Determinants of Automobile Part Packaging Optimization : An fsQCA Approach

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Abstract
In this study, we examine the factors that determine the success or failure of package planning that involves adjusting the shape or size of automobile parts and their assembly processes. Using fuzzy set qualitative comparative analysis of 15 cases identified in four Japanese automobile companies, we found that to optimize the packaging by adjusting parts' shape or size and assembly processes, collaboration between the logistics department and other departments is a necessary (core) condition, while front-loading of package planning based on early input of parts design information, transportation distance, and changes in production equipment or layout are included in the combination of sufficient conditions, but are not necessary conditions.

Key words: Package planning, Front-loading, fsQCA

1. Introduction

Package planning is an important aspect of the supply chain operations of automobile manufacturers. Vehicle assembly plants receive thousands of parts from Tier 1 parts makers daily. How these parts are packaged has a significant impact not only on procurement logistics costs but also on the efficiency of the entire supply chain operation, including the assembly process.

The Japanese Industrial Standards glossary defines the term "package" as "the outer shape of goods to be transported, stored and handled, including both packaged and unwrapped goods." Package planning includes activities such as designing and selecting packages by comprehensively examining factors such as the shape, properties, and value of materials, logistics efficiency, customer requirements, shipping lot, transportation and material handling requirements, and laws and regulations. In the case of automobile parts, package planning has traditionally been considered to include the following tasks: designing and selecting specific containers, determining the standard number of packages (SNPs), the placement of parts, and selection of inner materials (dunnage and attachments). The main purpose of packaging is to protect the parts in transit and maximize operational efficiency.

In practice, package planning has traditionally been based on predetermined part designs, resulting in limited improvements in efficiency. Therefore, in recent years, many Japanese automobile manufacturers have attempted to broaden the scope of package planning to include adjustments to parts' shape, size, and assembly processes with the aim of optimizing packaging. For instance, it was found that after making some minor changes to parts' shape or processing, the SNP could be significantly increased, cargo volumes could be reduced, and the use of dedicated containers was no longer necessary, and thus overall costs were reduced. As the standardization and generalization of containers have progressed, more and more logistics professionals have recognized that adjusting the shape or size of parts to correspond to standard containers is one way of improving logistics efficiency, as this can reduce both cargo volume and idle space.

These practices have become widespread among automobile manufacturers. The logistics engineers (LEs) in charge of package planning not only consider the type of container and placement given constraints such as the shape of the parts, but also look at modifying the constraints with the aim of optimizing the packaging. In particular, they analyze the constraints and propose revised packaging plans involving adjustments to part shapes and assembly processes.

It is difficult, however, to gain approval for packaging plans requiring changes to part designs because other functions such as production technology and manufacturing are affected. Thus, while some of the revised packaging plans proposed by the logistics department have been successfully implemented, numerous proposals have been rejected in response to opposition from other departments such as design and manufacturing. Furthermore, some packaging plans have been implemented but failed to achieve the expected cost reductions.

Although practitioners have accumulated a considerable amount of experience, no empirical studies have identified the factors that determine the success or failure of proposals aimed at optimizing packaging by adjusting the shape and assembly of parts. Therefore, in this study, we aim to identify the combination of conditions that facilitates packaging optimization using fuzzy set qualitative comparative analysis (fsQCA) to analyze case studies from Japanese automobile companies.

2. Literature review

Many practitioners use the term "design for logistics (DFL)" to describe package planning that involves changes in the shape of parts or process engineering. However, most previous studies on DFL have examined the relationship between the overall logistics flow from raw material procurement to delivery of finished products and product design, while few have focused on package planning. Mather (1992) argued that designing in a logistically friendly manner led to shorter manufacturing lead times and reduced inventories, thereby strengthening a company's competitive advantage. In particular, Mather pointed out that the adoption of standard components and postponement of design decisions are important for improving logistics efficiency and customer service.

The DFL approach proposed by Mather was subsequently discussed in relation to the concepts of concurrent engineering and postponement (Taylor, 1997; Dowlatshahi, 1999; Ernst & Kamrad, 2000; Anumba & Siemieniuch, 2000; Krikke & Wassenhove, 2003). These studies found that designing for product diversification leads to complexity and inefficiency in relation to logistics and pointed out that by postponing the engineering of a variety of products until this step could be synchronized with operations including logistics, it would be possible to improve the performance of various aspects of logistics such as lead time and inventory turnover.

Kao (2006) argued that logistics performance should be included in the criteria used to evaluate product design proposals, and thus decision-making regarding product design should be postponed where possible until the optimum design proposal could be identified based on demand information obtained from the market.

While some studies on DFL have not focused on the relationship between package planning and product design, they have noted that packaging must be taken into account in addition to other logistics-related factors such as transportation, distribution processing, and material handling when designing products (Simchi-Levi et al., 2003; Kao, 2006, Bowersox et al., 2012). However, a DFL approach requires attention to be paid to issues related to market acceptability and logistics efficiency in the early stages of the product design process. Conversely, package planning that involves adjusting the shape and processing of parts is a cross-functional collaboration in which the logistics department takes the initiative, often suggesting design changes from the viewpoint of packaging optimization.

Regarding collaboration between the product design and logistics departments, the DFL approach and package planning share some characteristics. Focusing on this collaborative relationship, Dowlatshahi (1996) analyzed the normative rules of DFL, positioning package planning as an important part of the interface between product design and logistics. Dowlatshahi (1999), who verified the effectiveness of DFL using band energy algorithm modeling, found that it is important to involve logistics-related activities such as package planning in the early stages of the design process. He also found that integrating the package planning process and the design process increased the effectiveness of DFL.

The concept of front-loading is strongly associated with this issue when considering the early stages of the design process. As mentioned above, package planning involving adjustments to the shape and processing of parts may lead to design changes. The earlier in the design process this happens, the lower the cost of these changes (Baldwin & Clark, 2000; Ando, 2015). Therefore, it is considered preferable to practice front-loading in relation to package planning. The practice of front-loading, which was devised by Japanese automobile companies, was originally used as a means of shortening the development period and improving performance by partially overlapping the upstream and downstream processes in the overall new vehicle model development process (Clark & Fujimoto, 1991; Fujimoto, 1997). Since it was first recognized as a significant contributor to productivity improvements in relation to product development, the practice of front-loading has gradually been expanded beyond the design process to other processes including production engineering, testing and trialing, quality assurance, and part production (Brown & Eisenhardt, 1995). The aim of front-loading is to increase the efficiency of downstream processes and maximize overall efficiency by increasing the quality and quantity of adjustments in upstream processes wherever possible (Nobeoka & Fujimoto, 2004; Ikeda, 2007).

Front-loading involves not only the advancement of processing or a shift in man-hours to upstream processes, but also an early, comprehensive solution aimed at optimization of the overall process (Fujimoto, 1997; Thomke & Fujimoto, 2000; Ikeda, 2007). To achieve this objective, intensive information exchange and knowledge transfer are indispensable, and organizations need the ability to process information effectively. In addition to using the knowledge accumulated during past projects, linking information between upstream and downstream tasks and functions will lead to the identification and solution of potential problems. The information exchanged in this regard is often uncertain and preliminary because it occurs in the early stages of development. Thus, to ensure the effectiveness of front-loading, it is essential to deal with ambiguous information through collaboration and close communication (Fujimoto, 1997; Itohisa, 2012). This form of collaboration is called either concurrent engineering or simultaneous engineering.

Japanese automobile companies have applied the concept of front-loading to their package planning processes since the early 2000s. Conventionally, package planning starts when the parts design stage is completed. That is, the package planning process is one of the downstream processes that follows the design process and is commenced almost at the same time as the trial mass production process. However, in the case of front-loading package planning, the process is brought forward and occurs simultaneously with the parts design process. For instance, since 2005, one of the companies we examined in this study, company C, has been conducting simultaneous package planning activities, whereby parts design information is shared with the logistics department from the digital stage of component design, when the design drawings have not yet been completed, and only CAD data regarding parts specifications have been generated. On the basis of this early design information, the LEs undertake package planning and propose changes such as adjusting part shapes and manufacturing processes from the perspective of package optimization (Li et al., 2020).

Although previous studies on front-loading have examined numerous aspects of the automobile industry, few studies have focused on front-loading package planning activities. Package planning is an important element of the mass production process, and because it is positioned between the design process and the production process, it seems to have a high degree of affinity with front-loading. In particular, it is the use of front-loading that increases the possibility of introducing improved packaging plans that require design changes.

Whether early sharing of design information is indispensable in relation to creating the optimum packaging plan by adjusting the shape or processing of parts is, however, unclear. Therefore, it is necessary to analyze the factors involved in packaging optimization that might require design changes, and whether front-loading in relation to those factors is worthwhile.

3. Method and dataset

To explore the combinations of conditions that determine the success or failure of package planning involving adjustments to the shape and processing of parts, we conducted a series of interviews from September 2019 to January 2020 with employees responsible for package planning at four Japanese automobile manufacturers. We conducted two group interviews, on 23 September 2019 and 22 January 2020, involving employees from all four companies, and eight interviews at individual companies, on 4 October 2019 (company A), 8 October 2019 (company B), 11 October 2019 (company C), 14 October 2019 (company D), 11 November 2019 (company A), 19 November 2019 (company C), 27 November 2019 (company D), and 29 November 2019 (company B).

On the basis of information obtained during these interviews and archival records provided by the companies, we identified 34 separate cases relating to parts package planning. Of these, 15 cases involved changes in the shape and processing of parts. Of these 15 cases, packaging proposals were approved and resulted in efficiency improvements in nine cases, while the proposals presented in the other six cases were rejected. Because there are only 15 cases and some of them are contextual, no statistical methods that are adequate for analysis are available. The within-case method can be used to explain the characteristics of each case, but it is difficult to draw any generalized inferences.

We therefore used QCA, which uses set theory and Boolean algebra, and is suitable for analyzing small amounts of data to identify combinations of conditions that cause specific outcomes (Rihoux & Ragin, 2009). Indeed, because QCA not only provides a means of systematic analysis but is also case-oriented, integrating formal analysis similar to that using standard statistical methods and within-case analysis, it is considered to offer advantages in terms of explaining causal complexity and extracting causal patterns (Tanaka, 2015). Because package planning has many interfaces with other functions and activities, the factors that determine package optimization are complicated and intertwined. Thus, we believe that QCA is a valid approach given the purpose of this study.

We did not use crisp-set QCA and multi-value QCA, which try to force-fit cases into two categories (membership versus non-membership in a set) or into one of three or four categories, respectively (Rihoux & Ragin, 2009), but rather used fsQCA, which permits the scaling of membership scores, and thus allows partial membership and can analyze complex interactions between factors and identify necessary and sufficient conditions based on the degree of influence of each factor, because packaging improvement is affected by various factors, and some of the relationships among these factors are likely to be strong. Additionally, it is not possible to clearly assign each case for all factors as full membership or full non-membership because there is a subset relationship among them.

Of the 34 package planning cases we originally identified , we chose the 15 cases involving adjustments to the shape or processing of parts as the dataset for this study (see Table 1). For instance, in Case 1, when considering the packaging of the engine cooling module based on CAD data at the digital stage of the design process, the LEs estimated that the volume could be significantly reduced if the specifications for the module were changed so that the three parts comprising the module were integrated rather than remaining separated. Furthermore, if the tip of the module were reduced by 2 mm, an existing general-purpose container could be used for packing, resulting in reduced logistics costs. Therefore, the logistics department proposed a revised packaging plan necessitating design changes after consulting with the production technology department and the purchasing department. The proposal was adopted because of its perceived benefits in terms of efficiency. Owing to space limitations, detailed descriptions of each case will be presented in another article, and we only provide a brief summary of the 15 cases here (see Table 1).

Table 1 Summary details of the 15 case studies

Case ID	Components	Proposals	Timing of information input	Transportation distance	Changes in equipment or layout: Yes/No	Renegotiation of purchase price	General-purpose container or dedicated container	Collaboration with other departments when making proposals	Cost reduction (compared with the previous model)	Adopted: Yes/No
Case 1	KD, cooling module of engine	Integration of component parts, 2 mm dimension adjustment, assy outsourcing	Digital stage	International transportation	Yes	Needed	General purpose	With production technology	Approximately 30% reduction per unit	Yes
Case 2	KD, Isis front bumper	In-house painting, overlapping load	Digital stage	International transportation	No	Not needed	General purpose	With purchasing	Approximately 80% reduction per unit	Yes
Case 3	Domestic, tie rod assy	In-house assy	After the start of mass production	About 1650 km	Yes	Needed	General purpose	With purchasing	Approximately 20% reduction per unit	Yes
Case 4	KD, strg mbr assy	Parts split, in-house assy	After the start of mass production	International transportation	Yes	Needed	Dedicated (for main part), cardboard (for small parts)	With purchasing	Approximately 70% reduction per unit	Yes
Case 5	KD, hemming assy	Parts split, in-house assy	After the start of mass production	International transportation	Yes	Needed	Dedicated (for pressed parts), general purpose (for other parts)	With production technology and purchasing	Approximately 55% reduction per unit	Yes
Case 6	Domestic, rear end upper panel	Split into three parts, in-house assy	Digital stage	About 20 km	No	Not needed	General purpose	Alone	Approximately 16.6% reduction per unit	Yes
Case 7	Domestic, radiator upper support	Split bracket from main part, in-house assy	Digital stage	About 20 km	Yes	Needed	General purpose	Alone	Estimated cost increase	No
Case 8	Domestic, front suspension cross member	Split bracket from main part, in-house assy	Digital stage	About 20 km	Yes	Needed	Dedicated	With production technology and purchasing	Approximately 57% reduction per unit	Yes
Case 9	Domestic, front side member(LH/RH)	Parts split, in-house assy	Digital stage	About 15 km	No	Not needed	General purpose	With manufacturing	Approximately 68% reduction per unit	Yes
Case 10	Domestic, front bumper reinforcement	Split bracket from main part, in-house assy	Digital stage	About 15 km	Yes	Needed	General purpose	Alone	Estimated cost increase	No
Case 11	Domestic, airbag module	Split lid and base, in-house assy	Digital stage	About 20 km	Yes	Needed	General purpose + dedicated dunnage	Alone	Estimated cost increase	No
Case 12	Domestic, front cross member	Split into three parts, in-house assy	Digital stage	About 20 km	Yes	Needed	Dedicated	Alone	Estimated cost increase	No
Case 13	Domestic, door mirror assy	Parts split, in-house assy	After starting design trial production	About 200 km	Yes	Needed	General purpose + dedicated dunnage	Alone	Estimated cost increase	No
Case 14	KD, headlight	Adjusting the strength of the protrusion	After the start of mass production	International transportation	No	Not needed	General purpose + dedicated dunnage	With manufacturing	Approximately 6.4% reduction per unit	Yes
Case 15	KD, compressor assy	Clip specification change, separate packaging	Digital stage	International transportation	No	Not needed	Dedicated	Alone	Estimated cost increase	No

Source: Information provided by company employees during interviews. Note: The cost reduction percentage reflects the ratio of the change in total costs as a result of the proposal to the logistics costs.

4. fsQCA

Using the dataset shown in Table 1, we proceeded with fsQCA as follows. First, we selected the outcome variables and conditional variables based on the empirical facts of the cases and insights from previous studies. Second, we coded the conditional variables by calibrating the conditional variables and assigning them a membership score from 0 to 1. Third, we coded the outcome variable in the same way. Fourth, we generated a matrix of the coded variables, performed truth table algorithm analysis, and created an incomplete truth table. In this step, we checked the possible combinations of causal conditions, the number of cases corresponding to each combination, and the validity of each combination. Fifth, on the basis of the proportional reduction in error (PRI) consistency score of the incomplete truth table, a dichotomous value (0,1) was assigned to the outcome variable to create the complete truth table. Finally, by performing a standard analysis of the complete truth table, we calculated the logical formulas (solutions) showing the combinations of conditions, identified the conditions that caused the outcomes, and discussed the solutions obtained using fsQCA (Yokoyama, 2017).

4.1. Selection of outcome variables and conditional variables

Of the 15 cases in our dataset, nine featured packaging proposals that were adopted, while the other six cases involved proposals that were rejected. Elucidation of the factors determining the acceptance or rejection of packaging proposals that involve adjustment of the shape and processing of parts can provide useful guidelines for activities aimed at optimal packaging outcomes. Therefore, we first considered whether it would be possible to select the adoption or rejection of a proposal as an outcome variable.

When comparing the adoption or rejection of each proposal and estimating the change in total costs in each case, however, we found a clear correspondence between the two variables (see Table 1). Proposals that were expected to reduce total costs were adopted, while those that were expected to increase total costs were rejected. Thus, we conducted a pilot analysis using QCA in which the adoption or rejection of the proposal was selected as the outcome variable and the estimated change in total costs was included in the conditional variables. As a result, the extremely simple solution of “cost reduction → proposal adoption” was derived. Furthermore, as change in total costs has a clear causal relationship with other conditional variables such as transportation distance and capital investment, it cannot be considered an independent variable. Therefore, we decided to use change in total costs as the outcome variable instead of adoption or rejection of the proposal. It should be noted that in this study total costs include the cost of purchasing the parts, procurement logistics costs, and assembly costs at the finished vehicle factory.

To set the conditional variables, we mainly used the inductive approach, while also making use of knowledge from previous research on front-loading. The inductive approach is a methodology that involves selecting conditions based largely on real cases rather than theory (Rihoux & Ragin, 2009). It is difficult to apply methodologies such as the perspective approach and the conjunctural approach (Amenta & Poulsen, 1994) because few attempts have been made to theorize the determinants of package optimization by adjusting the shape and processing of parts. In the process of identifying cases for this study, we were able to hear from veteran practitioners regarding the substantive knowledge they had accumulated based on their abundant experience in package planning, and this knowledge was reflected in the setting of our conditional variables.

The package must be planned based on the shape and features of each part. Therefore, the people in charge of package planning need to obtain information on part design at the appropriate time. When trying to optimize packaging by adjusting the shape or processing of parts, some design changes may be required. The later the design change is implemented, the higher the costs, and so early design information sharing is important. This finding is consistent with insights from previous studies on front-loading (Fujimoto, 1997; Itohisa, 2012; Li et al., 2020). Therefore, the timing of inputting component design information into the package planning process should be considered an essential factor.

The LEs create packaging plans based on the parts design information they have received. If they consider that adjustments to the shape and processing of parts are necessary to optimize packaging, they will submit proposals seeking appropriate design changes. However, the design department might not pay much attention to proposals coming from LEs, as in many Japanese companies, the logistics department does not have sufficient influence to force other departments to take appropriate action. Therefore, the logistics department often collaborates with other departments such as manufacturing, purchasing, and production technology to submit joint proposals after analyzing simulations of the impact of a packaging plan that involves design changes. In reality, the implementation of some proposals might lead to cost trade-offs, such as a reduction in logistics costs accompanied by an increase in processing costs. For example, if some parts are separated from the main body of the component, volume efficiency can be significantly improved and transportation costs can be reduced, but in the finished vehicle factory, it is necessary to include an additional assembly process, which increases processing costs. This is one reason why the logistics department needs to collaborate with other departments regarding packaging proposals.

A packaging plan that involves a change in processing may lead to a reengineering of the equipment and/or layout in both the parts plant and the finished vehicle factory. In some cases, only a minor adjustment is needed, while in other cases, large-scale capital investment is required. Furthermore, adjustments to processing can affect the production costs of both the parts factory and the finished vehicle factory, which may lead to a renegotiation of the purchase price of the parts.

The logistics costs related to parts procurement are mainly determined by a combination of volume and transportation distance. While improvements in packaging directly affect the volume, the transportation distance has a significant effect on how much these improvements can achieve in terms of cost reductions. Even if the improvement in volume efficiency is small, the cost savings will be significant in the case of long-distance transportation. On the contrary, even if the volume can be significantly reduced, this will only lead to minimal cost reductions in the case of short-distance transportation. Therefore, transportation distance is one factor that determines the success or failure of packaging plans.

Container selection has traditionally been a central task in relation to packaging. Containers can be broadly divided into two types: standard general-purpose containers and dedicated containers for specific parts. In general, even though dedicated containers cost more to manufacture and use than general-purpose containers, some parts are only able to be stored in dedicated containers because of their characteristics. If an existing dedicated container can be reused by adjusting the shape of the parts, significant cost savings can be obtained.

Many package designers have claimed that the factors to consider in relation to the package planning process differ depending on whether they are domestic parts or knock-down (KD) parts. For example, KD parts must prioritize the use of standardized general-purpose containers such as shipping containers. Furthermore, most KD parts travel a longer distance than domestic parts, and are subject to repeated handling, and thus it may be necessary to take extra care when installing the dunnage in the container.

On the basis of the abovementioned knowledge from previous research and field experience, "timing of information input," "collaboration with other departments when presenting proposals," "change of production equipment and layout," "purchase price renegotiation," "transportation distance," "domestic parts or KD parts," and "general-purpose container or dedicated container" were selected as the conditional variables.

If these are all used as conditional variables in the QCA analysis, however, there are 128 possible combinations, making the analysis excessively complicated. Therefore, it is necessary to reduce the number of variables. First, "transportation distance" and "domestic parts or KD parts" are not independent of each other, and thus either one can be used. Similarly, "change of production equipment and layout" and "purchase price renegotiation" are strongly correlated. Design changes such as using separate or integrated parts will result in the relocation of some processes between the parts manufacturer and the finished vehicle factory, which will require capital investment and layout changes. This in turn will lead to changes in the cost sharing structure in relation to the parts, resulting in a renegotiation of the purchase price. As can be seen from Table 1, the sets of these two variables entirely overlap.

The variables "domestic parts or KD parts" and "purchase price renegotiation" are therefore integrated into "transportation distance" and "change of production equipment and layout," respectively. The variables "timing of information input," "general-purpose container or dedicated container," and "collaboration with other departments when presenting proposals" are also used, giving a total of five conditional variables. We can construct a raw data table by extracting the content related to the "cost reduction effect" (as an outcome variable) and the five conditional variables from Table 1. This raw data table is omitted because of space limitations.

We also examined whether the value (cost) of the parts should be adopted as a conditional variable. However, automobile manufacturers include approximately 200 "priority management parts" in their package planning, and these are selected based on volume (20 liters or more), regardless of whether they are core parts. Although there are some differences between companies, priority management parts account for about 85% of the total volume of parts used in a vehicle. As the ratios of the cost of individual parts to the total cost of the vehicle are confidential, we were unable to obtain this data. Thus, it was impossible to use component value as a conditional variable.

As can be seen from the literature review presented above, package planning that involves adjusting the shape and processing of parts is highly compatible with front-loading, and early access to design information seems to be a significant factor in the success or failure of package planning. Furthermore, collaboration between the logistics department and other departments is a crucial factor in relation to managing cost trade-offs and optimizing packaging. Therefore, we hypothesize that of the five conditional variables, "timing of information input" and "collaboration with other departments when presenting proposals" are the core variables, while the other three variables are peripheral.

4.2. Coding the variables

Next, we coded the conditional variables and the outcome variable. As shown in Table 1, some variables involve qualitative data, while others involve quantitative data. Because "timing of information input (inforinput)," "change of production equipment and layout (nolayout)," "collaboration with other departments when presenting proposals (collaboration)," and "general-purpose container or dedicated container (container)" involve qualitative data, we coded these variables by assigning membership scores based on the four-value fuzzy set.

Input of information during the digital stage of parts design was used as the criterion for setting the threshold value of "timing of information input." Therefore, input during the digital stage was scored as 1 and input during the physical stage (after the start of design trial production) or thereafter was scored as 0. Regarding "change of production equipment and layout," if any change was required, it was scored as 0, while if no change was required, it was scored as 1. As for "general-purpose container or dedicated container," the use of dedicated containers was scored as 0, using a dedicated container combined with general-purpose inner material was scored as 0.33, using a general-purpose container combined with a dedicated inner material was scored as 0.67, and using a general-purpose container was scored as 1. Regarding "collaboration with other departments when presenting proposals," a collaborative proposal was scored as 1 and an independent proposal was scored as 0.

The "distance" data were converted to membership scores using the fsQCA calibrator function. All international shipments were considered to occur over a distance of 1,000 km. Considering the degree of impact on the cost when changing the packaging plan, 500 km was set as the qualitative cut-off point, based on the experiences of the companies' transportation staff. Then, on the basis of the distribution of data, 20 km was set as the full non-membership threshold and 1,000 km was set as the full membership threshold.

We used dichotomization to set the threshold of the outcome variable "costdown," scoring "no total-cost reduction effect" as 0 (full non-membership) and "total cost reduction effect" as 1 (full membership). Conversely, when "no cost reduction (~costdown)" was used as the outcome variable, we scored "no total-cost reduction effect" as 1 (full non-membership) and "total-cost reduction effect" as 0 (full membership).

Table 2 shows the data matrix in which the outcome variables and conditional variables are coded based on the abovementioned thresholds and the raw data presented in Table 1. Subsequent calculations use the ID of the variable and the membership score of each calibrated variable.

Table 2 “Costdown” data matrix

ID	Infroinput	nolayout		Container	collaboration	distance	Costdown
Case 1	1	0		1	1	0.95	1
Case 2	1	1		1	1	0.95	1
Case 3	0	0		1	1	1	1
Case 4	0	0		0.33	1	0.95	1
Case 5	0	0		0.33	1	0.95	1
Case 6	1	1		1	1	0.05	1
Case 7	1	0		1	0	0.05	0
Case 8	1	0		0	1	0.05	1
Case 9	1	1		1	1	0.05	1
Case 10	1	0		1	0	0.05	0
Case 11	1	0		0.67	0	0.05	0
Case 12	1	0		0	0	0.05	0
Case 13	0	0		0.67	0	0.13	0
Case 14	0	1		0.67	1	0.95	1
Case 15	1	1		0	0	0.95	0

Notes: Data were processed using fsQCA3.0 software.

4.3. Combinations of conditions that determine “costdown”

On the basis of the data matrix (see Table 2) constructed using the procedure outlined above, an incomplete truth table and a complete truth table were built using the fuzzy truth table algorithm. The logical configurations of condition combinations that determine “costdown” can be obtained from these tables. Because the necessary conditions for the outcome variable must be confirmed before creating the fuzzy truth table (Rihoux & Ragin, 2009), the conditions that always exist in cases both with and without cost reduction must be identified (see Table 3). Necessary conditions require a high degree of consistency in QCA. In cases where “costdown” is 1, the causal condition is also always 1, and thus is a necessary condition. Calculations using fsQCA3.0 software showed that the consistency of all other causal conditions was 0.9 or less, while the causal condition of “collaboration” reached 1 in terms of both consistency and coverage. Therefore, “collaboration” is a necessary condition for cost reduction. Followed the same procedure, it was confirmed that “~collaboration” is a necessary condition for “~costdown.”

Table 3 Necessary conditions for “costdown”

Causal conditions	Consistency to costdown	Consistency to ~costdown
Inforinput	0.56	0.83
~inforinput	0.44	0.17
Nolayout	0.44	0.83
~nolayout	0.56	0.17
Container	0.70	0.56
~container	0.30	0.44
Collaboration	1.00	0.00
~collaboration	0.00	1.00
Distance	0.66	0.21
~distance	0.34	0.78

Notes: ～ indicates “not.” Data were processed using fsQCA3.0 necessary conditions software.

We then created an incomplete truth table based on Table 2 to search for sufficient conditions for cost reduction. The incomplete truth table lists all possible combinations of causal conditions (both their presence and their absence), and the number of cases and level of consistency corresponding to the various combinations (see Table 4). The validity of the combinations was evaluated using the PRI consistency scores. Using the threshold of 0.8 recommended by Rihoux and Ragin (2009) and scoring the outcome (“costdown”) as 1 if it exceeded the threshold and 0 if it was below the threshold, we constructed a complete truth table (see Table 5).

Table 4 Incomplete truth table (the outcome is “costdown”)

infroinput	nolayout	Container	collaboration	distance	number	costdown	CaseID	raw consist.	PRI consist.	SYM consist
1	1	1	1	0	2			1	1	1
0	0	0	1	1	2			1	1	1
1	0	0	1	0	1			1	1	1
0	0	1	1	1	1			1	1	1
1	0	1	1	1	1			1	1	1
0	1	1	1	1	1			1	1	1
1	1	1	1	1	1			1	1	1
1	0	1	0	0	3			0	0	0
1	0	0	0	0	1			0	0	0
0	0	1	0	0	1			0	0	0
1	1	0	0	1	1			0	0	0
0	0	0	0	0	0	The following lines shows logical remainders (no applicable cases)				
0	1	0	0	0	0					
1	1	0	0	0	0					
0	1	1	0	0	0					
1	1	1	0	0	0					

Table 5 Complete truth table (the outcome is "costdown")

infroinput	layout	Container	collaboration	distance	costdown	Case ID	raw consist	PRI consist	SYM consist
1	1	1	1	0	1	Cases 6 and 9	1	1	1
0	0	0	1	1	1	Cases 4 and 5	1	1	1
1	0	0	1	0	1	Case 8	1	1	1
0	0	1	1	1	1	Case 3	1	1	1
1	0	1	1	1	1	Case 1	1	1	1
0	1	1	1	1	1	Case 14	1	1	1
1	1	1	1	1	1	Case 2	1	1	1
1	0	1	0	0	0	Cases 7, 10, and 11	0	0	0
1	0	0	0	0	0	Case 12	0	0	0
0	0	1	0	0	0	Case 13	0	0	0
1	1	0	0	1	0	Case 15	0	0	0

Using the data presented in Table 5, fsQCA was performed with "cost reduction ("costdown" value of 1)" as the outcome variable to calculate the logical configuration, coverage, and consistency. First, the formulas for the complex solution were calculated using only the rows with relevant cases without considering the logical remainders. The complex solution consists of four logical configurations (condition combination patterns) (see Table 6). Furthermore, parsimonious solutions were derived by including all logical remainders without assessing their plausibility to make the logical configurations as simple as possible (see Table 6).

Table 6 Complex and parsimonious solutions of the outcome ("costdown")

	Logical formulas	Raw coverage	Unique coverage	Consistency
complex solutions	container*collaboration*distance	0.48	0.18	1.00
	~infroinput*nolayout*collaboration*distance	0.32	0.14	1.00
	infroinput*nolayout*container*collaboration	0.33	0.22	1.0
	infroinput*~nolayout*~container*collaboration*~distance	0.11	0.11	1
	solution coverage: 0.94			
	solution consistency: 1			
parsimonious solutions	collaboration	1	1	1
	solution coverage: 1			
	solution consistency: 1			

Note: * indicates "and," ～ indicates "not."

While the formulas for complex solutions, which are derived using only the rows with applicable cases, are difficult to generalize, the parsimonious solutions may include unplausible rows (Mori, 2016). To solve this problem, it is necessary to derive intermediate solutions, which are positioned between the complex solutions and the parsimonious solutions by restricting the logical remainders to the most plausible rows, using theoretical and empirical knowledge to predict whether the presence of each causal condition contributes to the occurrence of the outcome (Rihoux & Ragin, 2009; Mori, 2017).

We therefore anticipated the presence and absence of each causal condition for achieving cost reduction. As mentioned earlier, "collaboration between departments" is the necessary condition, and is always present. As noted in the literature review presented earlier, package planning that involves design changes has a high degree of compatibility with front-loading, and early receipt of information is likely to be critical. Furthermore, as can be seen from numerous cases included in this study, "long transportation distance" and "change of production equipment" likely have a significant impact on the cost effectiveness of packaging. Therefore, the four conditions "timing of information input," "collaboration with other departments when presenting proposals," "transportation distance," and "change of production equipment and layout" are considered to be present when calculating intermediate solutions (see Table 7).

Table 7 Intermediate solutions for "costdown" and "no costdown"

Logical formulas	Costdown			~costdown	
	①	②	③	④	⑤
inforinput	●	●			
collaboration	●	●	●	⊗	⊗
distance			●	⊗	
nolayout		●		⊗	
container	⊗				⊗
applicable cases (Case ID)	8	2, 6, 9	1, 2, 3, 4, 5, 14	7, 10, 11, 12, 13	15
consistency	1	1	1	1	1
raw coverage	0.11	0.33	0.66	0.78	0.44
unique coverage	0.11	0.21	0.53	0.51	0.18
solution consistency	1			1	
solution coverage	0.98			0.95	

Notes: ● = presence of condition, ⊗ = absence of condition, blank = absence or presence does not matter; larger symbols indicate core conditions and smaller ones indicate peripheral conditions.

The consistency of cost reduction formulas (1), (2), and (3) is 1, which exceeds the threshold of 0.8 recommended by Rihoux and Ragin (2009), so these three formulas are highly valid. The solution coverage of 0.98 means that the three formulas jointly cover 98% of the cases that achieved cost reductions. Moreover, because the consistency is 1 for all formulas, it is clear that they are effective in indicating the combination of causal conditions that is sufficient to achieve cost reductions. Therefore, the adoption of these three intermediate solutions is valid.

Expressing these intermediate solutions in words, if (1) design information is input early, and there is collaboration between departments, and dedicated containers are used, or (2) design information is input early, and there is collaboration between departments, and there is no change in production equipment or layout, or (3) there is collaboration between departments, and the transportation distance is long, package planning involving changes to the shape and processing of parts can lead to cost reductions.

5. Interpretation of results

Of the five conditional variables, "collaboration with other departments when presenting proposals," which is the necessary condition for cost reduction from the analysis presented in Subsection 4.3, is included in all three intermediate solutions. The QCA results supported some of the hypotheses presented in Subsection 4.1, that is, collaboration between departments is the core condition. Because packaging proposals that involve adjusting the shape and processing of parts are related to design changes, they cannot be achieved without the approval and efforts of the design department. Although the logistics department is responsible for optimizing packaging, it has a relatively weak voice within the organization, and thus it is extremely difficult to implement such proposals on its own. This is not only because of the power structure within the organization, but also because even though the logistics department is able to estimate the logistics cost reduction effect of their proposals, it is necessary to collaborate with other departments, such as production technology and manufacturing, to calculate the impact on total costs. In other words, the logistics department does not have sufficient information and know-how to present proposals that lead to overall optimization, nor does it have the necessary influence to enact such proposals. Thus, confirming the rationality of a packaging plan that involves design changes and presenting joint proposals in collaboration with other departments are the keys to success.

The hypothesis related to early input of design information, however, is not supported by the results of our analysis. Intermediate solution formulas (1) and (2), which include the early input of information, only represent 0.32 of the total coverage, meaning that only approximately 30% of the cost reduction cases are covered by these formulas. This shows that early sharing of design information enables front-loading of package planning and promotes packaging proposals that lead to cost reductions, but it is not a necessary condition for the development and realization of such proposals. In other words, the set of front-loading activities for package planning and the set of optimal package planning with design changes only partially intersect.

Formula (3), which includes a combination of collaboration between departments and long-distance transportation, has a unique coverage of 0.53, meaning that this formula is able to explain more than 50% of the cost reduction cases. The level of difficulty in relation to changes to the shape or processing of parts increases when package planning activities commence after late sharing of parts design information, such as after the prototype is completed or just before the start of mass production. However, as can be seen from many cases, design changes for the purpose of optimizing packaging are limited to slight adjustments to the shape of parts and rearrangement of the sub-assembly, and barely impact the functional design. Therefore, if an agreement can be reached between the related departments, there is room for adjustment even after the launch of mass production. In particular, in cases involving long-distance transportation, that is, Cases 3, 4, 5, and 14, even a slight reduction in volume resulting from a change in shape or processing can result in a significant reduction in transportation costs, and so agreement between departments on such design changes is easily reached. Furthermore, because changes to the shape or processing of parts require adjustments by not only the design department but also the manufacturing and purchasing departments, often involving increased man-hours, packaging proposals aimed at achieving significant reductions in transportation costs cannot be introduced without interdepartmental collaboration.

“Adoption of dedicated containers” is included in formula (1) as a peripheral condition. The use of general-purpose containers rather than dedicated containers enables cost savings, but in formula (1), the use of dedicated containers was included in the sufficient conditions for cost reduction. This contradiction can be understood by looking at Case 8, in which the component for the new vehicle model was larger than that used for the previous model, and so the existing dedicated containers could not be used. If the bracket were to be separated from the body of the component and the assembly process were to be postponed, then the volume would be reduced, and the existing dedicated containers could be used. The adoption of dedicated containers is a prerequisite rather than a peripheral condition when planning the packaging of parts for which the use of general-purpose containers is not possible. That is, when planning the packaging of parts that require the use of a dedicated container, packaging proposals aimed at using existing dedicated containers that can be realized when the conditions include early input of design information and collaboration between departments can result in cost savings.

“No change in production equipment or layout” is included in formula (2) as a peripheral condition. Modifications to equipment and layouts will require an appropriate level of investment. If the cost increase as a result of this investment exceeds the cost savings as a result of improvements in logistics, packaging proposals that involve changes in process engineering would be counterproductive. Furthermore, even if overall cost savings are expected, there are some cases where a proposal aimed at optimizing packaging is rejected because of a lack of funding for equipment modifications. Conversely, if no additional capital investment is required, then it would be easier to reach consensus between departments regarding proposals for packaging optimization.

To further test the hypothesis, the logical configuration was derived using the same procedure but with “no cost reduction effect” as the outcome variable. In this case, the values of 1 and 0 allocated to the “costdown” variable were inverted to derive the solutions. The presence and absence of the causal condition were also reversed. That is, the four conditions “timing of information input,” “collaboration with other departments when presenting proposals,” “transportation distance,” and “change of production equipment and layout” were set as absent. The intermediate solutions that were derived are shown in the far right-hand columns in Table 7.

Both of the formulas in the intermediate solution have a consistency of 1. Because the coverage (0.95) and consistency (1) of the solution are high, the validity of the derived formulas is confirmed. Expressing the two intermediate solutions in words, when the logistics department independently proposes a packaging plan and some changes occur in relation to the production equipment and/or layout, and the transportation distance is short (formula (4)), or the logistics department independently proposes a packaging plan and dedicated containers are adopted (formula (5)), it will be difficult to achieve cost reductions in relation to packaging. While both of the formulas include “no interdepartmental collaboration,” neither include “no early input of information.”

In the QCA analysis, the conditional combination for positive and negative outcomes is not necessarily symmetrical. However, the existence of symmetrical conditional variables suggests a more robust conclusion.

The following findings were also verified through the conditional combination for negative outcomes. That is, collaboration between the logistics department and other departments is a core condition that determines the success or failure of a project aimed at optimizing packaging by changing the shape and processing of parts. Furthermore, early input of design information enables front-loading of package planning and contributes to improvements in logistics efficiency, although this is not a necessary condition for packaging optimization. Although transportation distance and the need for additional investment in equipment are peripheral conditions, in some cases they have a significant impact on package planning.

6. Conclusions and further research

In this study, we focused on package planning involving adjustments to the shape and processing of automobile parts by analyzing the combinations of conditions that determine the optimization of the packaging process. Using fsQCA, we discovered that collaboration between the logistics department and other departments is essential for achieving packaging optimization. Conversely, early input of design information can partially explain the success of package planning involving changes to the shape and processing of parts, but is not a necessary condition, because interdepartmental collaboration based on late information sharing could also enable optimization of packaging. It was also found that transportation distance and the presence or absence of changes to production equipment and layouts have a significant effect on packaging optimization.

We should note that the impact of parts characteristics is not considered. However, to clarify the reason for distinguishing the three combinations of conditions discovered using fsQCA, it will be necessary to conduct further research focusing on the relationships with component attributes other than volume. For instance, future research should investigate whether various combinations of conditions are correlated with factors such as common parts for multiple models or dedicated parts for each model, rental drawing parts (car makers complete the parts design and lend the design drawing to suppliers) or approved drawing parts (suppliers complete the parts design drawing and obtain approval from car makers), and welded parts or plastic parts. Furthermore, it is necessary to consider the impact of procurement logistics practices such as delivery frequency, shipping lot, and location. We aim to explore these issues in the future using in-depth case-studies.

The findings of this study show the relationship between package planning and front-loading, and thus contribute additional insights to the front-loading literature. Additionally, by identifying the factors that determine the success or failure of package planning involving changes to the shape and processing of parts, the findings of this study provide some useful guidelines for package planning practitioners.

The findings of this study mean that we cannot ignore the importance of front-loading in relation to the package planning process. Rather, the formulas related to the intermediate solution including the early sharing of information have a coverage of more than 30%, indicating that early sharing of design information expands the range of activities included in package planning and contributes to improvements in volume efficiency. In fact, of the 34 package planning cases we examined, 14 (approximately 40%) included front-loading activities for package planning based on the sharing of design information at the early (digital) stage of component design.

Design information at the digital stage, however, is often ambiguous and preliminary (Fujimoto, 1997; Itohisa, 2012), and interdepartmental collaboration based on sharing of such preliminary information is much more difficult than in cases where precise information is available. Therefore, to include effective front-loading activities in package planning, there needs to be close communication between package planners, parts designers, and other related parties to enable synchronization of the parts design and package planning processes. Companies that lack such communication will find it difficult to include front-loading activities in their package planning. How are Japanese automobile companies achieving synchronization between the package planning process and the new vehicle design process by establishing an effective communication system? In future research, we aim to answer this question by examining in-depth case studies using process-tracing methods to increase our knowledge of approaches that are useful for enabling front-loading activities to be included in package planning,

How does the logistics department collaborate with other departments such as production technology and manufacturing, as well as parts manufacturers, to develop packaging plans that involve changes to the shape and processing of parts? Future research examining this issue from the perspective of knowledge fusion and supply chain integration should lead to important discoveries.

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