent decades, in respect of modelling and predicting the behaviours of key performance indicators (KPIs) used by organisations operating in various industrial, commercial, and governmental sectors. Consequently the authors explored how EM, CLD, and SM technologies might be used syn-ergistically, so as to bring together structural views of supply chains with behavioural views related to the reachable states of alternative supply chain structures. In this way, the authors' aim was to be able to explicitly describe supply chains from an organisational point of view and then to virtually test the ability of those organisational structures to facilitate competitive organisational behaviours. Consequent to their initial research explorations,
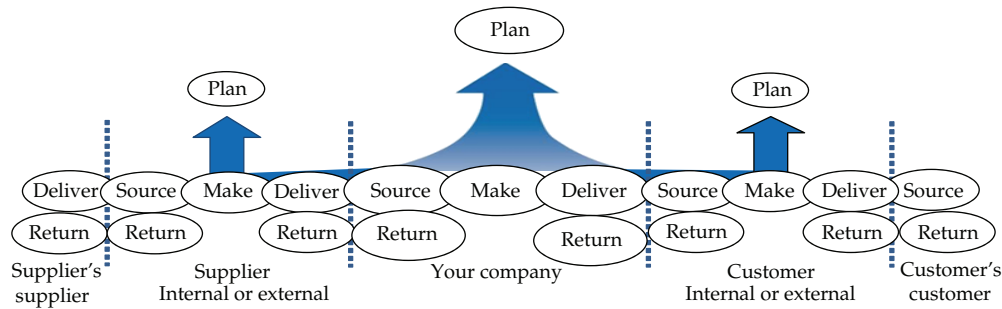
Figure 1: SCOR Model [16].

the author's research objective crystallised to become centred on conceiving and implementing an integrated methodology for the analytical design of complex supply chains. The design and application of this methodology is outlined in later sections of this paper.

2. Literature Review

2.1. Complex Supply Chains

The APICS dictionary, 10th edition, defines the term supply chain as "the global network used to deliver products and services from raw materials to end-customers through an engineered flow of information, physical distribution, and cash." This supply chain network provides a continuous path from dirt to the paying end-customer and operates through the integration of its three flows, namely, information, physical distribution, and cash [18]. According to supply chain operations reference (SCOR) model, each basic supply chain include five standard processes, namely: planning, source, make, deliver, and return [16]. SCOR chains can span from the supplier's supplier to the customer's customer [19]. The SCOR model is shown in Figure 1.

Each interaction between two execution processes (such as between source-make-deliver) is a "link" in the supply chain. Planning sits on top of these links and manages them [20]. Realistic supply chains have multiple end products with shared components, facilities, and capacities [21]. A focus on cash flow involves conceptual differences among supply chain management, logistics, and/or lean manufacturing [22].

Various dimensions of complexity that impact on supply networks are as follows: scale, technological novelty, quantity of subsystems components, degree of customization of components in the final product/service, quantity of alternative design and delivery paths, number of feedback loops in the production and delivery system, variety of distinct knowledge bases, skills and competencies incorporated in the product/service package, intensity and extent of end-user involvement, uncertainty and change of end-user requirements, extent of supplier involvement in the innovation and transformation process, regulatory involvement, number of actors in the network, web of financial arrangements supporting the product/service, and extent of political and stakeholder intervention [23]. Wider product variety, smaller production lot sizes, more tiers, and different actors involved in coordinated supply chains also cause supply chain complexity [5]. Complexity is a key driver for failure of synchronization among material, information, and cash flows across business processes [2].

To analyse strategic logistic and supply chain management systems, Meade and Sarkis [24] used graphical representation of supply chain entities and relationships between the entities. Christopher [15], Scott and Westbrook [25], and Christopher and Gattorna [26] used supply chain mapping to represent structural (i.e., relatively enduring aspects of) supply chain processes and activities in support of the reengineering of supply chains.

2.2. Complex Systems Modelling Methods/Techniques

2.2.1. Enterprise Modelling (EM)

A model is "a representation of some aspects of an entity under study which can be used to facilitate visualization, analysis, design, and so forth" [27]. Enterprise models capture certain perspectives (or foci of concern) about an enterprise, such as financial, business, information, and function views. When formally modelling any complex system, it is necessary to decompose (or breakdown) the system into manageable system elements [28]. A model can provide insights into system capabilities and highlights alternative solutions and application scenarios that prepare the system to adapt to business change [29]. There are many potential benefits from using enterprise modelling in respect of the life cycle engineering of a manufacturing system [30, 31]. Modelling techniques can help to analyse alternatives and help analytically to determine new system configurations that best fulfil requirements change before any real system reconfiguration needs to be activated [32].

A number of public domain EM techniques are described in the literature that provide systematic means of decomposing and representing, at various levels of abstraction, the network of processes used by any subject complex system (or indeed system of systems). This enables subject networks of processes to be decomposed into their subprocesses and unitary activities; following which other representational concepts can be used to attach other modelled entities to the process representations. Example entities that can be attached in this way (and hence positioned relative system processes and activities) include related information requirements, information and decision flows, required resource system functionality and behaviours, needed material and product flows and resultant value streams, and processing costs. By formally decomposing a complex (specific, semigeneric, or generic) process network into descriptions of its elemental parts and their dependencies, subsequent systems integration aspects of organization design and change can be enabled [33].

It follows that the application of EM techniques explicitly captures and helps to communicate requirements for system design and captures structural (i.e., relatively enduring) relationships that govern interactions among the elements of complex systems. It follows that EMs do not really capture time-dependent interactions among system elements, although some efforts have been made to view enterprise models with respect to time [34].

Different enterprise modelling architectures have been developed and used around the globe to model and design manufacturing enterprises (ME). Well-documented example EM methodologies and architecture include ARIS: Architecture for Information Systems, CIMOSA: Computer Integrated Manufacturing Open Systems Architecture, GERAM: the Generalised Enterprise Reference Architecture and Methodologies, GRAI/GIM: the Graphs with Results and Activities Interrelated/GRAI Integrated Methodology, IEM: The Integrated Enterprise Modelling, and PERA: The Purdue Enterprise Reference Architecture. CIMOSA is considered as a comprehensive EM architecture and is used for more than two decades by the authors and their colleagues in the Manufacturing Systems Integration Research Institute at Loughborough University [35].

2.2.2. Causal Loop Diagramming (CLD)

Causal loop diagrams (CLDs) are very commonly used to characterise system dynamics as they are easy to understand and can be used to show and explain the impacts of different feedback structures on dynamic behaviours of subject systems [36]. In this way, hypothesis about the causes of dynamics can be developed and theoretically tested. Essentially CLDs capture and visually represent the mental models used by individuals and teams [37]. It is a way used for communicating ideas and rationale that a modeller believes are responsible for a problem [37]. A causal loop diagram can show explicitly the direction and type of causality among major factors that influence a subject system [38]. Causal loop diagrams are flexible and useful for diagramming the feedback structure of systems in any domain. Causal diagrams are simply maps showing the causal links among variables with arrows from a cause to an effect [37]. It is important to mention that these diagrams capture the structure of the system and not its behaviour [37].

Any CLD should contain a careful selection of variables which are decided on the basis of the observed issue. The use of interviews, surveys and archive data relating to the enterprise issue under observation can be of great importance. These interviews are typically either structured or semistructured in which useful views of the people involved in the issue(s) give rise to understandings about causal variables [37]. Relationships in the causal loop diagram must be causal and not corelational. Correlation among variables shows the past behaviour of the system only and do not represent the structure of the system. Rather correlations among variables will influence the outcome from behaviour of the model after simulation. If there is an existing correlation in the enterprise among some widely different variables which are not causally related, their inclusion within CLDs must be avoided [37].

Limitations of causal loops are that these can never be comprehensive and should not be because "effective modelling" is the art of simplicity [35]. These are also never final, but always provisional. These maps evolve as the understanding of the modeller improves and as the modelling effort evolves. Causal loop diagrams do not distinguish between stocks and flows but are often helpful in this respect as they encode aspects of a stock and flow structure [37].

2.2.3. Simulation Modelling (SM)

Simulation modelling has been widely deployed in many disciplines to replicate and predict behaviours. However, in general, it is known that because simulation models need to encode both static and dynamic properties of systems then their complexity grows rapidly as either the scope or depth of modelling increases. Therefore, their practicability will depend upon a suitable matching of level of modelling abstraction to the problem being tackled [33]. Simulation modelling has been shown to be useful for capturing dependences among design elements of manufacturing organizations that change with time [39, 40]. During simulation modelling experiments, system behaviours can be compared with reference to selected performance measures [35].

Normally when simulation modelling is performed, a suitable simulation tool is required. Different simulation tools are available like SIMUL8, Arena, and iThink. Today's discrete event simulation modelling tools provide behaviour analysis capabilities which can predict system outcomes with reference to selected system performance measures [41, 42]. It provides means of computer executing discrete event simulations. SIMUL8 is a user friendly tool as it provides a simple pick and place approach to creating graphical and computer

executable models [43]. Different types of entities need to be modelled including work entry points, work centres, and work exit points each with a range of attributed properties that correspond to real conditions of an enterprise [35]. It is, therefore, necessary to populate attributes of the simulation model with specific case enterprise data and rules in order to replicate real working conditions of the enterprise. SIMUL8 also provides optional links to Microsoft Excel sheet data and also different checks and conditions can be applied when different simulated events occur [44].

2.3. Discussion and Gap Analysis

From the forgoing discussion and recent literature reviewed, the authors observed that graphical representation and mapping of complex supply chain has provided a key first step when reengineering complex supply chains and that it has been widely used for analysis and reengineering of complex supply chains. Particularly, for example, process mapping is very widely used by the providers of IT systems used to underpin supply chain integration and operation. Christopher [15], Scott and Westbrook, [25] and Christopher and Gattorna [26] separately report on their use of supply chain mapping to visualise their thinking when reengineering supply chains. Also Meade and Sarkis [24] used graphical representation of supply chain entities to support the strategic analysis of logistic and supply chain management systems.

Notwithstanding an apparently growing use of process mapping as a first step towards achieving various forms of supply chain reengineering, it is evident that graphical representation and mapping can only qualitatively analyse structural and relatively enduring characteristics of complex systems such as supply chain systems and supply chain systems of systems [33]. Quantitative analysis of the dynamic behaviours of supply chains can also provide a vital step towards virtually testing and comparing the design of current and possible future supply chain configurations; as time-based simulation can provide important information about ways of improving the performances of supply chains without making in appropriate investment risks [45]. Therefore, both static and dynamic analysis of the complex supply chain is required to be included in analytical design of complex supply chains. Furthermore, the authors observed that these two forms of analysis should be carried out in a coherent and synergistic manner at all needed levels of modelling abstraction needed to support reengineering decisions made.

Based on the forgoing, Figure 2 was constructed by the authors to conceptualise the need for the research reported in this paper, the current state of the art in modelling solution techniques that can contribute towards satisfying that need, and potential solution technologies that can be developed, and their application systematically integrated, to bridge the current gap in current industry provision when modelling complex supply chains.

Keeping in view the above requirements, an integrated methodology for the design of complex supply chains is needed which can address both static and dynamic aspects of any subject complex supply chain. The authors proposed that such a methodology should have the following capabilities.

(i) To graphically represent and explicitly describe key characteristic properties of complex supply chains.

(ii) To analytically explore dynamic properties of complex supply chains, so as to provide analytic means of reasoning about impacts of uncertainty in complex supply
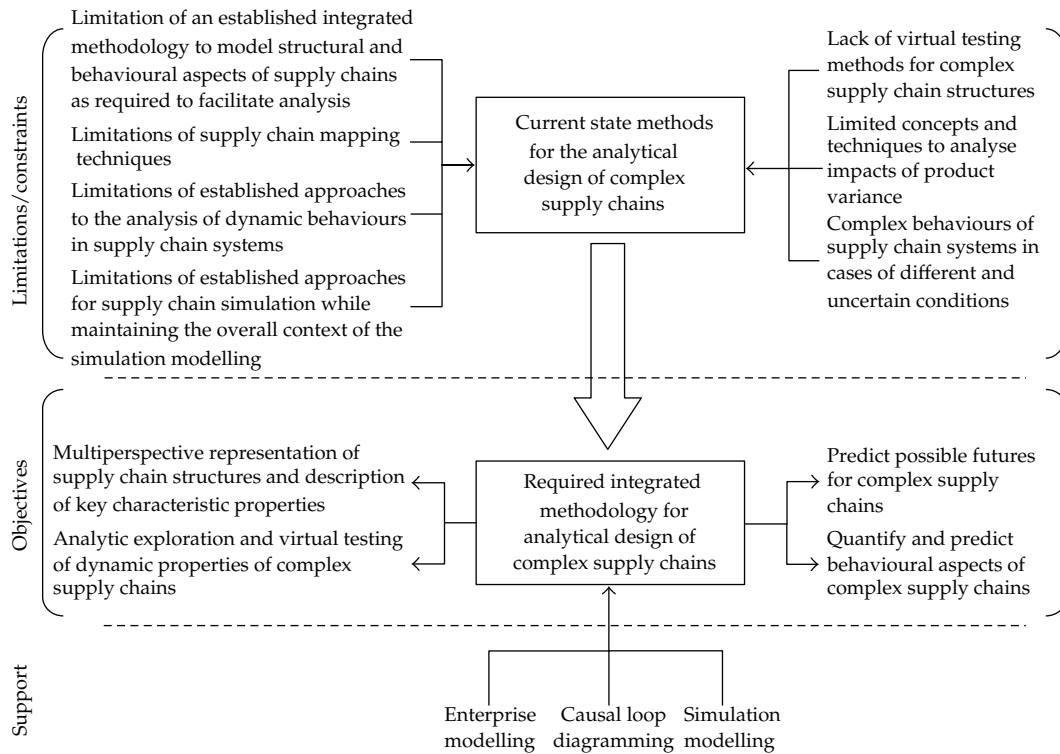
Figure 2: General review for research need.

chains, such as those introduced due to changes in demand, supply, make, delivery, and return processes.

(iii) To quantify and predict behavioural aspects of complex supply chains, so as to observe impacts of uncertainties and to assess possible risks should potential uncertainties arise; hence, a need to predict the reachable time-based behaviours of different supply chain structural configurations leading to improved supply chain performance and reduced the risk when justifying/making investments in new or changed supply chain systems.

3. Design of an Integrated Methodology for Analytical Design Complex Supply Chains

A number of different enterprise modelling (EM) techniques have been used by industry and academia to represent businesses and companies from various perspectives. These EM techniques can capture and enable the reuse of knowledge normally distributed amongst many knowledge holders who have various company and business roles. The kinds of knowledge that can be captured within an EM include relatively enduring models of processes, information, material flows, human and technical resources, and cash flows inside any subject enterprise [7]. A primary constraint on the application of any EM technique is its focus on modelling structural rather than time-dependent behavioural characteristics of the enterprise. This is, however, a necessary constraint on EM techniques as their prime

purpose is to capture a big picture of an enterprise and to decompose this big picture into essentially decoupled elements so that subsequently those elements can be analysed in detail within the specific context defined by their parent EM [33]. Therefore, the inclusion of both structural and behavioural aspects into the big picture would make any developed EM overly complex. However, the literature review also showed the importance of modelling dynamic, time-dependant characteristics of supply chains to enable performance prediction and measurement when alternative candidate supply chain configurations are conceived and developed [45]. With this second modelling purpose in mind, it was observed that causal loop diagramming and simulation modelling are capable of modelling time-dependant characteristics of complex systems such as complex supply chains. However, prior to the authors present research, the literature had not reported on ways of synergistically deploying EM, CLD, and SM in a coherent fashion to support the lifecycle engineering of complex supply chains. Hence, the exploration and development of such a coherent use was the subject of this research.

3.1. Potential Use of the Enhanced CIMOSA-Based MSI Technique

During the 1990s, various researchers in the Manufacturing Systems Integration (MSI) Research Institute at Loughborough University developed a CIMOSA-based enhanced enterprise modelling technique which can usefully be used to explicitly represent and decompose a "big picture" of the network of processes used by any enterprise. The extended CIMOSA modelling technique can also facilitate the detailing of structural aspects of some focused shop floor section of that ME or alternatively allow abstract representations of the ME and its complex supply chain domains to be developed and used as a basis for collective qualitative analysis.

Selection of the scope and focus of enterprise modelling depends on the purpose and the context of the current modelling exercise and particularly on what the enterprise model is to be used for short or long term. The big picture of enterprise processes can be created so as to encode various perspectives of the ME, which will be of concern to potential or specified model users. The perspectives may include processing and activity requirements, flow controls, information, physical (material) and human resources, and cash flows. The big picture can be created for one or more specific "contexts," and this helps to maintain a focus of the modelling work such as, in support of operational, tactical or strategic change projects. The extended CIMOSA EM building is carried out using four kinds of CIMOSA-MSI diagramming templates, namely, "context diagram," "interaction diagram," "structure diagram," and "activity diagram." Essentially these models can be used to visualise the processing requirements of an enterprise; namely, (1) the operational process network that is realised by the subject ME so that it adds value to "products" and "services" needed by "customers" and/or (2) those enterprise transformation processes that are or could be realised by the subject enterprise in order to maintain the currency (and hence efficacy) of its operational network of processes. CIMOSA-MSI enterprise modelling can be used to help identify and represent different actors and stakeholders involved and interactions between those actors centred on the flow of information, materials, and cash; thereby, it can explicitly represent the structure of the interacting processes and logical flows of processes. For the above reasons, enterprise modelling was selected by the present authors as a best in class technique to statically model, represent, and visualise a "big picture" of complex supply chains from the point of view of "defining the processing requirements" of any

specific ME or indeed semigeneric processing requirements of any subject group of "similar" MEs.

3.2. Causal Loop Diagramming (CLD)

Also described in the preceding literature review, causal loop diagramming can be used to understand and represent system dynamics associated with causal relationships that link different variables of complex systems. Change in system variables can affect other associated variables with a positive or a negative effect on behaviours of the complete system. Therefore, causal loop diagramming was also selected as a technique to be used as an integral part of a set of modelling approaches aimed at understanding and assessing the dynamics of complex supply chains. Here, it was presumed that causal loop diagramming would enable qualitative understandings to be developed about complex supply chain behaviours, when any given supply chain is subjected to uncertain conditions caused by change in selected variables where the source of those changes may be external to, or internal to, the system being studied. For example, change in demand, change in supply, change in resource availability, change in plant performance, change in production and inventory management, change in delivery, or indeed change in some "mix" of these different variables.

3.3. Simulation Modelling (SM)

Also observed in the preceding literature review was that simulation modelling can be used to computer exercise and graphically visualise time-based "flows" through complex supply chain "processes" and "resources;" thereby, it can predict and quantify likely outcomes from different what-if scenarios. For different combinations of uncertain conditions, different resource configurations can be tested and results can be quantified. In this regard, the suitability of industry best practices can be analysed, as can new emerging manufacturing paradigms (from academia and industry) in any specific case enterprise. Furthermore, it is presumed that quantitative results from using simulation modelling can be helpful to predict future behaviours of complex supply chain and can support analysis leading to improvement in any given supply chain design. However, it was also clear that some systematic stepwise technique of applying simulation modelling would be needed to undertake complex supply chain modelling which in general will involve interaction between many dependent variables on a large scale. Both discrete event simulation (DES) modelling and continuous simulation (CS) modelling could prove useful, so that both were selected as key contributors to an integrated complex supply chain analysis methodology which can graphically visualise and quantify behaviours of work flows through alternative complex supply chains. Selection between DES and CS modelling techniques depends on the requirements of simulation. For instance, if the requirements of simulation are to simulate a scenario at a high level of abstraction or for taking a policy decision in a complex supply chain, then CS is expected to prove most appropriate. While to implement the policy and to verify its impacts on operational level activities, DES is likely to prove most suitable. Also expected was that simulation modelling would quantify aspects of complex supply chain behaviours under different uncertain changes with this could help to quantify aspects of associated risks, such as when virtually testing the introduction of a new policy or when purchasing new supply chain systems in response to a changing scenario.

Table 1: Key observations about use of different modelling techniques.

Concept reviewed	Summary of purpose	Observations/limitations
Enterprise modelling (EM)	The CIMOSA EM architecture has been used by many researchers around the world and extensively in MSI to capture the big picture of the processes of an enterprise operating within a specific business context	EM techniques explicitly capture and help to communicate requirements for system design and capture structural (i.e., relatively enduring) relationships that govern interactions among the elements of complex systems. EMs do not really capture time-dependent interactions among system elements
Causal loop diagramming (CLD)	CLD has been widely used to capture mental models of systems subjected to different dynamic situations presented in terms of cause and its effects	Causal Loop modelling can facilitate representation and understanding about complex system dynamics. However, on its own it cannot quantify issues numerically
Simulation modelling (SM)	Simulation modelling is widely used by industry, commerce, and government to simulate different what-if scenarios and numerically quantify different performance variables	Small process portions of an enterprise can be simulated precisely, but as the size of model grows it become too complex and degree of precision decreases. Large process portions of an enterprise can be simulated at abstract level. Generally though current best practice simulation modelling is typically carried out in a piecemeal/stand alone way
Combined use of EM, CLD, and SM	Research has previously been conducted at MSI to unify EM, CLD, and SM to address different problems and support decisions within manufacturing enterprises	Ways of synergistic deployment of EM, CLD, and SM in a coherent fashion to support the lifecycle engineering of complex supply chains had not reported prior to the presentation of this research

3.4. Integrated Application of EM, CLD, and SM Techniques

Furthermore, the preceding literature review has shown that in other complex system domains significant benefits have arisen from applying enterprise modelling, causal loop diagramming, and simulation modelling techniques in an integrated fashion, thereby providing an analytical basis for underpinning key aspects of large-scale organization design and change (OD&C). However, in view of the context of this study, it was necessary to scope and focus an integrated use of these modelling approaches, by specifying and testing their systematic use as potentially widely applicable methodology which supports analyses needed by relevant actors as they engineer aspects of complex supply chains of concern to them.

Table 1 was constructed to summarise the intended purpose of the modelling techniques selected as base technologies to realise an integrated methodology for the analytical design of complex supply chains.

Based on the key observations presented in Table 1 about their potential to fulfil the required characteristics of an integrated methodology for the analytical design of complex supply chains, the candidate modelling techniques presented in Figure 2 were selected.

Figure 3 shows a static match between the required characteristics of an analytical design methodology for complex supply chains and state-of-the-art candidate techniques

Supply chain representation and visualisation	Supply chain issues/ characteristics description	Understanding supply system dynamics	Supply chain uncertainty qualification	Supply chain qualitative behaviour prediction	Supply chain quantitative analysis
Enterprise modelling (EM)	EM and candidate technique to describe issues ??	Causal loop diagramming (CLD)	Causal loop diagramming (CLD)	Causal loop diagramming (CLD)	Simulation modelling (SM)

Figure 3: Required supply chain analysis characteristics and its candidate techniques.

Table 2: The domain table.

		Domain table for CIMOSA-conformant domain(s)-DM			
	DPs and BPs	Domain issues related to enterprise modelling entities			
		Information	Physical	Human	Financial
DPs	BPs	**	**	**	**
	BPs	**	**	**	**

**Description of issue(s) with reference to related EA(s).

currently developed and used by different manufacturing enterprises. Selected EM, CLD, and SM techniques can provide some of the modelling capabilities required to develop an integrated analytical methodology for complex supply chains. However, to unify the use of these modelling techniques it was necessary for the authors to define characteristic entities of supply chains along with a suitable set of modelling concepts that can be implemented using the candidate technologies of Figure 3 to (a) explicitly represent organising structure of those entities and their interrelationships and (b) computer execute (and hence virtually test) reachable behaviours of selected entity configurations used to characterise subject supply chains. To define these characteristic "supply chain entities," "their interrelationships," and "their associated modelling concepts" the authors built upon the modelling concepts previously defined by CIMOSA-MSI diagramming templates. This thinking was facilitated by adopting the use of a so-called "Domain table." The domain table "relates" data entities which parameterise supply chain properties from different perspectives associated with information, physical (material), financial, and human aspects. The general structural design of such a domain table is illustrated in Table 2.

The designed purpose of using the domain table is to explicitly list and describe issues, bottlenecks, and potential improvements for any CIMOSA conformant domain (which is an entity or part of an entity selected for in-depth modelling and analysis). These issues will be shown in a structured way by maintaining these under specific categories, namely, information, material, human, and financial. Table 2 illustrates domain processes "DPs" which can comprise "sourcing," "making," "delivery," "returning," and "planning" processes, as defined by the SCOR model [16]. Business processes "BPs" are subprocesses of a DP. For example, for a specific making domain process, BPs could be machining, inspecting, and packing processes. With the use of the domain table forming an integral part of enterprise modelling, the subsequent use of causal loop diagramming and simulation modelling can be systemised, when analyzing a complex supply chain.

Hence, it is assumed that a synergistic use of enterprise modelling, causal loop diagramming, and simulation modelling, with their key integration aspects realised and explicitly defined by the domain table, can usefully support the analytical design of complex
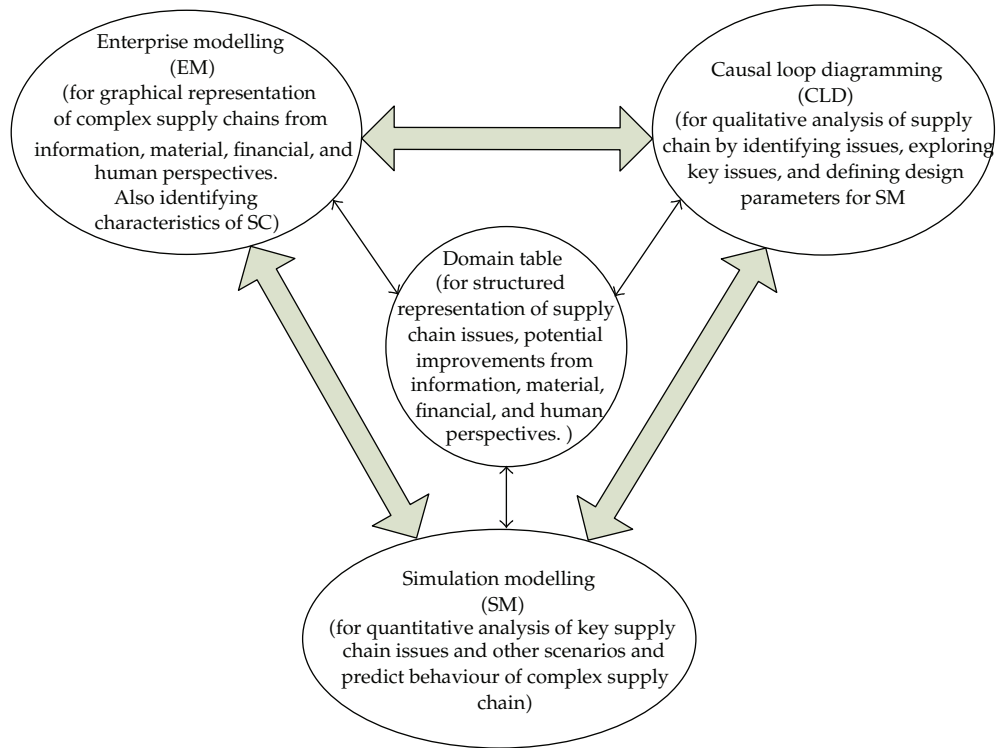
Figure 4: The integrated methodology for analytical design of complex supply chains.

supply chains. This constituted an enhancement of the modelling methodology previously proposed by Chatha and Weston [46] and Weston et. al. [47], and by so doing focused integrated modelling on supply chain analysis. The integrated methodology for analytical design of complex supply chains developed via this line of reasoning is conceptually represented by Figure 4.

A brief description about the role of each element of the integrated methodology for the analytical design of complex supply chains (shown in Figure 4) and an overview of synergistic aspects expected from achieving integrated modelling are presented below.

(i) Standard CIMOSA enterprise modelling constructs are implemented via the MSI graphical approach to enterprise modelling in order to facilitate the creation of holistic enterprise models of complex supply chains. This enables the explicit and graphical definition of "big picture" models of supply chain configurations, so as to capture the knowledge of relevant ME personnel in the form of relatively enduring structural dependencies between supply chain entities. These supply chain models are holistic because they can capture end-to-end supply chains at required levels of abstraction needed to support various kinds of supply chain engineering decision making. Hence, this kind of "big picture" EM will become a source of understanding about different supply chain entities/actors, different processes included in the entities, interaction of the processes with in the entities and outside the entities from various perspectives of information, physical (material), finance and human, structure of processes associated with the entities, and flows of

the processes from customer order to the supply of desired product/service in a given supply chain. Further, the "big picture" EM will become a source of explicitly modelled understandings that can help to unify the use and indeed reuse of the other selected modelling technologies listed into Figure 3.

(ii) Following which the domain table will be fleshed out for specific case supply chains, to capture attributes of issues related to selected domains identified during CIMOSA-based enterprise modelling. These tables will cover data from different perspectives associated with information, physical (material), financial, and human entities which are used for enterprise modelling of the CIMOSA conformant domain(s).

(iii) The causal loop diagramming (CLD) technique is then used to understand and represent causality associated with specific supply chain dynamics. CLD is used to explore the likely impacts of key causal effects related to the issues represented in the domain table. The resultant causal loops will provide a source of qualitative exploration of supply chain dynamics under different uncertain conditions within the context defined by enterprise modelling. Also causal loops are used for designing parameters associated with needed simulation experiments which subsequently are used to quantify supply chain dynamics related to key issues of concern to that enterprise.

(iv) Simulation modelling will be used to quantify and visualise dynamic supply chain processes and different flows through supply chain entities. The key issues identified by the causal loop diagrams will be focused with a view to quantification using simulation modelling. Also, much of the structural relationships linking the entities encoded into simulation models will be inherited from the EM. Business processes or enterprise activities related to the key issues will be found from the domain table. When designing and developing the simulation models, CIMOSA-based graphical models will be used to view specific process segments found from the domain table. Simulation model design parameters will be deduced from a study of the causal loops. Design parameters will include variables and performance parameters relative time-based behaviours of which need to be quantified during simulation modelling experiments. Simulation modelling will be performed by using computer-based simulation modelling tools. Either a discrete event simulation (DES) or a continuous simulation (CS) or both can be used. The selection of the simulation technology depends on the problem to be simulated. For example, simulations at a high level of abstraction in support to make policy level decisions for complex supply chains like selection of suitable paradigm in complex supply chains, size of inventory required in case of a selected paradigm, inventory turnover for selected paradigm and, CS can be used. For problems where in-depth details are required to be modelled and the implementation of the policies are required to be tested for different small segments of the whole supply chain, DES can be used.

4. Research Approach Adopted to Case Study Test the Integrated Methodology for Analytical Design of Complex Supply Chains

A systematic use of the integrated modelling methodology for the analytical design of complex supply chains is presented in Figure 5, which was devised and subsequently
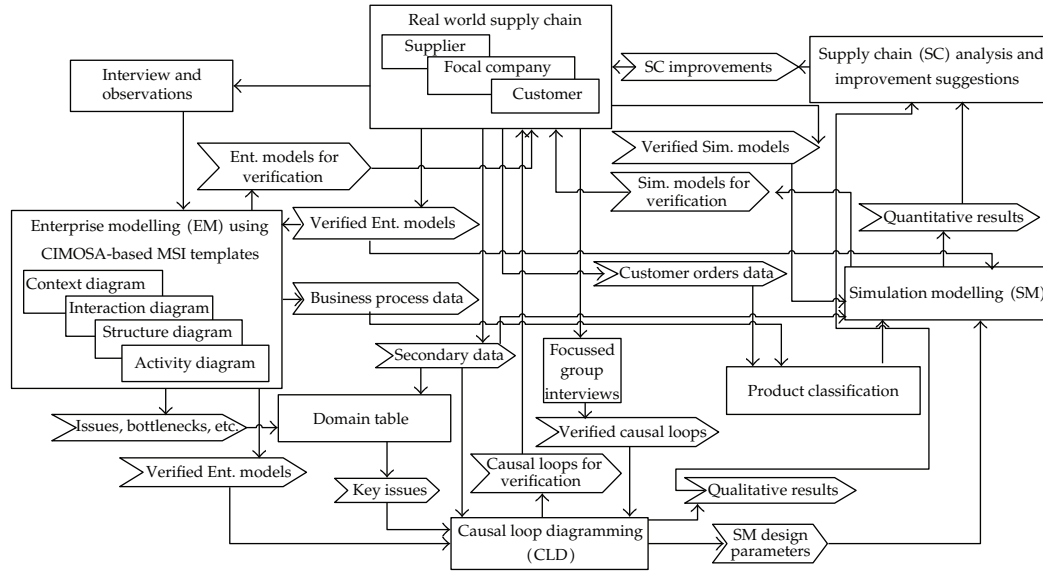
Figure 5: Research approach to using the integrated methodology for analytical design of complex supply chain.

deployed when modelling the supply chains of two real case MEs. This figure illustrates that when creating an enterprise model of a real world supply chain, specific data about the organisational structures currently used needs to be elicited by conducting focussed group interviews of relevant knowledge holders of the supply chain and via shop floor walk-through and observations made by the modeller. The model so constructed will be in the form of multiple instances of four kinds of diagrams (namely, context diagrams, interaction diagrams, structure diagrams and activity diagrams) which are populated with specific supply chain data. The validity of the enterprise model developed in this way needs to be verified by relevant knowledge holders. Following which supply chain problem issues can be discussed with relevant ME personnel, and the knowledge gained can be related to organisational structures depicted by the developed enterprise model. Secondary data related to those problem issues can be used to populate the domain table with a defined focus for later supply chain dynamic modelling. Verified enterprise model and key issues encoded into the domain table then provide key inputs for the development of causal loop diagrams. To verify the validity and focus of causal loop diagrams, focussed group interviews with the supply chain knowledge holders need to be carried out. Outcomes of the causal loops are qualitative results about key causalities that will likely impact on specific supply chain behaviours along with key design structures and parameters needed to develop one or more simulation models. At this stage, an "in context," "fit for purpose" simulation model can be conceptually designed, then implemented, by using the big picture captured by the enterprise model along with outcomes from causal loop modelling and by gathering related facts and figures about the operations of the supply chain. The behaviours generated by the simulation model(s) also need to be verified by the supply chain knowledge holders. Via simulation, known behaviours of current supply chain configurations can be replicated (such as in response to known scenarios of operation), and possible future behaviours of new supply chain configurations and/or new operational scenarios can be predicted. In this way

quantitative testing can underpin scientifically based analysis and design of complex supply chain and investment risks can be much reduced.

A list of instructions which should be followed when applying the proposed methodology is documented into Table 3. This table includes guidelines for the application of each step of the methodology, the data collection method recommended for each step, and expected outcomes as a result of the application of each step.

5. Novelty and Potential Benefits of the Integrated Modelling Methodology for Analytical Design of Complex Supply Chains

The integrated use of EM, CLD, and SM along with the synergistic application of the domain table constitutes a new systematic way of analysing and designing complex supply chains, which considers both structural and behavioural view points in a coherent fashion. The novelty of this systematic approach stems from three main things: (i) its synergistic use of modelling concepts implemented via the domain table, which glues together the use of alternative modelling technologies in complex supply chain domains to provide an explicit description of issues, bottlenecks, and potential improvements, (ii) it constitutes a new combination of EM, CLD, and SM techniques which can be systematically applied, and (iii) it is targeted at the focused field of supply chain analysis for which no previous analysis methodology of equivalent coverage existed.

The first author's Ph.D. thesis describes in two real case supply chains the virtual testing of the "Design and realisation of an integrated methodology for the analytical design of complex supply chains" [7]. It is recommended that the reader wishing to apply the methodology in a supply chain for which they are responsible should study the case study models developed and described in that thesis.

6. Conclusions

The main aim of this research was to "to develop an integrated methodology for analytical design of complex supply chains." The capabilities envisaged for this methodology were as follows.

(i) To graphically represent and explicitly describe key characteristic properties of complex supply chains.

(ii) To analytically explore dynamic properties of complex supply chains, so as to provide analytic means of reasoning about impacts of uncertainty in complex supply chains, such as those introduced due to changes in demand, supply, make, delivery, and return processes.

(iii) To quantify and predict behavioural aspects of complex supply chains due to observed impacts of uncertainties and to assess possible risks potential uncertainties should arise.

Previous existing integrated modelling methodologies were also reviewed that were previously designed to integrate the use of different modelling techniques in other manufacturing system domains. Analysis of the reviewed work showed that no integrated methodology suitable for modelling complex supply chains which can fulfil the set of capabilities required to analytically design complex supply chains. Based on the required

Table 3: Guideline for the application of the integrated methodology for case complex supply chain.

Steps of integrated methodology	Step description	Guideline for application	Data collection method	Expected outcome
Enterprise modelling	Create enterprise model for graphical representation of the focussed enterprise and its complex supply chain	(i) Use the four CIMOSA-MSI enterprise modelling graphical templates and populate these with data of the focussed enterprise and its complex supply chain (ii) Verify the enterprise model from the related knowledge holder in the complex supply chain (iii) Use the verified enterprise model for graphical representation and static structural analysis of the complex supply chain	(i) Introductory visits and shop floor walk-through of the focal enterprise (ii) Semistructured focussed group interviews of complex supply chain knowledge holders (iii) Participant observations	Verified enterprise model in the form of "Context diagram," Interaction diagram," "Structure diagram," and "Activity diagram" representing big picture of processes of the focal enterprise and its complex supply chain
Domain table	Create the domain table for explicit description of the issues of focussed enterprise and its complex supply chain	Use the standard template of the domain table and populate it with the data about observed issues of the focussed enterprise and its complex supply chain	(i) Data collected for creating enterprise models (ii) Some secondary data like quality and performance records	A domain table explicitly representing issues of the focussed enterprise and its complex supply chain
Causal loop diagramming	Create causal loop diagram(s) to understand dynamics about some important issues of complex supply chain	(i) Construct causal loop diagram(s) for some important issues of the complex supply chain (ii) Verify the causal loop diagrams from the related knowledge holder in the complex supply chain (iii) Use verified causal loop diagrams for qualitative analysis of complex supply chain and define KPI's for performing simulation modelling	(i) Information and understanding already conceived focussed group interviews, and participant observation of complex supply chain knowledge holders	Verified causal loop diagram(s) created for some important complex supply chain issues, exploring and presenting dynamic issues of complex supply chain related to the issues and in a way defining KPI's for simulation modelling
Simulation modelling	Create simulation model to numerically quantify important issues of complex supply chain and predict future behaviour of the complex supply chain in that case	(i) Construct simulation model for the related process segment of the complex supply chain (ii) Validate the simulation model from the relevant knowledge holders of the complex supply chain (iii) Use the validated simulation model for the numerical quantification of the complex supply chain issues and predict future behaviour of the complex supply chain	(i) Complex supply chain process information presented in the "Activity diagrams" (ii) Key performance indicators presented by the causal loop diagramming (iii) Some secondary data like process duration, work flows, resource utilization, and availability	Validated simulation model for a related process segment of the complex supply chain, which can be used for the quantitative analysis of the important issues of complex supply chain

capabilities, an integrated methodology for analytical design of complex supply chains is developed. To use the methodology, a graphical approach is illustrated and a detailed step by step guideline is presented which include guideline for application of each step of the methodology, data collection method for each step, and expected outcomes as a result of application of each step.

The integrated modeling methodology for analytical design of complex supply chains is case tested for supply chains of two case enterprises, that is, a UK's leading Point of Purchase (POP) equipments manufacturing enterprise, namely, Artform International and a service enterprise providing parking and valeting service at a UK airport. Results of both case studies show usefulness of the integrated modelling methodology to analyse selected issues of the supply chains and thereby help in suggesting changes in supply chains design.

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