Concurrent Product – Supply Chain Design: A Conceptual Framework & Literature Review

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Abstract

The capability to concurrently design the product and the supply chain is becoming a key competence in manufacturing companies. In spite of this development, this competence is still underdeveloped in industry. Research has not been able to fill this industrial capability gap partly because there is a lack of convergence of the methodologies for concurrent product and supply chain design in the research community. Moreover, a dominant and practical methodology in concurrent product and supply chain design in the industries has not yet emerged. This paper addresses this gap by introducing a novel conceptual framework termed Concurrent Design Attribute Trade-Off Pyramid (CDA-TOP). Based on this framework, we provide a literature review with special focus on design trade-off attributes and methodologies.

Keywords: product design; supply chain design; concurrent design; trade-off methodologies

1. Introduction

For a manufacturing company to be successful in today’s competitive, complex and globalised world, the capability to design product has to be complemented by the capability to manage a complex supply chain that delivers the product to the market. However, researchers in product design (PD) and supply chain (SC) management have kept mainly within their domains for various reasons such as complexity of cross-disciplinary research or simply due to unexhausted mono-disciplinary research potentials [1-2]. Even though many researchers have already identified the benefits of concurrent design of products and SCs such as greater SC performance and risk mitigating flexibility as well as lower SC costs, few have systematically quantified these benefits by using complex industrial cases [3-7]. Uncertain of the complexity and effort of concurrent design, we believe that industry has been reluctant in adopting concurrent design methodologies at all or to the full extent. This paper explores the state of the art of concurrent product and supply chain design (CP-SCD) in the research community. It aims to bridge the gap between the two distinct but equally important research domains.

In the first section of this paper, we briefly discuss product design (PD), supply chain design (SCD) and design trade-off methodologies. Based on this, we develop a novel conceptual framework termed the Concurrent Design Attribute – Trade-Off Pyramid (CDA-TOP). This framework presents a high level taxonomy of concurrent design attributes and interfaces between the product and SC domains. In addition, CDA-TOP introduces the concept of design trade-off asymmetry that illustrates the impact of design attribute selection on the balance between PD and SCD.

In the second section, we use our CDA-TOP framework for analysing the state-of-the-art in research with a focus on design trade-off attributes and methodologies used in CP-SCD. First, we present the literature review methodology, showing the process and criteria used for the search and selection of relevant literature. Then, we provide an orientation for researchers and industrial managers by clustering research foci in terms of research trends, design attributes and trade-off methodologies.

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In the last section, we provide a synthesis and analysis of our findings and highlight the research gaps in CP-SCD.

1.1. Product and supply chain design

PD theories and methodologies are more established than those for SCD. An explanation for this is the transformation of the industry. The need for systematic PD methodologies predates the need for SCD. Research in PD has been documented for more than a century [8-9]. In contrast, SC management is a comparatively new research domain that emerged from the fields of management science such as operations research during the era of globalization [10]. Despite its head start, PD remains a combination of art and science as its sub-disciplines are not always quantifiable or intuitive [11]. Tomiyama et al. [9] have provided a comprehensive review of PD methodologies and theories.

Several PD methodologies have highlighted that PD can be represented by PD attribute levels (architectural, detail and performance) [9, 12]. These product levels enable a systematic top-down approach in PD. Among these three PD attribute levels, the product architecture has recently received strong attention in the research community due to their impact on downstream design as well as product lifecycle and the SC. Cornerstones of product architectural design are the axiomatic design theorems, according to which, PD has to generally account for design for manufacturability and design-manufacturing interfaces. Ground-breaking research using architectural attributes such as modularity and commonality [e.g. 9, 13-14] resulted and much more qualitative and quantitative followed [e.g. 15-16].

In comparison, the need for systematic end-to-end SCD has been recognized by leading operations management researchers much later (e.g., Lee [17], Simchi-Levi [10], Fine [18], and Graves & Willems [19]). Contemporary research in SCD usually assumes a fixed PD before “creating” the SC, hence, leaving very limited design space for SCD. Useful for the purposes of our research are the SCD frameworks using multi-echelon attributes. Simchi-Levi et al. [10], Günther and Tempelmeier [20] use three-layer structures (strategic, tactical and operational) to represent the SC attributes dependent on their different decision horizons and impacts on the SC performance. Meyr and Stadtländer [21] introduce a framework of structural and functional attributes with a similar hierarchical differentiation.

1.2. Design trade-off methodology

The search for global design optimality of both the product and the SC requires methodologies to support trade-off decisions between conflicting design objectives. Trade-off methodology is a pivotal methodology for CP-SCD. Trade-off methodology can be defined as an analytical approach for evaluating and comparing competing design solutions based on stakeholder-defined criteria [22]. For design trade-off, Multi-Criteria Decision Analysis (MCDA) methodologies are particularly relevant. Colson and Bruyn [23] classify MCDA into compensatory, non-compensatory or partially compensatory types. For compensatory type, the value of one criterion can be used to compensate the performance of the other (i.e. a trade-off is possible). This requires criteria to be commensurable. For non-compensatory types, trade-off is not possible due to lack of direct commensurability. Guitouni and Martel [24] state the need for aggregation of criteria in decision trade-off. Aggregation allows compensation between different criteria and hence enables trade-off to occur. In the context of our review, we define trade-off methodology as the process of finding the best overall solution (global solution) to a problem based on a set of target objectives, evaluation criteria and constraints using commensuration, compensation and aggregation. MCDA methodologies that are of particular interest to trade-off are those of compensatory and partially compensatory types such as Weighted-Sum, MAUT, ELECTRE, PROMETHEE, AHP and Multi-Objective Programming (MOP). Detailed descriptions of the algorithms and a comparison between the methodologies can be found in [24-25].

Simulation is another type of methodology that can be used to support trade-off analysis. Simulation is not a trade-off methodology per se but can be used with other methodologies (e.g. MCDA, Design of Experiment) to analyse more complex trade-off (e.g. over time) and with stochastic model attributes [e.g. 26-27].

1.3. Concurrent design attribute – trade-off pyramid (CDA-TOP)

In order to provide an overarching framework for mapping and linking key relationships and interactions between PD and SC attributes, we developed the conceptual framework Concurrent Design Attribute – Trade-Off Pyramid (CDA-TOP) (Figure 1) as a multi-layer pyramidal structure for illustrating the concurrent design trade-off domains with the following main features:

- a 3-layer hierarchy of PD and SC attributes,
- a positioning of attributes along the design process and the horizon of the SC planning decisions,
- a boundary between the PD and SC domains indicating the coupling-decoupling of attributes in different domains.
CDA-TOP uses a 3-layer hierarchy, which is well-established in both domains, to classify different types of design attributes (architectural, detail, dynamic types) according to their relative leverage on the product and the SC. We employ multi-layer attribute hierarchy as such structures have often been used as an effective way to represent attributes in trade-off studies [22], PD [12, 28-29] and SCD [10, 20-21].

Design alternatives are functions of design attributes. At the upstream PD process and SCD strategic level, architectural attributes determine the arrangement and configuration of the product (e.g. modularity) and the SC (e.g. locations in a SC network). At the PD process mid-stream and SCD tactical level, detailed design attributes are generally related to the physical aspects of the PD (e.g. size, weight, material and form) and mid-term SCD attributes (e.g. transportation, inventory, replenishment policies). Finally, at the PD downstream and SCD operational level, dynamic attributes are typically performance related PD functional attributes (e.g. speed, range) and SCD short-term decisions (e.g. scheduling) [10]. This hierarchy of attributes helps to avoid the “chicken and egg” dilemma between product designers and SC architects by highlighting that architectural design can begin concurrently without waiting for detailed designs of the other side.

CDA-TOP also shows the trade-off boundary between the PD and the SC domains. More importantly, this trade-off boundary not only marks both the coupled region at architectural and detailed levels, but also the decoupled region at dynamic level. In order to bridge between the terminology used in CDA-TOP and commonly used terminology in the product and the SC research domains [10, 12, 18, 20-21], further terms are shown on both sides of CDA-TOP for comparison (Figure 1).

1.4. Significance of CDA-TOP

CDA-TOP has been created to be conceptually useful to product and SC designers. CDA-TOP provides a holistic view of the different types of design attributes and their conceptual relationship between them. CDA-TOP is shown as a symmetrical pyramid with balanced design attributes in product and SC domains for optimum trade-off. In reality, this symmetry rarely occurs as the design processes are usually skewed either in favour of the PD engineers (PD-centric) or the SC managers (SC-centric). For high-mix/low-volume and complex products such as aircrafts, PD engineers have typically very compelling reasons to dominate over SC managers. In comparison, high-volume/low-mix and low value products such as packaged products for which SC attributes are more important, SC managers take the lead in the concurrent design. This is in-line with contemporary view that SC designs of innovative and non-innovative products are different [8]. However, we believe that such industrial practices of asymmetrical trade-off are sub-optimal as they are a result of practicality rather than optimality.

CDA-TOP offers a conceptual visualization of the design trade-off asymmetry when one of the abovementioned trade-off scenarios occurs (see dotted lines in Figure 1). In the event of design trade-off symmetrical level change (illustrated by a horizontal shift of the pyramid peak towards either ends of the two domains), the greatest impacts of such a shift are on the architectural level, followed by the detailed level and lastly the dynamic level of the other design domain. These impacts are graphically represented by the change of the overlapping areas between the symmetrical and shifted asymmetrical pyramids. For example, a change of the automotive SC make-buy architecture will impact...
the product modular architecture (e.g. modularization to enable outsourcing [30]), consequently the choice of material (product detail), which may have an impact on maximum speed due to material weight change (product dynamic). Conversely, a change of the product modular architecture (e.g. product standardization [17]) will impact the SC push-pull boundary (SC architecture), the replenishment policy (SC detailed) and the lead time (SC dynamic). This impact on the SC detailed and dynamic attributes also affects the choice of production technology and infrastructure, which are reflected in SC attributes such as lead times and costs. Such dominating influences of upstream design attributes over downstream design attributes have been widely accepted by many PD and SC researchers [12, 29, 31-33]. It is important to note that there is always a direct interdependence between product and SC architectural attributes [31], but there may not always be a linkage between detailed design attributes (e.g. replenishment policy, choice of material) and hardly any direct relationship between dynamic attributes (e.g. completion time, product speed).

Based on our CDA-TOP framework, the implications of design trade-off asymmetry can be explained using the concepts of trade-off leverage and quality. First, we argue that design trade-off should be pursued at architectural level first before other levels to ensure greatest trade-off leverage on the product design and the supply chain in the early stages of concurrent design process. Second, we argue that symmetrical architectural design trade-off should be pursued to ensure higher trade-off quality. As explained in the two aforementioned conceptual examples, the coupling between attributes weakens across hierarchical levels (e.g. Product architectural-SC detailed) due to the need for cross-hierarchical abstraction in the trade-off model. In contrast, design trade-off on the same hierarchical level allows for more accurate modelling of attribute relationships and hence higher trade-off quality. Based on these two arguments, CDA-TOP provides a structure for our literature review, which investigates the following:

- type of design attributes used for CP-SCD,
- symmetry of design attributes across design domain (product versus SC),
- choice of design attributes across design hierarchy (architectural vs. detailed vs. dynamic), and
- type of the trade-off methodology.

2. Literature review scope and methodology

2.1. Scope and methodology

Based on our analysis of CP-SCD in the previous section, we designed our literature review methodology such that it addresses specifically the cross-disciplinary research boundary between PD and SCD. Hence, the criterion for inclusion in our literature review is the presence of design concurrency and a trade-off methodology across the product and supply chain design domains. This also means that the design attributes used in the literature must possess the elements of commensurability, compensation and aggregation. With this specific scope in mind, we conducted a search in international journals that are related to PD, SC, operations, management and other related fields. We have also noted the large body of literature in the field of product lifecycle design (PLCD). While PLCD generally encompasses PD and SCD, most PLCD papers do not address SCD in detail. Our focus is on the design trade-off between PD and SCD. Hence, papers concerning PLCD are reviewed only if they fall into this category.

2.2. CP-SCD research – an underexplored and emerging research area

A total of 33 papers were found to be directly related to the review scope and were selected for further analysis. Among these, only 17 papers were found to fulfill the criteria of our scope (i.e. CP-SCD with trade-off methodology). The remaining 16 papers are of qualitative type (e.g. literature reviews, case studies), which do not provide analysis of CP-SCD trade-off but only qualitative discussions on CP-SCD issues and their applications in real industrial cases. Among these 16 qualitative papers, four are of literature review type. Our paper goes beyond these four papers by including the analysis of the interdependence between PD and SC attributes and of the CP-SCD trade-off methodologies. Furthermore, our paper has a more focused review scope that provides more detailed insights into CP-SCD trade-off analysis than these four papers, which provide more generic discussions of research trends and potentials of CP-SCD. Finally, the low number of CP-SCD relevant papers over the last two decades indicates that CP-SCD research is still an emerging research area. Most of the CP-SCD related papers were in fact published after 2005 [1, 5-6, 30, 35-36].

2.3. Asymmetrical CP-SCD design trade-off

A comparison of the quantity and diversity of PD and SCD attributes used in the reviewed papers reveals some interesting insights. First, the number of PD (10 types) and SC (12 types) attributes used in reviewed papers are comparable. Second, Table 1 shows that the PD attributes used in these papers are mostly product architectural types (24 out of 40, e.g. modularity, configuration). 15 out of 17 papers use product architectural attributes for the trade-off. One explanation
is that product architectural design attributes have greater impact on SC performance than other lower level PD attributes. Also the difficulty in modelling the relationship between product detailed and dynamic attributes to SC attributes leads to a focus on architectural attributes. Only two papers use solely PD detailed attributes with SC attributes [3, 26].

In contrast, the SC attributes used are mostly of detailed type (48 out of 62). Only 7 out of 17 papers use SC architectural attributes. This comes as no surprise as modelling SC using detailed attributes (e.g. production and sourcing costs) and dynamic attributes (e.g. lead time) is a common approach in SC research, while the numerical characterization of supply network structures (e.g. in terms of complexity) is less proliferated in management science.

We have only found four papers that address non-greenfield SCD [5-6, 17, 30]. These papers consider existing SC by using penalties of deviation from existing designs (costs of integrating new suppliers [6]) and constraints (existing locations [5]) or by comparing between existing and alternative SCD [17, 30]. This small number of non-greenfield analyses in CP-SCD trade-off does not reflect industrial requirements as the reuse of existing assets for new products reduces new investment and is hence a necessity. In the following, we have classified the papers based on their trade-off symmetry according to the highest level used on either side (i.e. if architectural and detailed attributes are used – it is considered as architectural level) (number of papers in bracket):

- PD architectural-SC architectural trade-off (7)
- PD architectural-SC detailed trade-off (8)
- PD detailed-SC detailed trade-off (2)
- PD dynamic-SC dynamic trade-off (0)

As highlighted by the CDA-TOP decoupled region, which suggests no direct linkage between PD and SCD dynamic attributes, no paper involving direct trade-off between PD dynamic and SCD dynamic attributes has been found. Most importantly, no paper provides a methodology for CP-SCD in which the trade-off is made by addressing the hierarchical levels systematically one after the other.

2.4. CP-SCD trade-off methodologies

In section 1.2, we analyse the different types of MCDA methodologies. 13 of the 17 papers use at least one of the MCDA methodologies [2, 5-6, 17, 30-31, 33-39]. These papers use MOP-type (e.g. MILP, GP, GA) methodologies, with 12 using cost functions and one using a utility function [39]. Interestingly, other types of MCDA have not been used. We have also found four papers that use simulation [3, 26-27, 40]. We believe that the complex relationships of trade-off attributes and the ease of quantifying certain target objectives (e.g. cost, utility, quality) favour the use of MOP and simulation over other types of MCDA methodologies. Other MCDA methodologies use either pairwise comparison (e.g. AHP) or scoring are only suitable for selecting discrete design options and not suitable for continuous attribute trade-off. Discretisation of continuous attributes by ranking or scoring is required for aggregation, which can be unwieldy if there is large number of attributes with complex relationships.

Table 1. Overview of papers (in order of publication year), trade-off attribute type count. (Architectural (A), Detailed (D), Dynamic (Y)) and their trade-off methodologies

<table>
<thead>
<tr>
<th>Product Attributes</th>
<th>Supply Chain Attributes</th>
<th>Trade-off Method</th>
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<tbody>
<tr>
<td>A</td>
<td>D</td>
<td>Y</td>
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<tr>
<td>Lee &amp; Sasser (1995) [17]</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Krikke et al. (2003) [36]</td>
<td>1</td>
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<tr>
<td>Blackburn et al. (2005) [3]</td>
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<td>1</td>
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<td>Füe et al. (2005) [31]</td>
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<tr>
<td>Huang et al. (2005) [34]</td>
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<tr>
<td>Su et al. (2005) [27]</td>
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<tr>
<td>Lamothe et al. (2006) [37]</td>
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<td>1</td>
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<tr>
<td>Zhang et al. (2008) [2]</td>
<td>1</td>
<td>1</td>
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<tr>
<td>Seliger &amp; Zettl (2008) [39]</td>
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<td>1</td>
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<tr>
<td>Elmarghity &amp; Mahmoudi (2009) [51]</td>
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<td>1</td>
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<tr>
<td>Gokhan et al. (2010) [6]</td>
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<tr>
<td>El Hadj Khalaf et al. (2011) [38]</td>
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<td>Izui et al. (2010) [26]</td>
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<tr>
<td>Jiang et al. (2011) [33]</td>
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<tr>
<td>Ülkü &amp; Schmidt (2011) [40]</td>
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<tr>
<td>Nepal et al. (2012) [30]</td>
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<tr>
<td>Baud-Lavigne et al. (2012) [35]</td>
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Legend:
Mixed-Integer Linear Programming (MILP)
Weighted Goal-Programming (WGP)
Genetic Algorithm (GA)
Non-dominated Sorting Genetic Algorithm (NSGA-II)

3. Conclusion

This paper has introduced a new conceptual framework CDA-TOP, which structures CP-SCD by classifying different types of design attributes. In addition, we highlight design trade-off asymmetries and methodologies in our literature review. From our analysis, we have identified some potential areas for further research. First, to what extend does CP-SCD asymmetry affect the leverage and quality of CP-SCD trade-off? Second, the design sequence issue of CP-SCD deserves a closer look. When should concurrent design really begin? Only one [6] of the 17 reviewed papers compares between sequential and simultaneous CP-SCD processes. Third, ways to consider non-greenfield SCD deserve more attentions. Finally, we have not identified
any process that provides prescriptive and holistic guidance for CP-SCD trade-off analysis. For example, such process should address the organisational and implementation aspects of CP-SCD. We hope that our paper has highlighted some critical areas in the emerging field of CP-SCD and provided orientation to other researchers in advancing their theories and methodologies.

References


