# SYNOPSIS

of the PhD thesis

# Approaches to Supply Chain Coordination: Decomposed and Decentralised Decision Making Models

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**Anu Thomas**

Supervisors:

Prof. Mohan Krishnamoorthy
*Department of Mechanical and Aerospace Engineering, Monash University*

Prof. Jayendran Venkateswaran
*Industrial Engineering and Operations Research, IIT Bombay*

Dr. Gaurav Singh
*CSIRO Computational Informatics, Australia*

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# 1 Introduction

Supply Chain Coordination (SCC) focuses on optimising operations such as supply, manufacturing and distribution in the supply network of an enterprise, with the rationale of reducing costs and inventories, and maximising profit, asset utilisation and responsiveness of the entire network [6]. The issue is to achieve coordination without compromising the autonomy of individual units or partner organisations. SCC is a rapidly developing and challenging area in Supply Chain Management (SCM) and it provides ample opportunities for research [7, 16]. Thus, today's supply chain faces increasing pressures to remain competitive in the global marketplace.

Different modelling approaches can be used to address supply chain problems. An *integrated model* is one which combines the constraints and objectives of different (sub) decision-making units (DMUs) into a single, big optimisation system. However, in a coordinated system, DMUs operate separately and decisions—that potentially affect many other units—are shared between them. The quality of the coordination depends directly on the information that is shared between the units (or the 'players' in the system). If the players are not willing to share all of the information, then an attempt at an integrated model is extremely difficult. In general, the non-availability of shared resources such as vehicles and warehouses, creates major bottlenecks in production-distribution logistics. Integrated approaches are not always viable for large and complex supply chain coordination problems. Therefore, the development of alternative approaches for SCC becomes increasingly necessary.

The problem considered in this thesis is a large and complex multi-resource constrained scheduling problem (RCSP). Unlike traditional RCSP, in our problem, the resource manager has more than one way of meeting the requirements. This problem is partially motivated from the RCSP proposed in [9] and the coal supply chain problem discussed in [10].

In this thesis, new approaches for SCC are proposed using decomposed and decentralised decision-making models, based on the *Lagrangian relaxation* and *column generation* methods. These models can be employed appropriately based on information-availability and the levels of interaction between the DMUs. The aim of this research is (*i*) to provide a better understanding of decomposed and decentralised decision-making in supply chains and (*ii*) to develop an implementable decentralised decision-making approach for multi-party supply chains. This thesis presents the transition of solution approaches from integrated to decomposed and then to decentralised ones. The industry seeks a coordination approach that can deliver quality solutions in a reasonable amount of time without compromising the autonomy and confidential information of the individual DMUs. Therefore, we envisage that decentralised decision-making will be a prime enabler of SCC in the future.

## 1.1 Supply chain scenario

Our research is motivated by a coordination problem in Australian coal mines. The main players in this supply chain are *mines* and *mining units*, *ports*, *rail operators*, *track owners* and *terminal*. Coal normally ends up at the *terminals* or *ports* where it is loaded onto ships that set sail to their destination markets. Coal, which is mined at the various mines located at hinterlands, is usually transported by rail, subject to track and train availability. We start with a two-party coordination problem, which involves multiple mines and a common rail operator, and extend it to a three-party case by considering the terminal.

The coal shipping terminal receives orders from ships with an expected arrival date. A ship's order is made up of many parcels of coal. So, the terminal splits these ship-orders and passes them to the mines – along with suitable due-dates – in these smaller quantities (parcels). Every mine incurs an inventory cost at the mines, a stocking cost if the coal reaches the terminal before the due-date, and a demurrage cost for any late deliveries which necessitate the ship's late departure. The individual mines typically plan for and request trains of a particular class at appropriate times (so as to minimise their inventory holding and other costs). A single rail operator acts as a common resource manager that links the mines to the terminal. The rail operator provides the trains to transport the coal from the various mines to the terminal. The terminal also acts as a common resource and links all the mines. A mine is generally not concerned about the specific train that is allocated to it. The rail operator does not bother about the orders received at the terminal and at the mines. Similarly, the only decision that is important to the terminal is on-time procurement of coal from the mines, and its shipping. Nevertheless, the decisions of the mines, the rail operator and the terminal are, as is quite obvious, interlinked. The critical resources in this supply chain are: (*i*) the limited number of trains managed by the rail operator; *and* (*ii*) the limited number of unloading slots at the terminal.

# 2 Objectives of research

The overall objective of the research is to study decentralised decision-making approaches for a multi-party supply chain. To achieve this, the following objectives are identified and addressed in this thesis.

1. Conduct extensive literature review of supply chain coordination and different modelling approaches. Based on this, propose a classification and a framework for SCC models.

2. Identify and formulate mathematical models of coordinated/integrated production-

planning and resource-scheduling decisions in a two-player supply chain (anchored to a specific supply chain, namely, coal).

3. Develop decomposition approaches based on *Lagrangian relaxation* and *column generation* to solve the integrated problem. Explore various strengthening methods to improve convergence of the decomposition methods.

4. Benchmark and analyse the performance of decomposition approaches in solving large, realistic, randomly generated problem instances.

5. Identify the role of information-sharing in two-party supply chain and analyse the key components in decentralised decision-making. Then, propose a framework for the decentralised approach—which has limited access to the information and does not require any central coordinator. Develop a decentralised approach for the two-party case and quantify the impact of information-sharing and decentralisation.

6. Identify and formulate mathematical models of production-planning and resource-scheduling decisions in a decentralised three-player supply chain (anchored to a specific supply chain, namely, coal). Develop a decentralised decision-making framework, and quantify the impact of having an additional player and information-sharing.

7. Propose a generic framework and guidelines to develop and to implement decomposed and decentralised decision-making in multi-player supply chains.

## 3 Supply chain coordination models

Coordination models can be classified based on their operational and decision-making aspects. Different models can be grouped based on whether they are managed by a single operator or multiple operators or whether they have centralised decision-making or a decentralised decision-making model.

Theoretically, forming an integrated model is the *best* solution to solve the SCC issues. However, in reality, integrated models are not preferred or practical due to ($a$) lack of information availability, ($b$) the autonomy of DMUs and ($c$) large model size and higher complexity, for example. If the various operations are independent and if none of the players possess confidential or private information, then the various decision-making models can be decomposed and linked by a central coordinator. Decentralised approaches are useful when the DMUs possess some confidential/private information and there is no central information repository. In this thesis, we discuss three key modelling approaches.

**An integrated model** is a single decision-making model which includes all the constraints and objectives of all DMUs. We assume here that these are known, although this is often not the case in complex, multi-party supply chains. This can be modelled using an optimisation program (say) and solved using commercial solvers. Due to their size and complexity, integrated models are more difficult to handle when compared to the smaller sub-problems that could be formed and considered for each of the DMUs. Moreover, such a model requires complete information-sharing.

**Decomposed models** allow us to split the integrated model into easily-solvable sub-problems. There are many popular decomposition techniques such as the *Lagrangian relaxation* and the *column generation*. The traditional implementation of these algorithms involves a central player/coordinator to update the bounds and the multipliers.

**Decentralised models** are inspired from the decomposed models which do not have any centralised player. The bounds are updated using decentralised methods. Compared to the previous approaches, the decentralised model requires only minimal information-sharing. The quality of solutions may not be good as compared to the solutions from the decomposed models.

Figure 1 shows the flow of the thesis, which address the supply chain coordination using different modelling approaches. We have developed two decomposition approaches (see Chapters 4 and 5) and two decentralised approaches (see Chapters 6 and 7) in this thesis. Even though the coal supply chain is taken as an example, the proposed models can be applied to any coordination problem which has a similar structure.

## 3.1 Decomposed approaches for supply chain coordination

In the two-party coal supply chain, multiple independent mines (producers) need to coordinate with a rail operator (resource manager) to improve their performance. The production planning for each mine will include constraints such as inventory balancing, production capacity and order satisfaction. Backlogs are not permitted at mines. The rail operator has a pool of trains of different *classes*, classified based on the rake capacity and other features. Individual mines typically plan for and request trains of a particular class at appropriate times, irrespective of the demands from other mines. A mine is not necessarily concerned about the specific train that is allocated to it. The scheduling of specific trains that satisfy a set of jobs is a separate and non-trivial decision that needs to be made by the rail operator.

Thus, for such problems, the use of a single integrated model is not viable. The special structure of the constraint matrix allows us to decompose the overall problem into

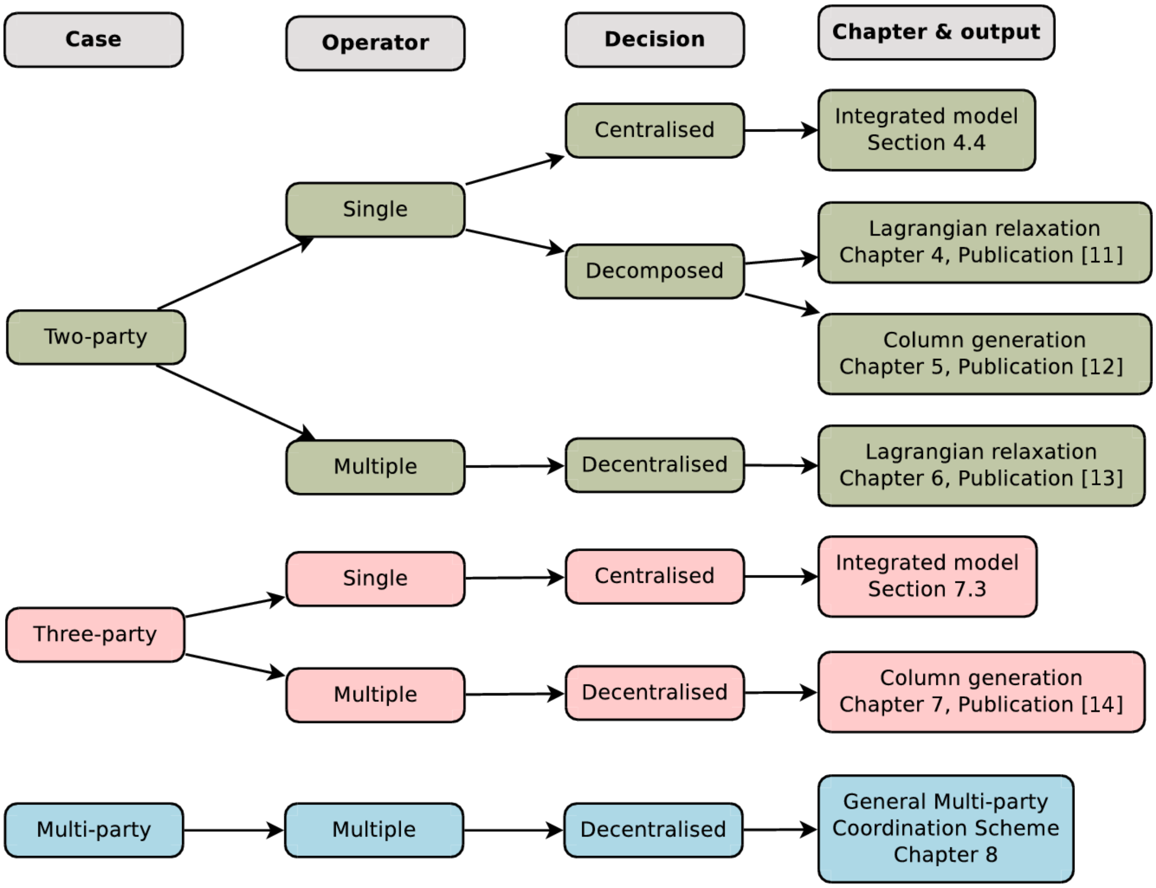


Figure 1: Schematic view of the thesis

one problem for each of the $n$ mines *if* we ignore the train (resource) availability constraint. This creates $n$ easily solvable production planning problems, provided we have one resource-scheduling problem linking the single rail operator and the (many) mines. Thus, we decompose the problem into two parts:

**Production planning** Each mine plans their production based on their priorities and their objective and places a set of requests to the rail operator for a certain class of trains. In other words, each mine defines a set of *jobs* with certain properties in order to meet their orders. The objective of the mines is to minimise the total cost of inventory holding, the demurrage, and the cost of order placing.

**Resource scheduling** After receiving the requests (jobs) from the mines, the rail operator prepares a schedule based on resource availability. A simple merge of requests for the resource utilisation may not be globally feasible with respect to the resource constraint. This problem is equivalent to a job scheduling problem. The objective of the rail operator is to minimise total weighted tardiness and earliness.

A feasible schedule needs to: $(i)$ assign the right combination of train-classes to mines, and $(ii)$ create a schedule of resource allocations for the rail operator. Each train trip is considered as a *job*. The orders that are given to the producers need not have one-to-one correspondence with jobs. Usually, more than one job is required to meet a complete order. It is also possible that one job might also satisfy two separate orders. Multiple orders and the indefinite nature of resource allocation make this problem unique.

A decomposed decision-making approach based on the *Lagrangian relaxation* for an integrated planning and scheduling problem is proposed (see Chapter 4). The proposed decomposition scheme splits the production planning and resource-scheduling decisions. The *Lagrangian relaxation* method based on sub-gradient optimisation exhibits slow convergence, especially when it has a small step size [15]. Therefore, the proposed approach is strengthened with the Volume algorithm [2], the Wedelin algorithm [17] and an heuristic to compute the upper bound.

A process to benchmark the distributed approaches against the integrated model using a computational experiment is also illustrated. It includes the data generation, experiment design, implementation, and analysis with different performance measures. 240 randomly generated instances were generated in eight series with 30 instances per series. Each series represents a scenario with $5, 6, 7, 8, 9, 10, 12$ or 15 mines. The strength of the algorithm is demonstrated by comparing its performance with the integrated MILP model, via extensive computational experiments. While the LR-based approach achieves less than 10% gap in 198 (82.5% of) instances, the MILP could not find a single solution in 111 (46% of) instances. The results show that the decomposed algorithm found significantly better lower and upper bounds than MILP.

Since the speed of convergence of the LR algorithm for large problems is not good as it is for the small problems, Dantzig-Wolfe decomposition together with a *column generation* technique was explored further to solve the two-party coordination problem (see Chapter 5). A CG algorithm has two components: *master problem* (MP) and sub-problems. The master problem (MP) is the train scheduling problem which does not have any production considerations. The production planning problem is considered in the sub-problems. The solutions (schedules) of each mines form the columns of the MP, from which a globally feasible solution is obtained. This method is computationally efficient compared to the LR method because it stores and manages multiple solutions at the same time. The proposed algorithm is strengthened with many techniques, including two-levels of stabilisation (See [5, 8, 1]). Similar to the LR-based approach, the CG-based approach was compare to the integrated model using different performance measures. The decomposed approaches compute a better solution than the integrated approach, with a relative gap less than 20% in almost all cases, with the CG approach outperforming LR approach. The CG could achieve less than 10% relative gap in 232 (97% of) instances. From elaborate computational experiments we conclude that the distributed and decomposed decision-making is preferable to the integrated approach.

## 3.2 Decentralised approaches for supply chain coordination

The decomposition models can be viewed as single-operator distributed models, where the single-operator uses centralised information to update the bounds and the multipliers. As an alternative, a *truly decentralised decision-making* approach which comprises of (*i*) multiple stakeholders, (*ii*) information asymmetry, (*iii*) conflict in objectives, and (*iv*) a negotiation protocol, is explored for the two-party and the three-party coordination problems (see Chapters 6 and 7).

The mines and the rail operator possess different sets of information. Hence the decision model has an inherent information asymmetry. The objectives of (each of) the mines and the rail operator are different. Every mine expects the rail operator to send a train to their mine to load the coal and deliver it ontime to the terminal. However, the rail operator may have different priorities and constraints. Hence there is a conflict in the objectives of the players. Decomposed approaches are not *truly* decentralised because there is no 'negotiation mechanism' in these models. In our approach, the negotiation protocol is partially implemented within the CG algorithm which is (in a sense) 'controlled' by the 'honest broker' rail operator. This allows the DMUs to be independent without revealing all of the information. The decomposed approaches expect the DMUs to share dependent information, with the DMUs managed/controlled by a central coordinator. Therefore, we further reduced the information sharing and the role of the central coordinator to develop *decentralised* approaches.

Information-sharing plays a key role in decentralised decision-making. The role of information-sharing and other factors in two-party coordination problems is analysed. Based on this analysis, we developed a decentralised approach which has limited access to the information and does not require any central coordinator. In a decentralised approach the lower bound and upper bound should be computed using decentralised methods. The *secure-sum* method [4] has been used to compute the lower bound so that no player will be able to find out the true objective cost of other players, but will be aware of the total supply chain's costs. We have developed a few heuristics to improve the upper bound that which does not require any central information. In the two-party decentralised case, the number of players is two and hence, the value of a column cannot be computed without revealing the actual cost. Hence, the CG algorithms cannot be deployed for the two-party decentralised case. Therefore, LR approach is extended to develop the decentralised approach for the two-party case. The impact of the decentralisation and the value of two critical pieces of information in the coal supply chain—(*i*) production capacity and (*ii*) resource availability—are analysed and compared with different performance measures. The results of computational experiment show that the lower bounds of the iterative algorithm can be significantly improved by sharing the necessary information. The overall comparison using the confidence intervals shows that resource availability information is more critical than production capacity information.

Even though the coordination problem with a single resource manager is complex and difficult, we extend the decentralised approach for the three-party case (Chapter 7) by adding one more common resource (the terminal to the coal supply chain). This is required as a step to generalise the decentralised decision-making approach for larger problems which has multiple shared resources. In the three-party case, there are two resource managers to link independent producers. The critical resources in the three-party coal supply chain are: (*i*) the limited number of trains managed by the rail operator; *and* (*ii*) the limited number of unloading slots at the terminal. The proposed decentralised scheme has two sets of multipliers—each one corresponding to the linking constraint of the two resource managers. The main challenge in designing a decentralised approach based on CG is computing the value of a column, updating multipliers and generating globally feasible columns. The three-party distributed decision-making models are also compared with the integrated model using extensive computational experiments (100 randomly generated data sets with 6, 9, 12 and 15 mines, a rail operator and a terminal). The computational results highlight the impact of an additional player and the value of information-sharing. The results show that the decentralised model could achieve better or equivalent solutions compared to that from the integrated model with significantly less information and interactions.

## 4 Generalisation to multi-party cases

A multi-party coordination problem can also be seen as an extension to the three-party case with additional shared resources. The decentralised decision-making approach based on decomposition techniques can be extended to the multi-party case as well, with suitable customisation. The number of multipliers might grow as the number of linking constraints increases.

The proposed decentralised approaches, for two-party and three-party cases, provide a framework of decentralised approaches for multi-party cases. Based on the experience of implementing different decomposed and decentralised models, we propose a framework, in Figure 2, for the multi-party case. The arrows in Figure 2 represent the flow of information and decisions. The decisions are made in two stages. In the first stage, each producer generates columns—which are the building blocks of globally feasible solutions—and the value of columns is computed by the *secure-sum* method. In the second stage, a best combination of columns will be selected such that it is feasible for all the DMUs. If there is any infeasibility or a chance for improvement, then feedback on resource utilisation is given in terms of the dual-prices of complicating linking-constraints.

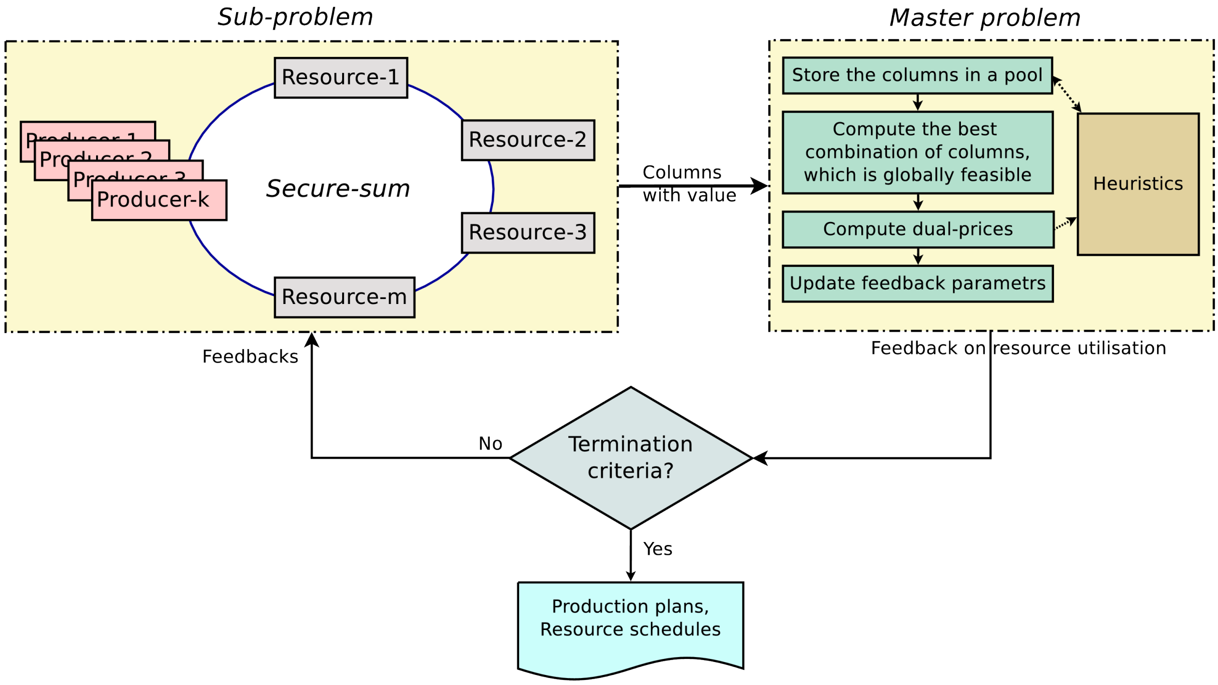


Figure 2: A decentralised decision-making framework for multi-party cases

Decentralised decision-making is closer to real-life industrial instances with some inefficiencies [3]. The real challenges in designing a decentralised decision-making model are, the ability to $(i)$ compute better bounds in order to tighten the search space, $(ii)$ handle multiple objectives, $(iii)$ design a negotiation scheme and proper incentive mechanisms, and $(iv)$ ensure information security and privacy. Our proposed models address all of these challenges to some extent. However, these models can be further improved with suitable customisation.

## 5 Conclusions

In this thesis, we explore alternative approaches for supply chain coordination using decomposed and decentralised decision-making models. We have analysed a coordinated production-planning and resource-scheduling problem that exists between a set of independent producers and a common resource manager. This is a multi-resource constrained scheduling problem. A coal supply chain coordination problem is considered as an example. Elaborate computational experiments were used to benchmark different modelling approaches using randomly generated data instances. Although the methods that have been developed in this thesis are validated within the context of a coal supply chain, it can be extended to other general RCSPs in contexts such as airline, wine, automobile manufacturing and also the service industry.

Decomposition is a proven technique for factorising large structured optimisation problems. The novelty of our research is in developing decentralised decision-making approaches based on well-studied decomposition techniques. The players in a supply chain have to share some amount of information to achieve coordination. The decentralised approach does not require any additional information. Also, it protects the autonomy of all the players. Therefore, it is suitable for industries which are looking for a coordination approach that can deliver quality solutions in a reasonable amount of time.

The major insights from the thesis are: (*i*) classification and discussion about supply chain coordination models, (*ii*) decomposed and decentralised approaches based on LR, and CG, (*iii*) mathematical models for the integrated problems, production planning and resource scheduling, (*iv*) a few heuristics to improve performance and convergence, (*v*) elaborate computational experiments and comprehensive discussion of the results, and (*vi*) a discussion on the 'value of information' and its role in SCC.

To conclude, we have proposed a scalable and robust, decentralised framework of decision-making for a multi-party supply chain, that is a better alternative to the integrated approach. It requires only minimal information sharing between the players and guarantees convergence by means of the underlying decomposition algorithm. The approach can be used even as the level of coordination (information-sharing) improves. The proof of the concept has been demonstrated using a large and complex multi-party coal supply chain.

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