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Review of the Model-Based Supply Chain Management Research in the Construction Industry

Aspasia Koutsokosta, Stefanos Katsavounis

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***Abstract*—**This paper reviews the model-based qualitative and quantitative Operations Management research in the context of Construction Supply Chain Management (CSCM). Construction industry has been traditionally blamed for low productivity, cost and time overruns, waste, high fragmentation and adversarial relationships. The construction industry has been slower than other industries to employ the Supply Chain Management (SCM) concept and develop models that support the decision-making and planning. However the last decade there is a distinct shift from a project-based to a supply-based approach of construction management. CSCM comes up as a new promising management tool of construction operations and improves the performance of construction projects in terms of cost, time and quality. Modeling the Construction Supply Chain (CSC) offers the means to reap the benefits of SCM, make informed decisions and gain competitive advantage. Different modeling approaches and methodologies have been applied in the multi-disciplinary and heterogeneous research field of CSCM. The literature review reveals that a considerable percentage of the CSC modeling research accommodates conceptual or process models which present general management frameworks and do not relate to acknowledged soft Operations Research methods. We particularly focus on the model-based quantitative research and categorize the CSCM models depending on their scope, objectives, modeling approach, solution methods and software used. Although over the last few years there has been clearly an increase of research papers on quantitative CSC models, we identify that the relevant literature is very fragmented with limited applications of simulation, mathematical programming and simulation-based optimization. Most applications are project-specific or study only parts of the supply system. Thus, some complex interdependencies within construction are neglected and the implementation of the integrated supply chain management is hindered. We conclude this paper by giving future research directions and emphasizing the need to develop optimization models for integrated CSCM. We stress that CSC modeling needs a multi-dimensional, system-wide and long-term perspective. Finally, prior applications of SCM to other industries have to be taken into account in order to model CSCs, but not without translating the generic concepts to the context of construction industry.

***Keywords*—**Construction supply chain management, modeling, operations research, optimization and simulation.

I. Introduction

DESPITE the lack of a universally agreed supply chain terminology, it can be widely contended that the notion of Construction Supply Chain (CSC) refers to the business processes and organizations involved in construction projects, while Construction Supply Chain Management (CSCM) refers to the management of information, materials and capital flows and the integration of key construction business processes [1]–[4]. Originated in the manufacturing industry, Supply Chain Management (SCM) dominates the field of Operations Management and aims to improve customer service and production efficiency, reduce costs along the supply chain, improve communication and coordination among stakeholders, etc. [2], [3], [5], [6].

Practitioners in the construction industry and researchers on construction management have long time been reporting several problems on the performance of construction and have been scrutinizing the CSC for possible improvements actions, especially after the Second World War. Many studies indicate the shift from a traditional project-based to a supply-based approach of construction management [2], [5], [7].

Admittedly, construction has some peculiarities that hinder the adoption of the SCM concept as exactly developed and flourished in the stable and highly controlled environment of the manufacturing industry. But then, the challenge is to adapt the SCM to construction – and construction to SCM – and render SCM possible to remedy these problems and eliminate the negative effects of construction peculiarities.

Modeling refers to the abstraction of reality and is a central process of Operation Research (OR). OR constitutes a problem-, consulting-, and research-oriented discipline that uses scientific methods and group work to deal with problematic situations [8]. Modeling the Supply Chain (SC) is a valuable tool to gain understanding into its structure and dynamics, evaluate, forecast or optimize its performance and generally make informed management decisions. Yet, the literature on SC modeling in construction is very limited compared to manufacturing and retail, because construction seems to lag behind in adopting the SCM concept and enjoying its benefits. It has been acknowledged that CSC models are limited, project-specific and predominantly descriptive, which results in limited findings and poor interpretation of broad CSC problems [5]. Most studies are qualitative and there is a lack of analytical models for analyzing and quantifying the effects of SCM on construction projects [9]. However, the last decade we discern a notable increase of research papers on CSC models, which demonstrates the growing interest in understanding and implementing SCM best practices in construction.

This paper reviews the model-based qualitative and quantitative research on CSCM motivated by the lack of any related literature reviews and taxonomies and aiming to interpret and rationalize the available body of knowledge. A comprehensive review on such an important and

A. Koutsokosta and S. Katsavounis are with the Production and Management Engineering Department, Democritus University of Thrace, 12 Vas. Sofias Str., Xanthi, Greece (phone: +30 254-107-9328; e-mail: aspasia.koutsokosta@gmail.com, skatsav@pme.duth.gr).

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multidisciplinary research field will help practitioners and academics understand, develop and use appropriate models for their management problems and will highlight future research directions.

The literature review conducted in this paper is not exhaustive but it captures the vast majority of the models that have been presented in the context of CSCM – explicitly or implicitly – in international journals and conferences. The main objective is to provide a broad knowledge of CSC models with regard to their modeling approach, the functions that these models perform, the contexts in which they are developed and used, and common tools for modeling and problem solving. The main focus lies on mathematical models, since the need to develop quantitative tools for analyzing and quantifying the effects of SCM on construction projects is widely acknowledged.

Following this introductory section, the paper is structured in five sections addressing: (a) the necessity to apply SCM concepts in construction, (b) the contribution of modeling techniques to the field of CSCM, (c) the review of CSC models divided in conceptual, simulation and optimization studies, (d) the general evaluation of the literature, and (e) the conclusions and future research.

II. Streamlining Construction through SCM

The construction industry has been justifiably criticized for high fragmentation, large quantity of waste, low productivity, cost overruns, schedule delays, economic uncertainty, opportunism, temporary and adversarial relationships [10], [11]. The well-known landmark reports of Latham, Egan and Holti on the performance of the United Kingdom construction industry [12]–[14] highlighted the need for a more competitive and profitable industry and identified the major contribution of SCM to this. Yet, although some progress has been made and there is definitely familiarity with the supply chain concepts in construction, recent reports on CSCM practices and strategies [15] reveal a persistently adversarial and non-integrated construction industry. Recent case studies reinforce the statements about problematic flows in CSC and a low maturity level of CSCM [16], [17]. According to [18], best practice in construction through the lens of SCM has not yet been truly explored and any related governmental initiatives do not guarantee the proclaimed win-win scenarios for the supply chain members. The authors point out that best practice in CSCM is conceived quite differently by clients and contractors as "Government is a political guardian of construction industry interests, but it is also a major consumer of construction services and goods."

It is conceded that the poor performance of construction stems mainly from the interfaces between the supply chain members and stages [2], [5], [7], [17] and it may be ascribed to: (a) inadequate conventional management practices, and (b) peculiarities of the construction industry that are difficult to handle. Analytically the traditional management practices contribute to the fragmented and temporal nature of supply chain flows and generally fail to manage from end to end the supply chains, which exist in any case in every construction project. SCM prescribes managing the supply chain as an integrated value-generating flow and not on the basis of individual activities [7]. Added to this, the peculiarities of construction industry call for an industry-specific adaptation of SCM. Some indicative features are the uniqueness, immobility and size of construction projects, the decentralized and discontinuous production which is confined to shifting sites, the creation of temporal multi-organization networks with complex reciprocal interdependences and the high intervention of regulatory authorities [19]–[21].

It could be contended that that it is both a challenge and an opportunity to develop an integrated, agile and robust CSC and to harness the build-to-order, movable and temporal networks of enterprises that converge to several construction sites with fragmented flows. CSCM core principle is cooperation and integration in an effort to streamline the construction process by bringing together the traditionally distinguished processes of design and construction, and strengthening long-term relationships of parties involved in order to keep supply chain together over time, project to project.

III. The Role of Modeling in CSCM

As construction remains impervious to an organizational and cultural change that would facilitate the implementation of integrated SCM, it is essential to provide construction managers with analysis tools that help them to realize opportunities, eliminate any bottlenecks, and make informed decisions. Scientific analysis comes to replace old traditions of construction.

The modeling of CSCs has been mainly investigated since the early 1990s [5] and many authors do recognize that modeling the supply chain is a prerequisite for effective SCM and integration [21]–[23].

From an OR perspective, we perceive modeling as a deductive tool for (a) describing and understanding complex systems and (b) structuring or/ and solving decision problems. Both qualitative and quantitative models are used for understanding the structure and the behavior of real-life systems. As a problem structuring technique, modeling helps to identify an agreed framework for complex, unstructured and unclear problems, usually in the form of qualitative models. As a problem solving technique, modeling helps further to reduce a complex real-life problem to an analogous problem that is more understandable and manageable by the decision maker and it can answer the same questions imposed to the initial real-life problem. In this context, decision makers employ mainly quantitative models.

CSCM covers a wide range of managerial principles and activities allowing this way the application of different modeling approaches and research methodologies. SCM requires decisions at several stages, such as production, inventory and distribution planning, supplier selection, location/allocation decisions, distribution channels selection, number of facilities, numbers of SC echelons, and service sequence. Moreover, the multidisciplinary nature of the present research field leads to the use of different vocabulary

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and terminology and accordingly poses difficulties in locating the modeling studies. In this paper, current research on CSC modeling is initially distinguished in conceptual, simulation and optimizations models that are further analyzed and discussed.

IV. Review of Models for CSCM

A. Conceptual Models

A remarkable percentage of the model-based literature on CSCM pertains to conceptual or symbolic or process models. Most of them focus on information flows and aim to improve the communication and coordination between supply chain members. In this context, there are CSC models that propound an e-business infrastructure [24], information technologies [25], enhanced communication, collaboration, learning, total quality management [10], strategic partnerships, third-party logistics, information management platforms [26], information and communication hubs [27], information technology-based lean ideas [28] and open information channels [6]. The conceptual model of [29] circumscribes the adoption of Building Information Modeling (BIM) in CSC which offers great potentials of information exchange and collaboration.

In the literature we may also find models that assess the progression of SCM in construction, adopting principles of the so-called maturity models in manufacturing and aerospace. Reference [4] presents a CSC maturity model which describes the maturity stages of CSC business processes with respect to the level of functional, multi-project and multi-firm integration achieved. Another maturity model defines assessment criteria and procedures to measure qualitatively the maturity level of CSC relationships which range from traditional adversary to fully collaborative [30].

In other context, the model of [31] describes the structural and behavioral characteristics of procurement in CSC using a combination of object-oriented modeling and industrial organization economic theory. Reference [32] presents a conceptual model which combines supply chain management and knowledge management resulting in creation of learning CSCs with supply chain capital and competitive advantage. Supply chain capital is developed through many years of collaboration, experience and knowledge sharing between the supply chain partners. The conceptual model of [33] includes the building elements of effective CSCM implementation including prerequisites, approaches, benefits and contextual factors related to SCM adoption in construction. From a logistics perspective, [34] maps material and information flows between supply chain members by adjusting the existing Supply Chain Operations Reference Model (SCOR model), which was originally developed for manufacturing, to the construction industry.

B. Simulation Models

With regard to CSC simulation (see Table I), most models describe or evaluate only parts or individual relationships of supply chain under several scenarios. Reference [35] presents a system dynamics model of a typical house building supply chain using the Inventory and Order Based Production Control System (IOBPCS), a well-known family of models in manufacturing. This model, which is republished and extended by [5], aims at studying the impact of different re-engineering scenarios on demand amplification. In [36] the impact of inventory management on the delivery time of a material is studied in the context of a capital project SC. Reference [37] presents a quantitative analysis of construction logistics costs in connection to different supply systems in order to examine the impact of outsourcing logistics. The impact of logistic centers supporting multiple site stores on the material management costs is studied in [38]. Other models simulate the material flow of a specific product type from builder merchants to construction sites and describe the impact of demand levels and vehicle fleet size on logistics costs [22], [39]. Reference [40] focuses on in-house supply chains and analyzes the effect of alternative outfitting processes and logistics activities on the logistics time and the construction time. Another simulation research investigates the bullwhip effect in several echelons of a tunneling supply chain of concrete segments as well as the impact of some variables of interest on the duration of the tunneling project [9], [41]. In the related literature we also find multi-agent modeling approaches [42], [43], which support CSC decision-making and improve the coordination among several agents with regard to their goals and behavioral attributes. The service-oriented framework of [42] and [43] employs the existing SCOR model and leverages web services, web portal and open source technologies in order to achieve CSC monitoring, coordination and collaboration among participants

C. Optimization Models

As far as optimization modeling of CSC is concerned, the research is also heterogeneous, but more limited. Although optimization studies make up a major and sizable share of the general SCM research (in manufacturing, automotive and chemical industries), there are a few cases for CSCM (see Table II), by means of either mathematical programming or simulation-based optimization.

The two-level programming model of [46] for collaborative scheduling in CSCM provides a compromising schedule to different supply chain partners with regard to profit maximization at two hierarchical stages. The bi-level (or two-level) programming decision model of [47] is a client-led negotiation process with the contractor which finds the optimal selection of the revenue incentive intensity and achieves a time-cost equilibrium with regard to optimization of net revenue. In [48] a model for CSC design and behavior analysis is created using the SCOR process model and simulation software, including also optimization of the procurement behavior with metaheuristics methods. The project-driven model presented in [48] and [49] focuses on interactions between CSCM and project management and jointly optimizes safety-stock and crashing decisions with regard to cost minimization. The multi-objective optimization model presented in [51], [52] finds the optimal utilization of interior building spaces with regard to minimization of

logistics costs on-site as well as to minimization of project criticality. Reference [53] proposes a bi-level programming model for coordinating production and distribution processes of CSCM with respect to cost minimization at two hierarchical levels.

TABLE I
CSC SIMULATION MODELS

Authors	Performance metrics	Alternative scenarios	Simulation approach or software
Hong-Minh and Strohhecker (2002) [35]	Demand amplification (through inventory and production costs, inventory error and mistrust)	Re-engineering policies	System dynamics based on IOBPCS
Walsh et al. (2004) [36]	Delivery time of a material	Positioning scenarios of inventory	SIMPHONY (CYCLONE template)
Sobotka and Czarnigowska (2005) [37]	Material acquisition cost	Deliveries directly to the building site or to an auxiliary stacking yard	Not defined
Xue et al. (2005) [42]	Quantitative and qualitative attributes for SC coordination	Interactions among agents	Multi-agent simulation and multi-attribute negotiation protocol and utility theory, ZEUS agent building toolkit
Vidalakis and Tookey (2006) [22], Vidalakis et al. (2011) [55]	Logistics costs (inventory and transportation costs)	Demand levels and vehicle fleet size	Discrete-event simulation, Simul8
Hamzeh et al.(2007) [38]	Material management costs	Presence of a logistics center in the SC or a decentralized supply system	Not defined
Voigtmann and Bargstädt (2010) [40]	Logistic time and construction time	Alternative outfitting processes, such as diversified equipment	Tecnomatix Plant Simulation framework, Simulation Toolkit Shipbuilding
Cheng et al. (2010a) [44], Cheng et al. (2010b) [45]	Integration and collaboration of SC through metrics of SCOR model (e.g. costs and reliability)	Information sharing and system integration factors	Service-oriented framework (open standards, open source software and SCOR), named SC Collaborator
Ebrahimy et al. (2011a) [41], Ebrahimy et al. (2011b) [9]	Bullwhip effect and duration of a tunneling project	Scenarios for production, storage, and quality control	SIMPHONY

TABLE II
CSC OPTIMIZATION MODELS

Authors	Objective / Variables	Analytical approach	Optimization method / Software
Xue et al. (2007) [46]	Maximization of profits (at an upper and lower level)/ Indicative variables such as construction duration and materials lead time are mentioned	Two-level nonlinear integer programming model	Simulated annealing and discrete search algorithm/ Not defined
Jian-hua and Wan (2010) [47]	Maximization of the expected profit of contracting parties/ Incentive intensity (money unit per unit time) and project's duration	Two-level programming model	Problem-specific heuristics/ Not defined
Xu et al. (2011) [49] Xu et al. (2012) [50]	Minimization of safety-stock and project crashing (delay cost per unit of time) for recurrent projects subject to random material delays/ Safety-stock decisions in material supply chains and crashing decisions in projects	Stochastic multi-stage optimization model	Not defined/ Not defined
Said and El-Rayes (2010) [51] Said and El-Rayes (2012) [52]	Minimization of site logistics costs and minimizing of project criticality (by shifting noncritical activities to exploit interior space for material storage)/ Categories of variables: material supply, interior storage plan, exterior layout, shifting of non-critical activities within their float	Multi-objective optimization model	Genetic algorithms/ Not defined
Xu and Wei (2013) [53]	Minimization of production and transportation costs (production model-lower level) and minimization of storage, transportation, and inventory penalty costs (distribution model-upper level)/ Material quantities supplied from production sites to warehouses and from warehouses to concrete mixing plants	Two-level fuzzy optimization model	Artificial bee colony algorithm based on a fuzzy random simulation/ MATLAB

V. EVALUATING THE MODEL-BASED CSCM LITERATURE

The most adopted modeling approach in CSCM is by far conceptual followed by mathematical modeling. Mathematical models are mostly simulation studies and the optimization paradigms are quite limited.

In conceptual and simulation models, there are some studies trying to transfer and transform SCM models from manufacturing to construction. For example, [35] exploits similarities of house building industry, a subset of construction industry, with manufacturing and base their model on IOBPCS developed in manufacturing. Reference [34] adapts the SCOR model to the characteristics of construction, while [4] develops a construction-oriented model based on maturity models of other industries. However, many researchers agree that, despite their possible conceptual similarity, SCM models from other industries are not directly applicable to construction and a sound transformation of generic concepts is necessary [2], [4], [6], [33]. It could be argued that especially the field of CSC optimization needs not just adaptations but ad-hoc analytical models capturing the intrinsic construction problems. Accordingly, the application of mathematical programming which is perfectly suited to the support of resource allocation decisions and is widely used is SCM, has been very limited in the case of the construction industry – most publications on CSC optimization have appeared during the last five years.

All the optimization models presented are single-period or do not incorporate a time dimension at all, which does not allow for a long-term evaluation of decision making.

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Moreover, their contribution is limited to relationships and processes of a stable pre-determined CSC structure dominated by single-sourcing. However, the impact of changing dynamic networks and temporal partnerships on the optimal decisions should be somehow incorporated in future models which reap diversification benefits and overcome the present inadequacies.

Furthermore, most optimization models fail to present modeling as a process that goes beyond the definition of an objective, variables and constraints for a given problem. The CSC modeling studies should be followed by numerical examples, interpretation of results, validation efforts and sensitivity analysis, exhibition of modeling techniques, justification of the algorithm used and the software selection, discussion of the model limitations and the insights gained, clear and concise reports etc.

Conceptual models for CSCM are mostly descriptive and, except for few instances, are not specific enough to be tested by means of case studies and pilot projects neither can be easily expressed from a quantitative point of view. Even if some conceptual models are evaluated by means of expert interviews and simple case studies, their authors refer to standard comprehensive assessment methods for sound validation and future research.

For such a fragmented industry, it is important to develop models that either are reusable or integrate flows of construction processes across several projects and periods of time. So far, quantitative CSC models show limited or none reusability and neither are designed in the direction of establishing as many continuous flows as possible within a wider supply network. Added to this, simulation models, which are common in the CSC literature, are modeling approaches that usually do not stress reusability because they are not developed to find solution to a problem, but to describe a system under investigation and gain insights into its internal mechanism.

In practice we observe that a construction company may have as many supply chains as there are the projects that undertakes. This usually results to temporal supply chains with no long-term implications. Arguably CSCM should somehow handle this differentiating feature of construction compared to other industries. We do not discern adequate initiatives towards CSC models that combine the supply demands of several projects, exploit any project similarities and use structured pools of subcontractors and suppliers. There is a need to manage the unique supply needs of different construction projects in an integrated manner by mobilizing similar paths within a strategically designed CSC. Admittedly, this is a challenging task and according to [6] "while developing SC models for a single independent construction project is already difficult, it is even more difficult for multiple projects".

Another common shortage in the CSC modeling literature is the explicit indication of the business entity or individual who manages and mobilizes the supply chain. A client-led or contactor-led perspective should be clarified in modeling efforts in order to stress the usefulness and long-term implications of the models if any and give practical directions to practitioners as well. The client-led supply chain is a project supply chain with temporal nature as it reflects mainly the relationship between the construction client and main construction contractor. On the other hand contractor-led supply chain, which reflects mainly the relationship between the main construction contractor and providers of services and products, i.e. construction sub-contractors and suppliers, has no specific project affiliation [18]. Thus, we believe that the contractor-led CSC in particular can be the true application field of the majority of SCM concepts and best practices. The client-led CSC could offer the same potential of integrated SCM only in case that the construction client is the government or an empowered client big enough to draw a supply chain strategy. For example, this applies to UK government which requires that the supply chain members will have to work collaboratively and use Building Information Modelling for all awarded contracts over £5M [29]. Alternatively, the focus may be on component manufacturers who should be responsible for the whole material chain and installation on site [19]. Reference [22] models the material flow of materials from builders merchants to construction sites and emphasizes their role in an effort to balance the contractor-centric approach that governs CSCM.

It is also remarkable that the final product to be delivered to the client through the CSC is not well defined in the proposed models. Some models are restricted to the products manufactured for use in the construction industry. The perception that the construction project is the "final product" to be delivered is not always present in CSC models, despite the fact that most CSCM problems should be managed in this context and not in a sub-product level. Despite the fact that construction production is primarily a site production combining fabrication and assembly [20], many researchers also refer to an off-site production which evolves upstream in the supply chain by prefabrication, modularization and preassembly [19], [21]. Thus, it would be appropriate to clarify whether models pertain to construction or manufacturing of construction materials.

Through the lens of Operations Research, mathematical models of CSCM fall under the hard OR domain, but we cannot accordingly relate any model with soft OR. The optimization and simulation approaches of problem-solving are based on analytical thinking and are indicative of the so-called hard OR methodology. The essential feature of hard OR is the construction of mathematical models that objectively and quantitatively represent the problems under study [8]. Soft OR includes qualitative and systems thinking-based models for structuring messy problems and supporting group decision-making with conflicting goals [8], [54]. Indicative soft OR methods include strategic options development analysis, soft systems methodology, theory of constraints, causal mapping, etc. We consider that the qualitative CSC models presented so far are mostly generic conceptual frameworks contributing adequately to theory building in CSCSM rather than soft OR approaches for practical decision problems.

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VI. Conclusions and Future Research

The literature on model-based CSCM is growing rapidly. To the best of our knowledge this paper is the first contribution to a comprehensive interpretation of any modeling attempts that address specifically SCM in the construction industry. This paper is part of a PhD research project which aims to conduct a systematic taxonomy and matching of CSC problems and models and develop new models that fill current research gaps.

The multidisciplinary research field of CSC modeling and the lack of universally accepted definitions of related concepts and terms have led to heterogeneous modeling studies which do not easily reveal their catholic contribution to CSC integration. Most modeling studies on CSCM are conceptual, followed by simulation models and then few optimization models in the form of either mathematical programming or simulation-based optimization.

Most researchers examine a supply chain pertaining to an individual construction project or even to an individual material, which leads to a simplified approach of SCM and neglects the complex interdependencies within construction. The combination of different supply chains feeding multiple projects has not been analyzed properly.

It is beneficial to all stakeholders in construction industry to manage CSCs end-to-end from a multi-project perspective. Accordingly, CSC modeling needs multi-dimensional, system-wide and long-term implications. Prior applications of SCM to other industries may be taken into account in order to model CSCs, but not without the adaptation of generic concepts to match the unique characteristics of the construction industry. The "what" questions may remain the same among industries but the "how" questions need industry-specific answers.

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