Trade-offs mathematical modelling of 3DCE in new product development: real three dimensions and directions for development

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Abstract. In the last two decades, coordinating product, process, and supply chain has become the main focus in recent years as a growing body of research, which mathematical modelling is leading technique used in the early phase design. In this paper, we aim to conduct a comprehensive literature review of published paper and propose directions for future research, especially in mathematical modelling. Our findings exhibit fact that evidently there are only a few papers coordinate “real three dimensions”. The other papers, in fact, show simply two dimensions. Finally, some suggestions are proposed such as paying more attention to “real three dimensions” research-based and more focus on minimizing time to market, product life cycle consideration, and product rollover.

1. Introduction
Three Dimensional Concurrent Engineering (3DCE) is a powerful model of new product development (NPD) supported by concurrent engineering, in which the traditional focus on an appropriate match between product and process is augmented by an additional consideration of supply chain configuration [1]. Decision making process is a key factor in product development that is made in every gate in Cooper's stage gate product development. The duration for making a decision is not always fast as needed, it takes weeks or even months to make decision. This long duration problem is caused by unspecified trade-offs that should be solved and considered for the decision making. Many researchers describe trade-offs in mathematical modelling and solve the trade-offs using common techniques in operation research. So, the decision making process can be made quicker as the trade-offs had been formulated and solved.

Literature review on 3DCE has been conducted several times, such as Ellram et al. [1], Forza et al.[2], Castellano and Dolado [3], Gan and Grunow [4], and Shahbazi et al.[5]. In Shahbazi et al. [5] review, mathematical modelling was the most common technique used that attracted attention most researchers to coordinate the three dimensions.

In distinct to above reviews, this paper goals are first to analyze on recent literature specifically on mathematical modelling trade-offs in 3DCE to support the “real three dimension” decision making. Second to identify the gaps in the existing literature and suggest directions for further research. Term “real three dimension” means that trade-offs are formulated considering product, process, and supply chain dimensions, since many mathematical models were formulated in two dimensions only.
This paper is organized as follows. Section 2 describes the background of the study. Section 3 is presented to define the method of collecting relevant papers. Section 4 provides highlights the mathematical model of selected relevant papers. Finally, in Section 5, the gaps and directions for further research are discussed.

2. Background
The concept of 3DCE as defined by Fine [6] is considered during product design phase. 3DCE means considering the requirements of manufacturing design and supply chain design in the product design phase. Surely, this consideration complicates the design problem that requires more complex multiple objectives model with a large number of constraints, variables, parameters, and trade-offs. However, by considering all requirements of product design, process design, and supply chain design, we have a great chance of giving responsiveness, agility, variety, quality, and price to win the market. This also strengthened by Fine [6] statement that “when firms do not explicitly acknowledge and manage supply chain design and engineering as a concurrent activity to product and process design and engineering, they often encounter problems late in product development, or with manufacturing launch, logistical support, quality control, and production costs...”.

Researches that modelled trade-offs with product, process, and supply chain as decision variables are conducted to help decision makers (designer) decide product, process, and supply chain configuration simultaneously (the real three dimensions). Simultaneously means all decisions are done together in the product design phase, so that manufacturing and supply chain configuration can be prepared directly after the decisions are made. Researches on mathematical modelling in 3DCE area are increasing in the last 15 years. There are only seven papers found during 2000 - 2005, and eight papers found during 2006 - 2010. However, during 2011 - 2015, there is a significant increase where there are 16 papers. This fact led to the questions which become the objectives of our study that are “what is the most sub topics or focus of the researches?” and “what direction needed for researchers to develop 3DCE trade-offs modelling?”

3. Methodology
Selecting papers is the first step to review the literature. Journals in the areas of operation management, supply chain, product development, production economics etc. are collected using several databases such as Google Scholar, Scopus, Science Direct, Taylor & Francis, and Emerald. References of the paper are reviewed to add possible additional papers once the paper is identified. We use several key words for searching the references such as “3DCE”, “Three Dimensional Concurrent Engineering”, “integrated product process supply chain alignment”, “coordination product process and supply chain”, “matching product process and supply chain”, “integrated production and distribution planning”, and “concurrent engineering”. The papers with mathematical model are selected, we organize them into several categories based on sub topics or focus of the researches, and then the papers are analyzed.

4. Result and Discussion
After analyzing and organizing the papers, 35 papers are selected, the selected papers were presented in categories and can be seen in table 1, which classifies the papers based on dimensions. Fact that researches in trade-offs mathematical modelling are still scarce in 3DCE environment can be seen from the number of papers that is only five papers. We call these five papers as “real three dimensions” as they include all three dimension as decision variables and comprehensively coordinated all the three dimensions. The models presented in the other papers are limited to two-dimension model-based research, which are Product-Process, Product-Supply Chain, and Process-Supply Chain consideration.
Table 1. Papers selected based on dimensions.

| Dimensions                        | Authors                                      | Num. of Papers |
|-----------------------------------|----------------------------------------------|----------------|
| Product- Process (A-2D)           | Xu and Liang [7], Wu and O’Grady [8]         | 2              |
| Process- Supply Chain (B-2D)      | Cunha et al. [9], Graves and Willems [10], Kuang et al. [11], Shahrokhi et al. [12], Park et al. [13] | 5              |
| Product- Supply Chain (C-2D)      | Amini and Li [14], Chiu and Okudan [15], Chiu and Okudan [16], Deng et al. [17], ElMaraghy and Mahmoudi [18], Ernst and Kamrad [19], Famuyiwa and Monplaisir [20], Gabor and Abdelsalam [21], Jiang et al. [22], Nepal et al. [23], Baud-Lavigne et al. [24], Khalaf et al. [25], Khalaf et al. [26], Lamothe et al. [27], Langenberg et al. [28], Metta and Badurdeen [29], Moon et al. [30], Rezapour et al. [31], Syam and Bhattacharjee [32], Ulku and Schmidt [33], Wang et al. [34], Zhang et al. [35], and Zhang et al. [36]. | 23             |
| Product-Process-Supply Chain (3D) | Fine et al. [37], Huang et al. [38], Jafarian and Bashiri [39], Shidpour et al. [40] | 5              |

Table 2. Papers group based on sub topics.

| Sub Topics                        | Authors                                      | Dim    | Num. of Papers |
|-----------------------------------|----------------------------------------------|--------|----------------|
| 1. Modularity                     | Xu and Liang [7]                             | A-2D   | 9              |
|                                   | Cunha et al. [9]                             | B-2D   |                |
|                                   | Famuyiwa and Monplaisir [20], Baud-Lavigne et al. [24], Khalaf et al. [25], Khalaf et al. [26], Zhang et al. [35], Ernst and Kamrad [19], Fine et al. [37] | C-2D   |                |
| 2. Inventory and Supply Chain Consideration | Graves & Willems [10], Kuang et al. [11], Shahrokhi et al. [12], Park et al. [13], Chiu and Okudan [15], Chiu and Okudan [16], ElMaraghy and Mahmoudi [18], Gabor and Abdelsalam [21], Jiang et al. [22], Nepal et al. [23], Lamothe et al. [27], Langenberg et al. [28], Rezapour et al. [31], Syam and Bhattacharjee [32], Ulku and Schmidt [33], Wang et al. [34], Zhang et al. [36], Huang et al. [38], Shidpour et al. [40] | B-2D   | 20             |
|                                   | Chiu and Okudan [15], Chiu and Okudan [16], ElMaraghy and Mahmoudi [18], Gabor and Abdelsalam [21], Jiang et al. [22], Nepal et al. [23], Lamothe et al. [27], Langenberg et al. [28], Rezapour et al. [31], Syam and Bhattacharjee [32], Ulku and Schmidt [33], Wang et al. [34], Zhang et al. [36], Huang et al. [38], Shidpour et al. [40] | C-2D   |                |
| 3. Time to market                 | Deng et al. [17], Jafarian and Bashiri [39]  | C-2D   | 2              |
| 4. Product life cycle             | Metta and Badurdeen [29]                    | C-2D   | 1              |
| 5. Product rollover               | Moon et al. [30]                            | C-2D   | 1              |
| 6. Impact of dynamic demand       | Amini and Li [14]                           | C-2D   | 1              |
| 7. Design for assembly           | Wu and O’Grady [8]                          | A-2D   | 1              |
Product-Supply Chain model is the highest number with 23 papers, this is a significant indication that inventory management in the supply chain is strong as topic of interest. Meanwhile, Product-Process or Process-Supply Chain model is far less then Product-Supply Chain model with two and five papers respectively.

After grouping, the papers based on dimensions, the papers then grouped based on their focus of interest. The focus grouping result can be seen in table 2, it shows that at least there are 5 sub topics of trade-offs mathematical modelling, which are: (1) inventory allocation or supply chain perspective; (2) product modularity; (3) product development time or minimizing time to market; (4) product life cycle consideration; and (5) product substitution or rollover. From table 2 we can see that sub topic 1 and 2 have more number of research. However, for sub topic 3, 4, and 5, there are only a few. Based on this fact, we highly recommend future research must be conducted in the area of sub topic 3, 4, and 5. Minimizing time to market guarantees the new product to be in the market as fast as possible which increase product delivery, meanwhile considering product life cycle and product rollover maintain company competitiveness by ensuring the arriving of the new product at the right time.

Another remarkable point is a very limited 3D mathematical model literature in all sub topics. As can be seen in table 2, product life cycle and product rollover has no 3D model at all. Therefore, research on mathematical modelling for decision making in new product development are need to be accelerated in all sub topics of new product development, especially product life cycle consideration and product rollover.

5. Conclusion
The “real three dimensions” mathematical modelling research are still scarce which is shown by the number of papers that is only 5 papers. This number is far less than two-dimension model-based research, especially Product-Supply Chain model-based research. From this point of view, we recommend more research on 3D mathematical modelling that emphasis all three dimensions.

Regarding the limitations of literature found in all sub topics, it is necessary to recommend 3DCE mathematical modelling research in the area time to market, product life cycle, and product rollover for the future research, as those sub topics are very limited. It is prominent to answer such questions of how to consider product life cycle in the model, or how to put time to market as an objective function or constraint in the model, and how to consider rollover product as constraint or variable in the model.

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