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The Role of Data Quality and Visibility in Risk Management and Performance Optimization in the Downstream Supply Chain

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A R T I C L E I N F O

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A B S T R A C T

One of the objectives of this research is to analyze the relationship between the quality of shared data and risk management in the supply chain. In this regard, a function for measuring visibility based on the data quality dimensions has been defined, and dimensions that are more significant in the downstream supply chain have been identified and introduced. Subsequently, a single-objective mathematical model for production planning, allocation, and pricing, considering data quality and risk was developed. Moreover, its applicability and validity were examined by solving a numerical example using GAMS software. This study highlights the importance of data quality in supply chain management, especially in the downstream supply chain where data quality significantly impacts decision- making. The results of this study can assist supply chain decision-makers in identifying the most critical dimensions of data quality and prioritizing their efforts to improve data quality. The proposed approach can also contribute to cost reduction and performance improvement by optimizing related decisions. Overall, this research contributes to the existing literature on supply chain management and data quality by providing a comprehensive framework for assessing the impact of data quality on supply chain visibility and risk management.

Introduction

It is no secret that the business landscape is undergoing significant changes. Especially considering the disruptive events of recent years, such as the COVID-19 pandemic and the war in Ukraine, companies are striving intensely to maintain their positions in competitive markets.

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In such conditions, the preparedness of the supply chain to confront existing risks and threats is more necessary and crucial than ever. Natural disasters, demand variability, uncertain delivery times, supply uncertainties, costs, and inter-organizational issues are recognized as common sources of supply chain risk (SCR), which can lead to significant economic losses and poor supply chain performance (Rajagopal et al., 2017).

Supply Chain Visibility (SCV) is one of the effective and important ways to deal with various disruptions, dangers, and risks present in supply chains. Managing supply chain disruptions within a network of suppliers, operations, and global markets has increased the focus on transparency to achieve sustainable and competitive business performance. In fact, transparency has become one of the foremost concerns raised by manufacturing companies (Swift et al., 2019)

Supply chain transparency and data sharing are closely related. The critical point in this regard is the quality of data shared among supply chain members (Kalaiarasan et al., 2022). Numerous studies have highlighted the fact that poor data quality limits the scope of SCV. Despite the immense importance of data quality in today's businesses, there are many reports indicating insufficient investment to improve it. Although many research works have studied data quality and SCV separately, the application of data quality in supply chain decision-making to meet data-driven requirements, especially in downstream issues, has not been investigated. In addition to monitoring and tracking disruptions from an upstream perspective, observing downstream operations is equally essential, as deficiencies in customer service directly impact company sales (Sodhi & Tang, 2019). Transparency plays a significant role in preventing costs associated with warehousing, backorders, and excess inventory (Swift et al., 2019).

Transparency and supply chain risk are topics that have seen extensive research in recent years. Tse and Tan (2012) modeled a company's end-to-end supply chain for managing product quality risk and assessing SCV under a multi-sourcing strategy. They found that better transparency can minimize the risk of product damage. According to their conclusions, incorrect data and unclear information about product quality risk in the chain can lead to crises and product damage.

Shabani-Naeeni and Ghasemy Yaghin (2021) examined the impact of the quality of exchanged data between suppliers and buyers in addressing various risks and uncertainties related to supplier selection, and they planned the procurement of raw materials leveraging the synergistic effects of suppliers. In their research, while measuring overall data transparency, they analyzed the effect of exchanged data quality on supplier selection and order allocation issues. The study showed that high data quality can enhance the supply chain decision-making process. In another study, the issue of supply chain planning under risk was considered with respect to the capability of information transparency and sourcing flexibility. A new index was developed to measure purchasing transparency, emphasizing the role of data quality in providing transparency and addressing supply chain risks (Ghasemy Yaghin, 2024).

This research aims to introduce a two-tier supply chain, consisting of a manufacturer and several retailers, to examine the impact of shared data quality on managing existing risks within the chain. Additionally, by presenting a transparency function, objectives such as the required level of transparency and the integration of mid-term supply chain decisions will be determined. This research seeks to identify the relationship between data quality and risk management in the downstream supply chain, as well as to analyze the effects of transparency on the overall performance of the chain. Furthermore, filling the gap in the literature regarding the identification of important dimensions and characteristics in examining the quality of shared data in the downstream supply chain is another objective of this research.

Problem Statement

Consider a two-tier supply chain consisting of a manufacturer and several retailers that are integrated and have a single planner. The manufacturer is responsible for planning and managing the supply chain and physical supply channel to retailers, making decisions such as determining optimal production levels and allocating products to each retailer, as well as overseeing output transportation operations. On the other hand, each chain faces various risks and dangers that continuously affect performance, profitability, and resilience. Transparency is an effective factor that, in addition to impacting chain performance, plays a key role in confronting and even preventing various risks.

To model the aforementioned cases, the problem of two-tier supply chain planning (production-retail) is assumed with the objective of maximizing chain revenue, including one manufacturer, several retailers, multiple products, over a mid-term horizon and with a specified number of time periods. The focal company seeks to find the optimal production quantity for each product and optimal allocation to retailers. Shortages are not permitted, and the production capacity, production budget, transportation, and transparency are also limited and specified. The initial inventory of products is assumed to be zero. The demand for products is a function of their prices, and decision-making regarding their pricing and demand management is also on the agenda.

The mentioned supply chain planner faces three types of risks, including production risk, transportation risk, and demand risk. Information sharing and the resulting transparency are utilized to manage the existing risks in the chain. Transparency is considered a multidimensional component, and its function is measured. The impact coefficient of transparency on each type of risk is defined as a specific value. In general, the decision-making variables in the model, which aim to find answers considering the effect of transparency on costs and existing risks in the problem, are as follows:

- **Production Decisions:** Including whether to produce or not for each product and determining the optimal production level in each period.
- **Allocation Decisions:** Allocation or non-allocation and determining the optimal allocation level of each product to each retailer in each period.
- **Pricing Decisions:** Setting the selling price of products and managing demand in each period.

Supply Chain Transparency Decisions: Intervening with various dimensions of the quality of shared data.

Notation

Sets:

Time periods: t
Dimensions of data quality: d
Products: p
Retailers: r

Parameters:

Impact intensity of transparency on production risk of product p in period t: α
Variable cost of producing product p in period t: C_{pt}
Impact intensity of transparency on transportation risk of product p: β
Fixed cost of producing product p in period t: F_{pt}
Impact intensity of transparency on demand risk of product p: γ
Cost of sending each unit of product p to retailer r in period t: ${C^{Sh}}_{prt}$

Probability of production risk for each unit of product p in period t: $P(R^M{}_{pt})$
Distance from manufacturer to retailer r: S_r
Probability of transportation risk for product p to retailer r in period t: $P(R^{Sh}{}_{prt})$
Holding cost of product p in the manufacturer's warehouse in period t: h_{pt}
Probability of demand risk for each unit of product p at retailer r in period t: $P(R^D{}_{prt})$
Holding cost of product p at retailer r in period t: h'_{prt}
Impact of production risk for each unit of product p in period t: $I(R^M{}_{pt})$
Maximum cumulative demand function for product p at retailer r in period t: a_{prt}
Price elasticity of demand function for product p at retailer r in period t: b_{prt}
Impact of demand risk for each unit of product p at retailer r in period t: $I(R^D{}_{prt})$
Maximum production capacity of product p in period t: Cap_{pt}
Cost of mitigating or addressing each unit of production risk for product p in period t: $C^{MR}{}_{pt}$
Available production budget for product p in period t: $B^M{}_{pt}$
Cost of mitigating or addressing each unit of transportation risk for product p to retailer r in period t: $C^{ShR}{}_{prt}$
Available budget for transporting products in period t: $B^{Sh}{}_t$
Cost of mitigating or addressing each unit of demand risk for product p at retailer r in period t: $C^{DR}{}_{prt}$
Cost of improving each unit of transparency for product p at retailer r in period t: $C^V{}_{prt}$
Maximum allowable production risk for product p in period t: $U^M{}_{pt}$
Profit from each unit of transparency for product p at retailer r in period t: $Pr^V{}_{prt}$
Maximum allowable transportation risk for product p to retailer r in period t: $U^{Sh}{}_{prt}$
Maximum allowable demand risk for product p at retailer r in period t: $U^D{}_{prt}$
Minimum required transparency for product p at retailer r in period t: MV_{prt}
A large positive number: BN

Decision Variables:

Selling price of each unit of product p at retailer r in period t: Pr_{prt}
Production quantity of product p in period t: x_{pt}
Binary variable for producing or not producing product p in period t: Z_{pt}
Allocation quantity of product p to retailer r in period t: y_{prt}
Binary variable for allocating or not allocating product p to retailer r in period t: Z'_{prt}
Ending inventory of product p in period t at the manufacturer: I_{pt}
Ending inventory of product p at retailer r in period t: I'_{prt}

Functions:

Transparency function of product p in retail r in period t: V_{prt}
Price-dependent demand function of product p in retail r in period t: $D(Pr_{prt})$

Supply Chain Transparency Function

Supply chain transparency refers to the ability to share high-quality data among different stages of the chain, including suppliers, manufacturers, etc. (Kalaiarasan et al., 2022). This data includes customer demand, inventory levels, and transportation costs, but is not limited to these. Quantitative measurement of the level of SCV is conducted to identify weaknesses and areas for improvement, as well as to determine the value of increasing transparency and its resulting effects, including its impact on performance and the prevention of various risks. The relationship concerning supply chain transparency is defined as follows. Relationship (1) illustrates the transparency of each product at each retailer and is defined based on the dimensions of data quality. In fact, V_{prtd} refers to the transparency from the perspective of dimension d of the data quality of product p at retailer r in period t.

$$V_{prt} = \sqrt[|D|]{\prod_{d=1}^{|D|} V_{prtd}} \qquad \forall p,r,t \qquad (1)$$

Dimensions of Data Quality

As mentioned, to determine the level of transparency for each product, it is necessary to identify the quality characteristics used in the model. A review of the literature reveals that researchers have utilized various dimensions of data quality depending on their research type and field of study. Therefore, the quality dimensions used in the supply chain, particularly those related to downstream conditions and characteristics, are collected and introduced below.

1. **Accuracy:** This quality dimension has always been a focus in various research fields and is one of the most frequently discussed dimensions in all research areas. Definitions of accuracy vary. In one study, it is defined as the degree of alignment between the stored data in the database and the actual values in the real world (Ballou & Pazer, 1985). In another study, accuracy is defined as the correctness, reliability, and validation of data (Wang & Strong, 1996). If the data is not accurate and correct, it may lead to incorrect decisions. This characteristic has been repeatedly mentioned in studies conducted in the field of supply chain data quality (Hazen et al., 2014; Shabani-Naeeni & Yaghin, 2021).

2. **Timeliness:** This dimension is a key aspect of data quality that focuses on ensuring that the data used for decision-making and analysis is current and reflects the most up-to-date information available (Hazen et al., 2014). In summary, this characteristic indicates the recency of the data. In various studies, data timeliness has been divided into two aspects: the duration since the last update of the data and the intensity or frequency of updates (Shabani-Naeeni & Yaghin, 2021). Both aspects are of significant importance in the downstream supply chain, where activities such as inventory management, order fulfillment, and customer interaction take place.

3. **Completeness:** This refers to the extent of data in terms of content and the alignment of values for all expected characteristics. In other words, it indicates the degree to which the data has sufficient breadth, depth, and range for the intended task. When discussing data completeness, the volume of data is also considered, defined as the appropriateness of the amount and number of data points (Wang & Strong, 1996). If attention is not paid to the volume of data, the transparency index may indicate a desirable and acceptable value, but in practice, the calculated transparency may not exist, and the index may not represent a good status of data transparency in the chain.

4. **Velocity:** This, in big data, refers to the rate at which data is generated and the speed at which it should be analyzed (L'heureux et al., 2017). The agility of the supply chain and the rapid response to demand changes and other important factors in the

downstream chain have heightened the need to pay attention to this quality dimension; thus, velocity plays a key role in ensuring the quick transmission, sharing, and utilization of data. In a study aimed at measuring the impact of data dimensions on the bullwhip effect, it was concluded that the speed dimension of data has the greatest impact on supply chain performance (Hofmann, 2017).

5. **Trust:** Trust, including credibility, reliability, and reputation, refers to the amount of data obtained from a credible source (Batini, 2015). The reputation of a data source indicates the perception of its credibility, accuracy, and consistency in providing high-quality data. Since increasing agility and rapid response to changes is always one of the operational goals of the supply chain, there must be complete trust in the credibility of the data upon which decisions are made. Therefore, one of the important dimensions of data quality in this field is trust in the data. This quality dimension has been repeatedly highlighted and utilized in various studies (Shabani-Naeeni & Yaghin, 2021).

Mathematical Modeling

The proposed mathematical model is a mixed-integer nonlinear single-objective model with a number of constraints. The objective function of the model, as presented in Equation (2), is of the type of maximizing supply chain profit, expressed as the difference between total revenues and costs. The total revenues considered include two components: revenues from product sales and revenues from providing transparency to other stakeholders. The costs include fixed and variable production costs, transportation costs, storage costs at the manufacturer and retailer, costs associated with creating transparency, and risks related to production, transportation, and demand for products. Since holding inventory at lower levels in the chain incurs higher costs, and there is always an effort to maintain products at higher levels in the chain, the costs related to storage are considered separately based on the location of inventory storage.

$$
\begin{aligned}
Max\ TP = & \sum_{p}\sum_{r}\sum_{t} Pr_{prt} .D\left(Pr_{prt}\right) + \sum_{p}\sum_{r}\sum_{t} Pr^{v}_{prt} \times \sqrt[|D|]{\prod_{d} v_{prtd}} \times Z'_{prt} \\
& - \sum_{p}\sum_{t} c_{pt} x_{pt} - \sum_{p}\sum_{t} F_{pt} Z_{pt} - \sum_{p}\sum_{r}\sum_{t} c^{Sh}_{prt} s_{r} y_{prt} - \sum_{p}\sum_{t} h_{pt} I_{pt} \\
& - \sum_{p}\sum_{r}\sum_{t} h'_{prt} I'_{prt} - \sum_{p}\sum_{r}\sum_{t} c^{v}_{prt} \times \sqrt[|D|]{\prod_{d} v_{prtd}} \times Z'_{prt} \\
& - \sum_{p}\sum_{t} P\left(R^{M}_{pt}\right).I\left(R^{M}_{pt}\right) \times \left(1 + \frac{\sum_{r} \sqrt[|D|]{\prod_{d} v_{prtd}}}{|R|}\right)^{-\alpha} \times c^{MR}_{pt} Z_{pt} \\
& - \sum_{p}\sum_{r}\sum_{t} P\left(R^{Sh}_{prt}\right).I\left(R^{sh}_{prt}\right) \times \left(1 + \sqrt[|D|]{\prod_{d} v_{prtd}}\right)^{-\beta} \times c^{ShR}_{prt} Z'_{prt} \\
& - \sum_{p}\sum_{r}\sum_{t} P\left(R^{D}_{prt}\right).I\left(R^{D}_{prt}\right) \times \left(1 + \sqrt[|D|]{\prod_{d} v_{prtd}}\right)^{-\gamma} \times c^{DR}_{prt} Z'_{prt}
\end{aligned}
\qquad (۲)
$$

s.t:

$$I'_{pr(t-1)} + y_{prt} \geq D(Pr_{prt}) \qquad \forall p,r,t \qquad (۳)$$

$$x_{pt} \leq Cap_{pt} Z_{pt} \qquad \forall p,t \qquad (۴)$$

$$c_{pt} x_{pt} + F_{pt} Z_{pt} \leq B^{M}_{pt} \qquad \forall p,t \qquad (۵)$$

$$\sum_{p}\sum_{r} c^{Sh}_{prt} s_{r} y_{prt} \leq B^{Sh}_{t} \qquad \forall t \qquad (۶)$$

$$\sum_{r} c^{v}_{prt} \times \sqrt[|D|]{\prod_{d} v_{prtd}} \times Z'_{prt} \leq B^{v}_{pt} \qquad \forall p,t \qquad (۷)$$

$$\sqrt[|D|]{\prod_{d} v_{prtd}} \geq MV_{prt} Z'_{prt} \qquad \forall p,r,t \qquad (۸)$$

$$I_{pt} = I_{p(t-1)} + x_{pt} - \sum_{r} y_{prt} \qquad \forall p,t \qquad (۹)$$

$$I'_{prt} = I'_{pr(t-1)} + y_{prt} - D\left(Pr_{prt}\right) \qquad \forall p,r,t \qquad (۱۰)$$

$$P\left(R^{M}_{pt}\right) I\left(R^{M}_{pt}\right)\left(1 + \frac{\sum_{r} \sqrt[|D|]{\prod_{d=1}^{|D|} V_{prtd}}}{|R|}\right)^{-\alpha} Z_{pt} \leq U^{M}_{pt} \qquad \forall p,t \qquad (۱۱)$$

$$P\left(R^{Sh}_{prt}\right) I\left(R^{Sh}_{prt}\right)\left(1 + \sqrt[|D|]{\prod_{d=1}^{|D|} V_{prtd}}\right)^{-\beta} Z'_{prt} \leq U^{Sh}_{prt} \qquad \forall p,r,t \qquad (۱۲)$$

$$P\left(R^{D}_{prt}\right) I\left(R^{D}_{prt}\right)\left(1 + \sqrt[|D|]{\prod_{d=1}^{|D|} V_{prtd}}\right)^{-\gamma} Z'_{prt} \leq U^{D}_{prt} \qquad \forall p,r,t \qquad (۱۳)$$

$$y_{prt} \leq BN .Z'_{prt} \qquad \forall p,r,t \qquad (۱۴)$$

$$D\left(Pr_{prt}\right) = a_{prt} - b_{prt} .Pr_{prt} \qquad \forall p,r,t \qquad (۱۵)$$

$$x_{pt}, y_{prt}, I_{pt}, I'_{prt}, Pr_{prt} \geq 0 \qquad \forall p,r,t \qquad (۱۶)$$

$$I_{pt} = 0 , I'_{prt} = 0 \qquad \forall p,r,t = 0 or T \qquad (۱۷)$$

$$Z_{pt}, Z'_{prt} \in \{0,1\} \qquad \forall p,r,t \qquad (۱۸)$$

Constraint (3): Ensures that the demand for each product at each retailer is satisfied. Constraint (4): Guarantees that the production quantity of each product does not exceed its production capacity. Constraints (5) to (7): Ensure that the costs of production, transportation, and transparency do not exceed the allocated budget for them. Minimum required transparency for each product at each retailer is shown in Relation (8). Inventory at the end of the period at the manufacturer and retailer is indicated in Relations (9) and (10). Constraints (11) to (13): Specify the maximum allowable risks for production, transportation, and demand. The relationship between binary and continuous variables related to the allocation of products to retailers is defined in Constraint (14). Constraint (15): Calculates the price-dependent demand function for each product at each retailer. Finally, the sign constraints for decision variables are presented in Relations (16) to (18).

Numerical Example

In this section, a numerical example is solved to validate the proposed model and ensure its proper functioning. A supply chain with one manufacturer and three retailers, producing three products over a four-period horizon, is considered, taking into account the five dimensions of data quality introduced in this research. Other parameters of the problem are generated based on logical relationships. The proposed mathematical model is coded in GAMS software and executed using an AMD-FX9800P parallel processing system with 16 GB of RAM, employing the BARON solver, and its operational validity has been proven. Some final results of the decision variables after solving the model are shown in Tables 1 to 3.

Table 1. Production and End-of-Period Inventory of Each Product in Each Time Period

	Product Amount				**End Inventory at Manufacturer**			
Product	Period 1		Period 3	Period 4	Period 1	Period 2	Period 3	Period 4
1	2315.496	-	-	-	2199.582	1140.325	6.991	-
٢	558.562	-	-	-	74.076	-	-	-
٣	1511.127	-	-	-	1109.563	1109.563	1109.563	-

Table 2. Allocation of Products to Retailers in Each Period

Product	Retailer	Period 1	Period 2	Period 3	Period 4
1	1	115.914	-	-	-
	2	-	1059.258	1133.333	-
	3	-	-	-	6.991
2	1	-	-	-	-
	2	484.486	74.076	-	-
	3	-	-	-	-
3	1	-	-	-	-
	2	401.564	-	-	1109.563
	3	-	-	-	-

Table 3. Transparency and Selling Prices of Products at Retailers in Each Period

1 Product							Product 2				Product 3		
	Retailer	Period 1	Period 2	Period 3	Period 4	Period 1	Period 2	Period 3	Period 4	Period 1	Period 2	Period 3	Period 4
Transparency Function Value	1	2.491	2.702	2.491	1.516	2.169	1.741	1.888	2.491	1.644	1.741	1.783	2.639
	2	2.352	1.516	2.702	2.169	1.149	1.644	2.048	3.288	1.888	3.104	2.297	1.888
	3	3.288	1.741	2.297	3.178	3.366	1.516	2.862	2.221	2.297	2.169	2.000	2.297
The Selling Price of Products	1	1034	1089	1070	1076	1194	1240	1199	1230	1952	1887	1858	1851
	2	836	1071	1027	982	1175	1150	1158	1012	1937	1575	1484	1904
	3	1075	1056	1001	1073	1133	1192	1174	1203	1877	1892	1851	1895

Conclusion

Conclusion and Summary

In this research, the effects of data quality and transparency in the supply chain on risk management and costs were examined. Initially, a function was defined to measure transparency based on the qualitative dimensions of the data. To this end, five quality dimensions that hold greater significance in the downstream supply chain were introduced. Subsequently, a single-objective mathematical model was defined and presented for the issues of production, allocation, and pricing, considering transparency and supply chain risks. Finally, the applicability and validity of the proposed model were assessed through the solution of a numerical example.

Further investigation into data quality in other segments of the supply chain, the identification of dimensions with increased importance in other areas, and the consideration of additional factors contributing to risk and uncertainty are suggested for improving work in this domain..

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