 doi:10.20944/preprints201904.0160.v1

University of Oxford

Digital Supply Chains for Industry 4.0

Taxonomy of Approaches

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Engineering the supply chain requires a design that possesses the flexibility of a complex adaptive system, consisting of interlinking architecture, with external dimensions and system germane internal elements. The complexity of the subject, the multiple environments, dimensions, elements and concepts, require a research that does not set any limits to the conceptual, analytical or empirical nature of the existing approaches present in practice. This present the rational for applying a taxonomy approach to investigate the integration engineering of supply chain architecture, design and engineering, and building a framework for integrating the existing supply chain approaches.

The objectives of this paper are to critically analyse the key supply chain concepts and approaches, to assess the fit between the research literature and the practical issues of supply chain architecture, design and engineering, and to develop a methodology that could be used by practitioners when integrating supply chain architecture and design with strategy engineering.

Taxonomy approach is applied to consider criteria for strategy architecture, hierarchical strategy design, strategy engineering, and integration of supply chain architecture, design and engineering as a conceptual system. The results from this paper derived with the findings that the relationship between supply chain architecture, design and engineering is weak and challenges remain in the process of adapting and aligning operations.

This paper also derived with a novel approach for addressing these obstacles, based on a new methodology. The novelty that derives from this paper is a methodology for integrating supply chain architecture, design and engineering, with criteria that enable decomposing and building a digital (new and non-existent) supply chain as a system. The paper revealed a number of tools and mechanism which enabled the development of a new methodology for integrating the architecture, design and engineering of a supply chain. The review derived with improvements to current and existing theories for analysing interdependencies within and between their individual contexts. This issue is addressed with a hierarchical method for network design, applied for building and combining the integration criteria.

Introduction

The area of research for this paper is the field of supply chain architecture, design and engineering, in a digital (new and non-existent supply chain) and integration context. To evaluate the present approaches in supply chain practice, the paper begins with a review of existing supply chain models, which cover the relevant aspects in the context of digital supply chain integration. The research areas reviewed in the paper are: supply chain architecture, supply chain design, supply chain engineering, and supply chain integration. There is a vast number of developed or proposed supply chain models focused on one or more specific research areas. The objective of this paper is to group the factors in recognisable clusters and to derive with a new set of principles for digital supply chain architecture, design and engineering.

Research Objectives

The research problems investigated are related to integration of supply chain architecture, design and engineering. The research objectives of this paper are:

1. To derive with a set of principles for a digital supply chain architecture with multiple supply chain participants.
2. To derive with set of principles for digital supply chain integration design.
3. To develop a supply chain engineering principles based on the architecture and design criteria for systematically integrating individual activities towards pre-defined digital integration areas.

To relate the criteria to the methodology, a hierarchical concept map and conceptual diagram are applied. The objectives of the paper are oriented around external and salient dimensions, which directly affect the supply chain architecture, design and engineering and consist of elements, forces and factors.

Structure of the paper

This paper is structured in the following order: **firstly** the research aim and objectives are defined, along with the rationale for the study; **secondly**, the reasoning behind key tenants of the methodology are discussed in detail, with specific observations from existing literature on this topic. This step relates the key tenets to existing literature and elaborates on the benefits from this methodology to practitioners and academics in the fields of supply chain management; **thirdly**, the methodology that derived from this study is presented (Figure 1) followed by the principles key (Table 1) containing the full list of abbreviations of the key tenets; and **finally**, the emerging principles are analysed to clarify how the key tenets are applied to the new methodology for engineering the digital supply chain architecture and design.

Taxonomy of Approaches

The literature review is focused on revealing the tools and mechanisms that enabled this paper to derive with a principles for digital supply chain integration architecture, design and engineering. The objective of this literature review is to analyse the key tenets that enabled the architecture for inter-relating supply chain operations.

Digital strategic integration

The process of merging distinct digital operational areas into the supply chain area, creates an urgency to integrate the information and physical flow into relationships that link these areas and fosters 'trust and commitment' (TC) with supply chain partners (Bozarth et al., 2009). Pathak et al. (2007) designed a set of principles based on TC, however, the principles would benefit from being tested with case study and action research, in a similar way that other frameworks combined such methods (Martínez-Olvera and Shunk, 2006, Martínez-Olvera, 2008, Narasimhan et al., 2008, Perez-Franco et al., 2010). In addition, these frameworks would benefit from criteria to evaluate and measure performance of integrating supply chain participants into a 'networked organisation' (NO) (Sukati et al., 2012). Where performance depends on 'identification of best candidates (IBC) (Lee and Billington, 1992), and requires measurement system for 'interdependence and organisational compatibility' (IOC) in supply chain design (Beamon, 1998).

Characterising digital integration

'Supply chain strategy integration' (SCI) is described as a 'single entity system' or a 'confederation' (Mentzer, 2001) and a 'networked organisation' (Ivanov, 2009). The 'single entity system' should be focused on 'capturing the essence and forecasting the effect' of supply chain integration and performance (CEFE) (Mentzer, 2001), through combining resources and capabilities (Narasimhan et al., 2008). In addition, to 'characterise greenfield supply chain strategy and integration' (CGSI) the functional activities should be investigated to identify actual instead of desired strategy outcomes (Cigolini et al., 2004).

Strategic integration represents an effective method for implementing strategic choices and further research is required to include the 'architecture implementation' (FI) in integration (He and Lai, 2012). To address this, an algorithm has been described for selecting best supply chain integration strategy through separation in 'space, time, parts and conditions' (STPC) for scenarios when problems occur (Nikulin et al. 2013). The soundness and the logic behind (Nikulin et al. 2013) approach could be applied as a tool to build upon a methodology for supply chain strategy architecture. Such methodology should embrace collaborative commerce and synchronisation of supply chain information flow, promoting flexibility and effectiveness (Kim, 2006, Frohlich and Westbrook, 2001, Vickery et al., 2003, Manthou et al., 2004, Al-Mudimigh et al., 2004).

Categorising digital integration activities

Supply chain competences lead to diverse performance advantages in various business environments (Closs and Mollenkopf, 2004), but the same practices and patterns cannot be applicable in every industry context to achieve superior performance (Vickery et al., 2003, Van der Vaart and van Donk, 2008, Nikulin et al., 2013). Factors that improve performance in the context of supply chain integration and performance have been categorised into attitudes, practices and patterns (Van der Vaart and van Donk, 2008). The relationship between these clusters remains elusive and the number of 'architecture elements' (FE) and 'architecture concepts' (FCo), should be validated through further research. Formulating supply chain strategies in the context of 'digital architecture' (GF) with a singular focus on integration and performance (Frohlich and Westbrook, 2001), presents limitations (Rosenzweig et al., 2003, Perez-Franco et al., 2010, Childerhouse and Towill, 2011), because various supply chain aspects should be considered in the design and architecture stage, and supply chain integration activities have a unique set of benefits (Swink et al., 2007).

A holistic methodology for supply chain design (Melnyk et al. 2013) concluded that supply chain design must consider the 'external dimension' (ExD). The study recommended a process for uncovering the various pieces that orchestrate the overall supply chain architecture and design, through investigating the 'underlying factors' (UF) and 'salient dimensions'(SaD), such as 'external elements' (EE), 'factors' (EFa), and 'forces' (EFo) (Melnyk et al. 2013).

Digital supply chain decomposition design

Supply chain design is a dynamic process and interdependencies should be analysed 'within' and 'between' in individual context (Dubois et al., 2004). One approach for building and combining the criteria is a hierarchical method for network design (Dotoli et al., 2005). This approach can be strengthened by building upon the principles from 'Analytical Target Cascading' in context of decomposing a complete supply chain hierarchical tree (Qu et al., 2010), similarly to 'decomposing supply chain into hierarchical tree' (DSCHT) (Schnetzler et al. 2007). The DSCHT combined with the techniques from the customer–product–process–resource (CPPR) (Martínez-Olvera and Shunk, 2006) and 'analytical target cascading' (ATC), provide the background for designing a new engineering method that would include the process of getting from the 'present to (the) required' stage (PR).

The design process could apply a 'conceptual approach for supply chain inter-organisational integration' (CSCIOI) (Perez-Franco et al., 2010). Alternatively, conceptual system can be verified with system dynamics and mathematical modelling (Ivanov, 2009), however, mathematical modelling could hardly calculate with precision the perceptions of the individual decision maker perceptions. Engineering systems literature integrated a system dynamics principles to decompose supply chain and tested the approach though dynamic analysis (Hafeez et al., 1996). The engineering system approach could be applied as a visualisation tool for presenting and interlinking multiple supply chain areas with external business dimensions (Lertpattarapong, 2002), but such approach could hardly comprehend the supply chain complexities and multiple variables in 'integration as a method for integrating strategic choices' (IMSC), leading to the conclusion that conceptual architectures and supply chain decomposition design are stronger visualisation tools.

Nevertheless, engineering design techniques such as the Pugh Controlled Convergence (Pugh, 1990), the Enhanced Quality Function Deployment (Clausing, 1992), the Design Structure Matrix (Eppinger et al., 1994) the Engineering System Matrix (Bartolomei et al., 2007), and the 'techniques tool matrix' (Cigolini et al., 2004), can be applied in combination with 'cascading strategy' (Narasimhan et al., 2008), to case study, action research and grounded theory to build the architecture, design and engineering of a supply chain strategy as a conceptual system (Perez-Franco et al., 2010). Such an approach can be combined with supply chain decomposition (Schnetzler et al., 2007) to address the 'architecture criteria' (FCr) problem.

Digital conceptual engineering

'Conceptual model' approach (CM) has been applied for strategy architecture to evaluate decision makers strategic goals (Cigolini et al., 2004, Narasimhan et al., 2008, Perez-Franco et al., 2010). 'Conceptual system for supply chain decomposition' (CSSCD), could integrate operational level employees to identify relationship between the vision and goals and for explaining the relationship between concepts (Platts et al., 1996, Menda and Dilts, 1997).

Ontological semantic alignment for digital design

Alternatively, an 'ontological approach can be applied for semantic alignment' (OASA) where knowledge elicitation, containing, mapping and merging should represent the foundations for adapting or aligning supply chain principles (Sakka et al., 2011). The process should conceptualise strategy as a system of choices, patterns or decisions to address the phenomenon of 'strategy absence' (SA) in strategy architecture (Inkpen and Choudhury, 1995). The process should start by reaching a consensus on the 'preliminary salient dimensions' (PSaD) and strategic objectives (Platts et al., 1996, Menda and Dilts, 1997). The process can be further clarified by applying 'architecture criteria' (FC), such as: procedure, process and participation, which require communication mechanisms to enable concept understanding (Inkpen and Choudhury, 1995). The concept understanding should apply design 'integration criteria' (EC) through systematic innovation (Sheu and Lee, 2011), as a method for distilling innovation to strategy. However, strategy absence must be addressed through the architecture criteria prior to applying the integration criteria, because systematic innovation brings strategy dynamics through the 'process chain and virtual eChain' (PC-VC) feedback mechanisms, whereas strategy absence effectively disables the feedback mechanisms and reduces the 'supply chain agility' (SCA).

The feedback mechanisms enable the process of: (1) anticipating the demand for a product, market standards and influencers, product variety and life cycle (Fisher, 1997); (2) investigating the internal and external factors (Narasimhan et al., 2008); (3) determine the supplier or customer focus and level of integration (Frohlich and Westbrook, 2001); and (4) enable building trust and commitment, or interdependence and organisational compatibility (Mentzer, 2001). These feedback mechanisms enable building upon the supply chain architecture criteria and until present, the architecture criteria has not been built upon and combined with the 'integration criteria' (EC): visibility (Inkpen and Choudhury, 1995, Fisher, 1997), acceptance (Saad et al., 2002), participation (Menda and Dilts, 1997, Zhou and Chen, 2001, Qureshi et al., 2009), communication (Tracey et al., 1999), formality (Andrews et al., 2009), adaptability (Sakka et al., 2011, Saad et al., 2002), integration (Bozarth et al., 2009), effectiveness (Fisher, 1997) flexibility (Kim, 2006) and responsiveness (Fisher, 1997). Building upon and combining the criteria would represent a novel contribution from synthesising existing knowledge for deriving new findings.

Digital supply chain engineering in uncertain environments

Further concerning findings in recent literature are the indications that supply chain engineering and competitive strategy are commonly not linked to the 'corporate strategy' (CS) (Mckone et al., 2009). Adding to these concerns are the findings that challenges still remain in the processes for 'adapting and aligning' (AA) supply chain engineering (Saad et al., 2002) and operations (Sakka et al., 2011). The strategy architecture represents a process of 'capabilities integration' (CE) and accepting the reality and acting upon that reality in a given business environment (Miller and Friesen, 1978). The supply chain engineering topic remains inconclusive and there are remaining 'barriers to change and approaches to overcome' (BCAO) (Mckone et al., 2009, Saad et al., 2002, Sakka et al., 2011).

In a similar context, various algorithms have been applied to several supply chain problems, however, in some environments the 'participants aims and objectives' (PAO) problem is larger than the test data and optimal solutions cannot be found in reasonable time frame (Lee et al., 2010) leading to 'strategy absence' (SA). Metaheuristic algorithms could in the future provide a solution for identifying optimal logistic solution for a supply chain (Griffis et al., 2012). Such a method would be useful for addressing the logistics as a specific problem in strategy architecture, but metaheuristics would hardly anticipate aspects such as the individual decisions of decision makers in the vast numbered dimensions in multiple business environments.

In this context, the conceptual system approach has been proven effective for 'supply chain strategy articulation' (SCSA) and optimal solution detection (Perez-Franco et al., 2010).

Supply chain efficiency of digital architectures

The process of determining the underlying factors of salient dimensions in supply chain engineering, should be focused on preserving core-activities and outsource non-core activities (Gilley and Rasheed, 2000). For example, in the 'transport and logistics strategy' (TLS) third party logistic partnerships enable cost reduction combined with improvement in service and operational efficiency (Sheffi, 1990), bringing into focus the 'transportation and logistics integration strategic elements' (TLISE). In this context, further investigation of a potential 'fit' between companies outsourcing intensities and vertical strategic integration could strengthen existing understanding of the 'outsourcing through abstention' (OTA) problem (Gilley and Rasheed, 2000). Since greater collective operational activities need to be advanced through supply chain alliances, then the strategic problem of 'integration as a method for integrating strategic choices' (IMSC) grows into one of a degree (Frohlich and Westbrook, 2001), however, the right level of 'fit, intensity and integration' (FOI) should be identified to optimise performance (Jayaram and Tan, 2010).

Engineering the performance of digital architectures

Existing frameworks such as Kaplan and Norton (1996), which was expanded by Brewer and Speh (2000), are applicable to specific supply chain categories 'supply chain performance measures and integration' (SCPME). These frameworks are not applied to evaluate strategy architecture that can be defined as 'digital performance measures' (GPM) where measuring performance in effect refers to forecasting performance. The most advanced performance measurement system identified is the SCOR model (SCC, 2001) because the model is applied to industry and has evolved through feedback from industry. However, in an uncertain market demand and continuous new product development, flexibility and feasibility should also be included in the performance measures (Perez-Franco et al., 2010).

Engineering the environmental dimensions for digital architectures

Supply chain engineering must anticipate 'product and product family' (PF) in the design process, while supply chain architecture must be designed in accordance to the 'best product operating cost' (BPOC) (Lamothe et al., 2006, Lo and Power, 2010, Liu and Hipel, 2012). The supply chain design must anticipate 'design for environment, design for disassembly' (DE-DD) (Clendenin, 1997). Supply chain strategy architecture should be focused on: (1) optimising the company strategy and service elements through 'postponement strategy and market demand' (PS-MD) (Korpela et al., 2001b); (2) the relationship between buyer and supplier in the 'strategy dimensions' (StD) (Van der Vaart and van Donk, 2008, Closs and Mollenkopf, 2004); (3) the supply chain functions must be based on the 'business environment' (BE); (5) the supply chain integration strategy must be based on the 'market and distribution planning' (MDP) strategies (Narasimhan and Kim, 2002).

Methodology

The process of categorising, cataloguing and relating the key tenets from existing literature enabled the development of a new methodology, (Figure 1) representing the architecture, design and engineering of a digital supply chain.

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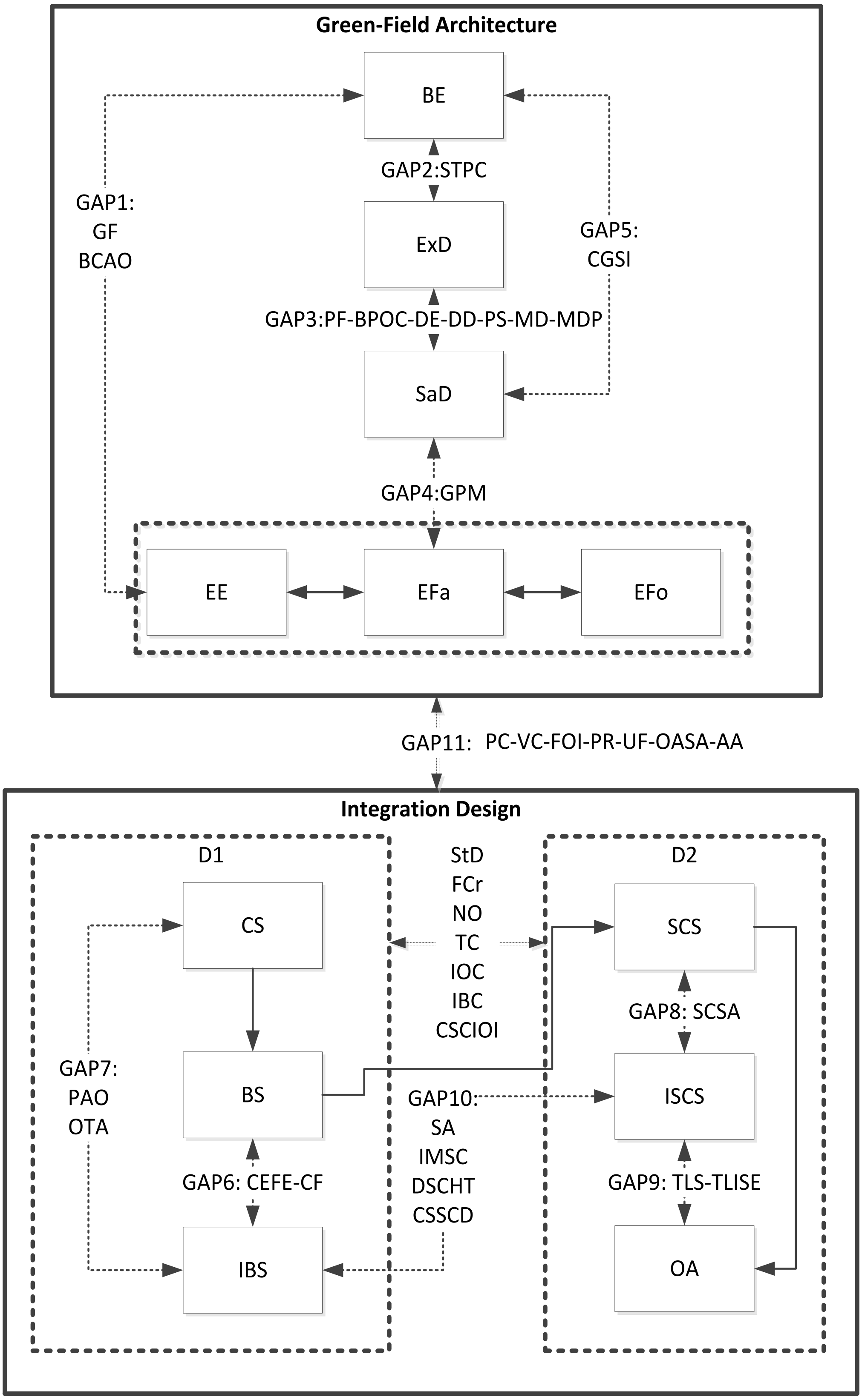

FIGURE 1: Methodology for digital integration

TABLE 1: Abbreviations of the key tenets from the methodology

Methodology key			
StD: Strategy Dimensions BE: Business environment ExD: External dimension SaD: Salient dimension **GF: Greenfield supply chain Architecture** SA: Strategy absence CS: Corporate strategy SCSA: Supply chain strategy articulation PAO: Participants aims and objectives	**FE: Architecture Elements** FCr: Architecture criteria NO: Networked organisation TC: Trust and commitment IOC: Interdependence and organisational compatibility IBC: Identification of best candidates CSCIOI: Conceptual supply chain inter-organisational integration	**FCo: Architecture Concepts** CE: Capabilities integration EE: External element EFa: External factor EFo: External force UF: Underlying factor **FI: Architecture Implementation** AA: Adapting and aligning OASA: ontological approach for semantic alignment	DSCHT: Decomposing supply chain into hierarchical three PR: process of getting from the present to the required stage CSSCD: Conceptual system for supply chain decomposition CF: Methodology approach
PSaD: Preliminary salient dimensions PF: product and product family BPOC: best product operating cost DE-DD: design for environment and design for disassembly PS-MD: postponement strategy and market demand MDP: market and distribution planning	**TLS: Transport and logistics strategy** TLISE: transportation and logistics integration strategic elements SCA: supply chain agility **SCPME: Supply chain performance measures and integration** GPM: Greenfield supply chain performance measures	**SCI: Supply chain integration** OTA: Outsourcing through abstention FOI: fit, intensity and integration CEFE: Capture the essence and forecast the effect of supply chain integration and performance CGSI: Characterise Greenfield supply chain supply chain strategy and integration	BCAO: Barriers to change and approaches to overcome IMSC: integration as a method for integrating strategic choices STPC: Separation in space, time, parts and conditions PC-VC: Process chain and virtual eChain

Principles emerging from the taxonomy of approaches

The process of building methodology (FIGURE 1) is relying on a number of key tenets.

- First principle: in supply chain architecture, to understand the companies' real strategies the architecture must be interacting with the design (activities) (Porter, 1996, Cigolini et al., 2004, Andrews, 1982, Bozarth et al., 2009, Perez-Franco et al., 2010, Sukati et al., 2012).
- Second principle: to understand how supply chains are designed, 'tacit knowledge' should be considered as instrumental in distinguishing between the engineering the strategy and the design of the activities (Perez-Franco et al., 2010, Sukati et al., 2012).
- Third principle: supply chain can be engineered as a conceptual system where the architecture is based on a conceptual design (Bozarth et al., 2009, Perez-Franco et al., 2010, Melnyk et al. 2013).
- Fourth principle: the supply chain activities are sufficient for conceptualising the architecture, design and engineering (Bozarth et al., 2009, Cigolini et al., 2004, Perez-Franco et al., 2010, Melnyk et al. 2013).
- Fifth principle: supply chain architecture contains engineering and design where the engineering is the central idea of the supply chain design (Perez-Franco et al., 2010) but the integrated design is representative of the participants and the design determines the architecture (Mentzer, 2001, Narasimhan et al., 2008, Melnyk et al. 2013).
- Sixth principle: the supply chain engineering relies on the integrated design and the design is the foundations of the architecture that is determined by the integrated design (Inkpen and Choudhury, 1995, Sukati et al., 2012, Nikulin et al. 2013), where the design represent a set of ideas incorporated in the engineering that; supplement, assist and enable the architecture (Martínez-Olvera and Shunk, 2006, Schnetzler et al., 2007, Martínez-Olvera, 2008, Perez-Franco et al., 2010, Melnyk et al. 2013).

Conclusion

The paper revealed a new methodology for architecting, designing and engineering integrated digital supply chain.

The methodology derived with the conclusion that digital supply chain architecture, design and engineering represents a dynamic process, and should be analysed in individual contexts. The critical summary of literature reviewed resulted in identifying the main themes (Table 1) necessary for generating a new methodology (Figure 1). The main themes are categorised in key tenants. The key tenants are catalogued for addressing several problems present in architecting, designing and engineering digital supply chains. These are critically appraised, with specific observations, to identify and catalogue the key tenants needed for building the methodology.

The hierarchical method for network design was applied for building and combining the architecture, design and engineering criteria. This approach was supported with principles from DSCHT, and combined with the techniques from CPPR and ATC. The new principles contribute to knowledge with: (1) architecting the supply chain elements from multiple supply chain participants; (2) designing the participants' main aims and objectives, and (3) engineering the process of getting from the present to the required stage. The new supply chain principles are also aimed at anticipating operational capabilities through internal competencies and by considering inter-organisational integration in combination with internal operations reformulation.

The methodology is further clarified by applying the process engineering criteria: procedure, process and participation. The concept verification applied architecture and integration criteria as a method for strategy engineering. The new methodology enables building upon the supply chain engineering criteria that until present, has not been built upon and combined with the design criteria: visibility, acceptance, participation, communication, adaptability, integration, effectiveness flexibility and responsiveness. Combining the criteria represents a holistic approach for supply chain architecture and result in deriving new understandings of digital supply chain engineering.

This research is part of research paper series related to this topic (Nicolescu, Huth, Radanliev, & De Roure, 2018b; Nurse, Radanliev, Creese, & De Roure, 2018; P. Radanliev et al., 2018; P. Radanliev, De Roure, Nicolescu, & Huth, 2019; P Radanliev et al., 2018; Petar Radanliev, 2019a, 2019b, 2014, 2015a, 2015c, 2015b, 2016; Petar Radanliev et al., 2019; Petar Radanliev, Charles De Roure, Nurse, Burnap, & Montalvo, 2019; Petar Radanliev et al., 2019, 2018, 2019, 2019, 2019, 2019, 2019, 2019, 2019; Petar Radanliev, Rowlands, & Thomas, 2014; Petar Radanliev, De Roure, Nurse, Montalvo, & Burnap, 2019a, 2019b; Petar Radanliev, De Roure, Cannady, et al., 2019)(Nicolescu, Huth, Radanliev, & De Roure, 2018a; Petar Radanliev, De Roure, Nurse, Rafael, & Burnap, 2019; Petar Radanliev et al., 2019, 2019; Taylor, P., Allpress, S., Carr, M., Lupu, E., Norton, J., Smith et al., 2018).

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