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Complexity management of vehicle wiring harnesses: An optimized model to analyse trade-offs between product and manufacturing costs

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by

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Complexity management of vehicle wiring harnesses: an optimized model to analyse trade-offs between product and manufacturing costs

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ABSTRACT

The large number of vehicle wiring harness variants during the design phase generates considerable complexity, which needs to be managed at the production level. The wiring harness design is usually optimized at the product level to minimize product costs. Issues related to the manufacturing processes are not considered.

The aim of this research is to develop a cost model which includes product and manufacturing costs to define an optimum level between product variant complexity and material costs (with the focus on wiring harness complexity).

The cost model consists of two parts, (i) the product cost and (ii) the manufacturing cost. Unlike product cost, which is relatively easy to obtain, the methodology for evaluating the manufacturing cost requires an in-depth analysis, which is done in this research.

The trade-off cost model is first applied to a case study based on real production data to evaluate the potential benefits. Then, a MATLAB simulation is developed to simulate a new scenario for managing wiring harness complexity. The results showed that cost savings can be achieved by applying a trade-off strategy between the product cost and manufacturing cost dynamically according to the forecast data.

The limitation of this research is using fixed manufacturing costs in the case study and the MATLAB simulation. For practical applications, the manufacturing cost should be a function of number of individual part numbers in the plant.

The concepts and methodology developed in this research could be used not only on automotive wiring harnesses, but also on parts and materials which are expensive and have many variants that need to be managed during production.

DEDICATION

I would like to dedicate this master thesis to my father, Baoping Wei and my mother, Lilin Han for their continuous support and encouragement during the long research period. Without them this work would have been very difficult to complete.

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CHAPTER

1. INTRODUCTION

There is a large variety of automotive wiring harness variants generated during the design phase for the vehicle platforms being studied. This large number of product variations introduces complexity into the system and results in higher management costs. The wire harness design is optimized at the product level, but process optimization issues are not considered. The aim of this thesis project is to develop a cost model which includes product and manufacturing costs to define an optimum level between complexity and material costs (with the focus on wiring harness complexity), which is a typical project of World Class Manufacturing (WCM).

The layout of this thesis is arranged as follows: first in Chapter 1, an introduction and background information for an automotive wiring harness is presented, together with the introduction to the WCM production system. In Chapter 2, a literature review is presented. In Chapter 3, the wiring harness complexity and relevant benchmarking information is illustrated. In Chapter 4, a cost model including manufacturing cost and product material cost is explained; the main attention is focused on the manufacturing cost deployment. In Chapter 5, a case study about an existing vehicle model is presented to show the potential benefits of reducing complexity. In Chapter 6, a MATLAB simulation model is presented to simulate a best approach of managing wiring harness complexity in concept. In Chapter 7, conclusions and future work are presented. In Appendix A, the application of WCM principles and continuous improvement with respect to wiring harnesses in an assembly plant is presented.

1.1 Wiring harness background

The vehicle wiring harness is the main part of the vehicle electric circuit network. It is an assembly of cables or wires which transmit information signals or operating currents (energy). The main components including the connectors, outer packages, and wires are shown in Figure 1-1. The cables are bound together by clamps, cable ties, cable lacing, sleeves, electrical tape, or a combination thereof.

The wiring harness should ensure the following functions: (i) the correct transmission of electric signals from control units to actuators, (ii) a reliable connection under all working conditions, (iii) supply of the predefined current value to the devices, and (iv) prevention of electromagnetic interference to the surrounding circuits while excluding electrical short circuits.

Figure 1-1: Wiring harness elements. (Internal correspondence)

For manufacturing a wiring harness, the wires are first cut to required length with a special wire-cutting machine. Secondly, the metal conductor is exposed by stripping the ends of the wires which are then fitted with the designed terminals or connector housings. The next step is to form the cable harnesses by assembling and clamping the cables together according to product based design specifications. The last step is to fit protective sleeves, conduit, or extruded yarn, to protect the wire harness.

For a vehicle wiring harness, the commonly used nominal section areas for the wires are 0.5, 0.75, 1.0, 1.5, 2.0, 2.5, 4.0, 6.0 square millimetres as shown in Table 1-1. They all have their own maximum allowed load current values.

Nominal section area	**Application**
0.5 mm^2	Lights on the dashboard
0.75 mm^2	lights of license plate
1.0 mm^2	Turning lights , fog lights
1.5 mm^2	Head lamp
2.5~4.0 mm^2	For main power supply such as an alternator

Table 1-1: Applications of wiring harness with various nominal section areas.

For instance, 0.5 mm^2 wire can be used for the lights on the dashboard, door lamps, roof lights; 0.75 mm^2 wire is suitable for lights of license plate, braking lights; 1.0 mm^2 wire is appropriate for tuning lights and fog lights; 1.5 mm^2 wire can be chosen for head lamps and the horn. The wires for a main power supply such as the alternator require 2.5~4 mm^2 nominal section area.

For efficient of assembly, car makers often divide the total wiring harness sets into different families according to the function unit of a wiring harness or the position in which it is installed on the vehicle. For instance, a wiring system consists of four wiring families, including a front wiring harness family, a rear wiring harness family, a wiring harness family for the dashboard, and a wiring harness family for the doors. Figure 1-2 displays a front wiring harness related to the engine components.

Within each wiring harness family, there are a certain number of individual part numbers designed. A part number is a digital number used to identify a particular wiring harness design. For example, a wiring harness can be called part number 66 instead of using another complex naming method. The number of individual part numbers indicates the quantity of wiring harness parts in a wiring harness family or in a system. The colours and shapes of the connectors are different from each other in a part number to facilitate assembly on the vehicle.

Figure 1-2: Front wiring harness for engine part. (Internal correspondence)

The requirements for an automotive wiring harness are stricter than other kinds of wiring harnesses. It has higher requirements in terms of electrical properties, and temperature resistance, especially for the parts related to safety issues such as steering control and braking systems. The choice of the wires and the outer package should consider the working environment of the cables. For instance, the surrounding environment for the engine compartment has the characteristics of high temperature, as well as surrounding gaseous and liquid substances. Therefore, the chosen wires must be able to resist high temperature, high vibration, high friction and corrosion. Another example is the wires at the hood of the luggage compartment. They should keep their elasticity even at low temperature. The typical conductor used for vehicle wiring is stranded copper wire.

In terms of materials for the outer cover, three types of materials are mainly used:

1) Corrugated pipe with the characteristics of: good abrasive resistance, good fire resistance, good water resistance, excellent high temperature resistance. The temperature resistance range is in between -40~150℃. All the engine wiring harnesses should use corrugated pipe.

2) Poly Vinyl Chloride tube （PVC tube）. Compared to corrugated pipe, PVC tubes have better softness and better resistance to bending strain. However the temperature resistance is much lower (around 80℃). It can be used for the branches for the front part of the wiring harnesses.

3) Adhesive tape: used in relatively benign working environments such as cables for dashboard and cables inside the doors (Xiaowei 2006).

1.2 World Class Manufacturing (WCM) introduction

World Class Manufacturing (WCM) is a production system that has been developed to apply the same fundamental lean manufacturing principles in different production environments in an effective manner.

WCM represents the level of excellence of the entire logistic-production cycle measured according to the methods applied and the performance achieved by best-in-class companies worldwide. It is based on the concepts of Total Quality Control (TQC), Total Productive Maintenance (TPM), Total Industrial Engineering (TIE), and Just In Time (JIT), which combine to result in high quality, low cost production.

The aim of the WCM implementation is to maximize the production system performance in accordance with logistic plans and defined quality objectives through:

1) Improvement of processes,

2) Improvement of product quality,

3) Control and gradual reduction of production costs,

4) Flexibility in meeting market and customer requirements, and

5) Involvement and motivation of people who operate on industrial processes.

1.2.1 WCM structure

The structure of WCM is shown in the Figure 1-3, and it covers all the main technical systems in a production plant, including: workplace organization, quality systems, maintenance systems, and the logistic systems.

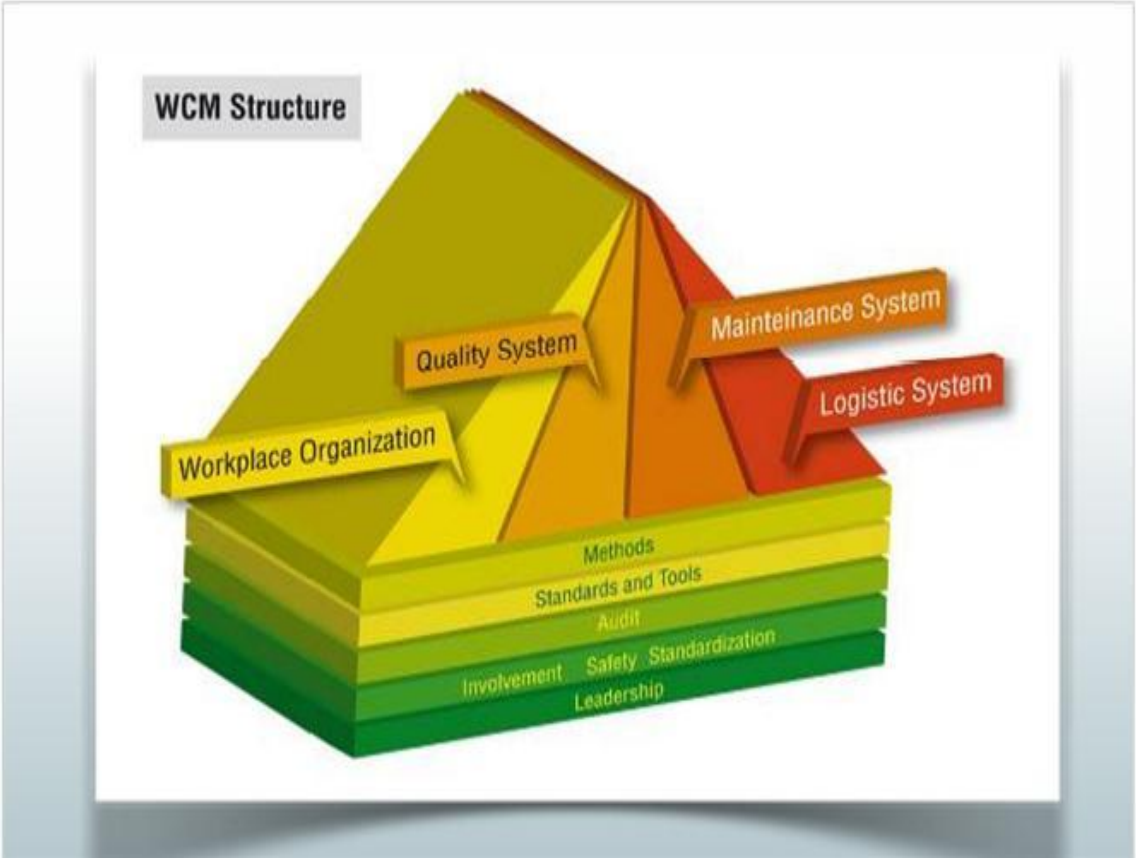

Figure 1-3: World Class Manufacturing (WCM) structure. (Internal correspondence)

These four systems are supported by a set of methods, standards and tools aimed to meet the following targets:

1) Zero waste within the workplace organization. This means eliminate items that are not necessary, tidying and cleaning the workplace, and continuous analysis and elimination of non-value added activities to elimination labour and material losses to improve productivity and achieving process related cost reductions.

2) Zero defects for quality. This corresponds to improved customer satisfaction and significant reduction in terms of manufacturing defects, rejects and product

reworking. This is achieved through a set of activities such as rigorous defect analyses to determine the origin of the problems.

3) Zero breakdowns for maintenance. This means the improvement of overall equipment efficiency, extension of the useful life of the equipment, and the reduction of machine faults through both autonomous and professional maintenance.

4) Zero inventories for logistics. The benefits of this include the prompt filling of orders, reduction of stock and work in process, the reduction of damage and material obsolescence through activities such as application of value stream maps to identify losses and opportunities, and redesign packaging systems.

The major methods used in WCM are summarized in ten technical pillars and ten managerial pillars. Figure 1-4 and Figure 1-5 shows the 10 technical pillars which include: 1) safety; 2) cost deployment; 3) focused improvement; 4) autonomous activities; 5) professional maintenance; 6) quality control; 7) logistics & customer service; 8) early equipment and product management; 9) people development; and 10) environment.

Figure 1-4: Technical pillar 1 to 5 of World Class Manufacturing (WCM). (Internal correspondence)

Figure 1-5: Technical pillar 6 to 10 of World Class Manufacturing (WCM).

(Internal correspondence)

Among those ten pillars, the cost deployment is the compass to identify and quantify the losses and waste through transforming key information into currencies to assist in driving the plant to define priorities.

The implementation of all the technical pillars are conducted an approach called "7 steps". Each pillar has its own "7 steps" according to its topic. Figure 1-6 shows the "7 steps" for early product management from the problem definition to implementation of standard solutions.

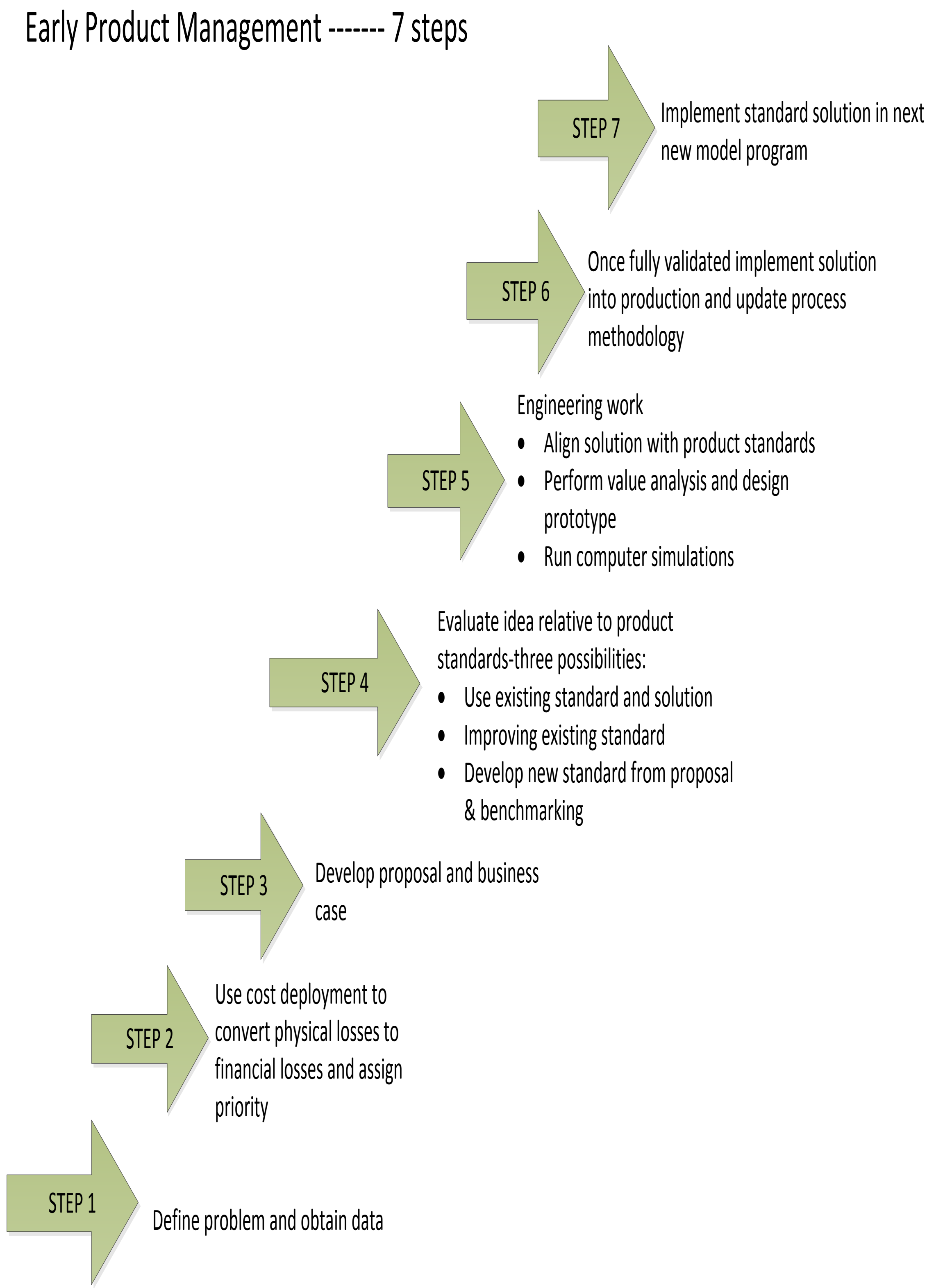

Figure 1-6: Seven steps of early product management. (Internal correspondence)

Figure 1-7 and Figure 1-8 shows the ten managerial pillars which include: 1) Management commitment, 2) Clarity of objectives, 3) Roadmap to WCM, 4) Allocation of highly qualified people, 5) Commitment of organization, 6) Competence of organization, 7) Time & budget, 8) Level of detail, 9) Level of expansion, and 10) Motivation of operators.

The ten managerial pillars are mainly used for driving the change through a clear WCM road map. Some of them, such as management commitment, and the clarity of objectives, are key management issues to be considered when evaluating a plant.

Figure 1-7: Managerial pillar 1 to 5 of World Class Manufacturing (WCM). (Internal correspondence)

Figure 1-8: Managerial pillar 6 to 10 of World Class Manufacturing (WCM). (Internal correspondence)

<u>1.2.2 World Class Manufacturing (WCM) audit system</u>

An audit system is used for evaluating the production performance of a plant which has implemented the WCM processes. Clear evaluation criteria have been set in the audit system, each of which is strictly linked to the implementation level for each pillar. Each pillar has a scoring system from 0 to 5 (0 is low, 5 is high) which means for all twenty pillars, a full score of 100 is the goal for each plant.

For instance, in the pillar of Logistics/customer service, the 0 to 5 score system is clearly defined as follows:

Score 0: no synchronization between sales, manufacturing and material handling. High stock levels exist due to the absence of JIT (where appropriate) and the use of conventional handling methods. The principle of reducing handling is not fully understood and applied.

Score 1: assembly produces according to the orders and receives materials in an organized manner. The body shop produces the main sub-assembles with a cell type system to reduce lead times and to minimize handling. Synchronization is achieved between the press shop and body shop.

Score 2: activities exist to create a flow through the entire plant. There is shared internal handling and physical transport is applied as appropriate. Synchronization is achieved between materials management and assembly. Suppliers deliver directly to the line. First In First Out (FIFO) is applied.

Score 3: sales management tries to sell vehicles continuously to level production and create a homogeneous flow in the entire plant. Internal and external logistics are designed to minimize handling. There is synchronized production for most parts produced internally. FIFO is applied for many materials. The maximum time for parts stay in assembly line waiting for assembly on vehicle for bulky, expensive materials with many variants is two hours.

Score 4: integrated sales, distribution, manufacturing and material handling functions to create a precise flow from receipt of order to delivery. FIFO is applied to most materials. Stocks turnaround is larger than 25 in a year. The maximum time for parts stay in assembly line waiting for assembly on vehicle for bulky, expensive materials with many variants is one hour.

Score 5: rigid sequence programming in the entire plant. Complete synchronization between sales, distribution, manufacturing and materials handling. The lead time from receipt of an order to delivery to the network is five days. Minimum handling is achieved. FIFO is always applied. Stocks turnaround is larger than 40 in a year. The maximum time for parts stay in assembly line waiting for assembly on vehicle for bulky, expensive materials with many variants is half hour.

A summary of the score and key points for logistics/customer service is shown in Table 1-2. Some key points for the evaluation including: level of synchronization, handling reduction, level of application of FIFO, stock turnaround value and existing time in assembly for bulky, expensive materials with many variants.

Score \ Key point	Synchronization	Reducing handling	FIFO	Stock turnaround	Stocks stay in line for complex materials
0	No	Not applied	Not applied	NA	NA
1	Between press and body shop	Applied in body shop	Not applied	NA	NA
2	Between materials and assembly	Shared internal handling	Applied	NA	NA
3	Between sales and production.	Internal and external logistics minimize handling	Many materials	NA	Max 2 hours
4	Between sales, distribution, manufacturing and handling	Low level of handling	Most materials	Turnaround > 25	Max 1 hour
5	Complete synchronization	Minimum handling	Always applied	Turnaround > 40	Max 0.5 hour

Table 1-2: Key points for evaluating scores for logistic/customer service pillar.

Figure 1-9 presents the audit system for the WCM system. A plant which gets a score of more than 50 can be given a bronze award, silver awards can be given if the score is more than 60, and gold awards are to be given to a plant which has a score of more than 70. A score of more than 85 means the production performance of the plant has achieved the world class level, which is the highest level in the audit system. The audit system will create a comprehensive ranking between plants, and should lead to healthy competition.

Figure 1-9: World Class Manufacturing (WCM) audit system. (Internal correspondence)

1.3 Problem statement

When applying the WCM principles to the wiring harness components, it can be found that large costs, losses and waste are generated during the vehicle production process in assembly plants. This is due to the high level of wiring harness complexity (too many wire harness part variants). By performing a root cause analysis, it can be found that the high level of complexity is coming from the product design phase, as a result of the high level of product variety (or option content) provided to the customer.

From the plant point of view, it is better to reduce the wiring harness product complexity (reduce the number of individual part numbers) to reduce the assembly related losses and waste such as the obsolescence cost. However, this will increase the cost of the wiring harness (product cost). If the wire harness product content is standardized over a large set of potential variants (resulting in fewer part numbers), these wire harnesses will contain unused extra wires or connectors which will not be paid for by customers.

Coordination between the product development department and the associated manufacturing departments is essential to solve this problem. As cost deployment is the compass used in WCM, it is necessary to systematically and rigorously quantify all related costs. The aim of this thesis is to develop a cost model including both product and manufacturing costs in a vehicle assembly plant for wire harness variants through which trade-offs between product and manufacturing costs can be assessed to reduce the total overall costs.

CHAPTER

2. LITERATURE REVIEW

At this time in the public domain, it is difficult to find information related to the reduction of vehicle wiring harness complexity and there is little information on how to quantify wiring harness manufacturing cost factors.

Consequently, the literature is reviewed in the following three complementary areas: 1) Effects of component commonality, 2) Inventory control and obsolescence, and 3) Complexity management in the automotive industry.

2.1 Effects of component commonality

Component commonality denotes that one component can be installed on more than more end product or product version. In the case of automotive wiring harnesses, it is quite common that one part number can be assembled on multiple product versions, which will affect several factors in inventory control, such as the safety stock requirements.

Baker and Kenneth (Baker, Kenneth 1985) studied safety stock behaviour with the application of component commonality using the “assemble to order” approach that is typical in the automotive industry. In his case, the safety stock of specific components was kept the same while the total safety stock was reduced due to the fact that the standard deviation of a sum is less than the sum of standard deviations when the independent demands are aggregated. He also studied the case of correlated end item demand, which means the demands for two end items are correlated with a specific correlation coefficient and found that benefits of using component commonality also exists. However, the benefit is less compared to the case without correlation and the benefits will disappear in the case of perfect positive correlation.

Baker and Kenneth (Baker, Kenneth 1986) also studied the same topic using a simple model with a uniform demand distribution that was subject to a required service level. The results showed that the total safety stock was reduced by using a commonality component while the total safety stock of specific component increased at the same time.

Gerchak, Magazine and Gamble (Gerchak, Magazine, Gamble 1988) extended this model, considering general demand distributions and an arbitrary number of products. The results showed that utilizing commonality is beneficial but nothing general can be concluded in terms of component stock level changes. The above papers used a single period model, which means that the order is made only once to satisfy all the future demand. In reality, most “assemble to order” approaches work with multiple periods.

Hillier (Hillier 2000) studied the minimization of production, holding, and storage costs with component commonality using a multi-period model with a general demand distribution and an arbitrary number of end products and components. The results showed that in the case of a multi-period model, the benefits from using commonality components often disappear when the common component is much more expensive than the original one, which relates directly to this research.

Hillier (Hillier 2002) continued his research on this topic using a (Q,r) policy for component replenishment. In this model, he also considered other benefits from commonality related to order pooling: The ordering costs are reduced (since fewer types of components need to be ordered) and the cyclic carrying costs are reduced (since orders are placed more frequently). The results showed that in many cases, order pooling is much more important than risk-pooling benefits. So considering this, even if the cost of commonality component is much higher than the original one, the benefits of commonality still exist.

Mohebbi and Choobineh (Mohebbi, Choobineh 2005) studied the impact of commonality under supply and demand uncertainty i.e., demand levels have random variations, and component procurement orders experience random delays. The results showed that, by introducing commonality, the average percentage of products' on time delivery increases significantly. What is more, increasing commonality has more advantages when facing uncertainty in both product demand and component procurement processes than those with uncertainty only in one process.

2.2 Inventory obsolescence

Reducing inventory obsolescence is an important issue for effectively managing automotive wiring harnesses, as the market requires product content to update frequently (usually once a year for small modifications). When a new model launches, many parts become waste, except a small portion which can be used as spare parts. In addition, the unit price of each wiring harnesses part number is quite expensive (usually several hundred dollars), which means the obsolescence costs may result in huge financial losses.

Oudheusden and Cobbaert (Oudheusden, Cobbaert 1996) studied inventory models for fast moving spare parts subject to "sudden death" obsolescence. In the paper, three conditions are considered: the first is constant obsolescence risk with no shortage allowed. Although this condition is very exceptional, it can be used as a rough estimation through simply regarding the obsolescence cost as an additional holding cost based on the

Economic Order Quantity (EOQ) model. The EOQ model considers the trade-off between the cost of ordering and the cost of storage to determine the optimum replenishment quantity (Schwarz 2008). The second case includes a varying obsolescence risk with no shortages allowed. This is a modified EOQ model with an obsolescence factor, which is a time dependent factor added to the holding cost. The last model deals with the condition of varying obsolescence risk with shortages being allowed. In this case, a shortage cost was considered and obsolescence cost was considered as an additional holding cost. A numeric example showed the importance of including obsolescence cost in the model.

Song and Lau (Song, Lau 2004) studied a stochastic-demand periodic-review inventory model with sudden obsolescence. A periodic review model was established first and then a dynamic programming algorithm was used for calculating optimal parameters. For approximating the EOQ model with a general obsolescence distribution, a discrete-time approximation scheme was proposed. The discrete approximation costs are very near to the optimal solution obtained by David et al (1997) from both analytical results and numerical experiments. The authors also believed that the discrete approximation approach could also be applied to stochastic continuous-review models in the case of sudden obsolescence although without numerical verification.

Dekker and Jaarsveld (Dekker, Jaarsveld 2010) focused on a case study and developed a method which could be used to calculate the obsolescence risk for service parts using demand data. The basic idea of the method is based on observations of service parts demand data used in products with long life cycles. Some numeric examples showed the method has some advantages. For example, the model will recommend stocking more fast moving parts than the slower ones as the model can recognize stocking slow parts costs more because of the higher risk of obsolescence.

Dekker and Pince (Dekker, Pince 2011) studied a continuous review inventory system for a slow moving item. The demand rate was assumed to drop to a lower level at a known future point. A one for one replenishment policy was used before a demand decrease. At certain point, the policy will be changed, letting the demand take away from excess stock. The results showed that the change of timing of the replenishment control policy mainly determined the trade-off between stock out and obsolescence cost. The optimal time for switching the policy can be found by an approximate solution; thus, a significant cost saving can be obtained and minimum total expected cost can be estimated.

Teunter, Syntetos and Babai (Teunter, Syntetos, Babai 2011) proposed a new method to forecast intermittent demand. Compared to the standard method by Croston, (Croston 1972) the new method overcomes two major disadvantages, but does not address adding complexity. The new method updates the demand probability in each time period while the Croston method only updates when a new demand condition happens. By doing this, the new method is able to quickly respond to conditions with sudden obsolescence or with an increased risk of obsolescence; therefore, more accurate forecast results can be expected. The numeric investigations showed the new method is the only one which performed well for all the scenarios with stationary demand, linear decreasing demand, and sudden obsolescence.

2.3 Complexity management in the automotive industry

Recently, the product complexity within the automotive industry is growing, as more equipment and features are being installed on vehicles as car manufacturers try to offer as many choices as possible to the customer. Consequently, complexity management is becoming an important challenge for car makers.

Ishii and Martin (Ishii, Martin 1997) studied the topic of design for variety which focused on methodologies to quantify the cost of providing variety and guiding engineers in developing products that have minimum variety costs. The research tools they used are the following: 1) quantitative tools to estimate manufacturing costs of providing variety which includes a commonality index, differentiation index and set up index; 2) qualitative tools for increasing engineers' understanding of how to reduce those cost including process sequence graphs and commonality graph, and 3) qualitative methods for determining customer preference for variety such as customer requirements for variety. The qualitative tools can give a view of best practices when designing for variety while the quantitative tools could help managers to decide what variety to offer and how to distribute resources to reduce the cost of providing variety.

Fisher and Ittner (Fisher, Ittner 1999) studied the impact of product variety on automobile assembly operations based on the data from a plant. The results showed that option variability increases overhead hours, rework, the level of inventory, and extra labor capacity required to a work station. The cost minimization in mixed-model assembly operations requires labor capacity higher than that of the actual amount of time spent assembling the vehicle. A simulation also showed that bundling options could reduce the level of buffer capacity required so the cost reduction can be done by bundling options into a few packages.

Schleich, Schaffer and Scavarda (Scavarda, Schleich, Schaffer 2006) studied the topic of managing complexity in automotive production and focused on a method for measuring variety driven complexity costs and the difference in terms of product variety between emerging and established markets. In the paper, a preliminary version of a complexity cost model that can identify the complexity cost which resulted from product variety is provided. The empirical results showed that the product variety found in emerging markets is not determined by the factors such as domestic market size, economic development, and existence of a local plant at the market.

2.4 Summary of literature review

Due to the lack of public literature directly related to the topic of managing automotive wiring harness complexity levels, the review is focused on three sub-topics which are related to this project in some extent. This thesis focuses on addressing this knowledge gap, which is explained in detail in the following chapters. As well, insights are provided for future work topics for researchers who wish to continue working in this area.

CHAPTER

3. WIRING HARNESS COMPLEXITY

As presented in the first chapter, the root cause of the cost-complexity problem is due to the high level of wiring harness variants generated during the design phase. In another words, there are too many designs or part numbers for a plant to manage effectively in a lean production system. So it is necessary to look into details on how wiring harness complexity is generated and what are the effects on the related costs.

3.1 Vehicle product complexity and wiring harness complexity

The origin of the wiring harness complexity is the high number of product variants provided in some markets such as the European and North American markets. For a general vehicle model existing on the market, the product content can be classified into two domains: 1) mandatory features that are the features which must be present in any version of the model regardless of what customers' choose, and 2) option features, of which the presence of these product features depends on the choice of customer.

For mandatory features such as the engine and transmission, usually more than one type is offered to customers. Different types can be called "variants". For instance, a typical B segment model offered in European market has four engine variants. Normally for different engines, different wiring harnesses are needed. Therefore, in this case the complexity is four for the engine features. Consider that there are many other mandatory features that also have variants; therefore, the total complexity of mandatory features is given by the product of the number of variants from each feature.

To write this into a mathematical expression, denote "Vi" as the number of variants for the mandatory feature "i", and "n" as the number of mandatory features that have variants. Thus the complexity for mandatory feature "Cm" is:

$$C_m = \prod_{i=1}^{n} V_i \tag{3.1}$$

For the option features, since the feature can be present on the vehicle or not, there are two possibilities. Generally speaking, the total complexity of option features can be calculated as an exponential of 2 (two choices: present or not present), where the exponential number is the total number of option features.

For instance, a common set of ten comfort and safety options are listed in Table 3-1, along with the options selected for four customers. For each of the different option combinations, a different wiring harness is needed for each of them. Even for these 10 options set listed here, the total amount of possible combinations is 2^{10}, which equals 1024 combinations.

Number	**Options**	**Customer 1**	**Customer 2**	**Customer 3**	**Customer 4**
1	Navigation	Yes	No	Yes	No
2	Sky roof	Yes	Yes	No	No
3	Electric adjustment seat	No	No	Yes	Yes
4	Auto-hold	No	Yes	Yes	Yes
5	Radar	Yes	No	No	No
6	LED head lamp	Yes	Yes	No	No
7	Electric heating seat	Yes	No	No	Yes
8	Number of airbags	High	Low	High	Low
9	Keyless starting	No	Yes	No	No
10	Blind point reminder	No	No	Yes	No

Table 3-1: Examples of customer chosen options.

To write this into a mathematical expression, denote “O” as the total number of option features for a vehicle model. The complexity of option features “Co” is:

$$\boldsymbol{C_o} = 2^{\boldsymbol{O}} \tag{3.2}$$

Thus the total model complexity level can be roughly estimated using the formula:

$$Complexity = \prod_{i=1}^{n} V_i * 2^o \tag{3.3}$$

In a few cases the formula is not accurate enough. Consider the air conditioning option feature: some car makers provide three different types of air conditioning systems; in this case, the combinations for air conditioning are 3+1=4, where the additional “1” is for the case of not choosing air conditioning.

For reducing product variants, most of car makers divide the total product versions into several price classes in which the number of options is limited. In this case, the total product complexity is the sum of the complexity of the price classes.

In theory for a typical B segment model “Vehicle W” offered in the European market, the total complexity for wire harnesses can reach 4 million.

In reality, since some of the product versions are not available due to limitations based on regulations, policies and laws, the real product complexity for that “Vehicle W” is about 30,000.

Obviously, it is unrealistic to design and manage 30,000 wire harness part numbers when they are only one basic element of a vehicle. Therefore, actions must be taken to reduce the wiring harnesses complexity.

3.2 Methods for reducing wiring harness complexity

To reduce the complexity, the model "Vehicle W" uses the following methods:

1) Reduce the number of free options by aggregating several options together as a small package. The customer can either choose the package (obtain all the options in the package) or do the opposite (lose all the options in that package).

2) Use rich cables, which means during the design and product development phase, regardless of the customer choice for this option, the car maker will always include this option within the wiring harness. For instance, when designing the harnesses for seats, the same cable configuration is to be used in the vehicle assembly whether the customer chooses a seat with electric adjustment or not. Of course this increases the wiring harness product cost. With this option content variant (no electric seat adjustment), the car maker includes extra cables and connectors which are not needed. The costs associated with using rich cables that have unused wires and connectors in them is called the giveaway cost.

3) Divide the total wiring harness set into different wiring harness families. This method is not able to reduce total complexity but it could reduce the total number of individual part numbers of wiring harnesses, as adding more wiring families will result in less combinations because either the number of mandatory features or the number option features are reduced in each family. For the model "Vehicle W", the complete wiring harness set is divided into four wiring families: the front harness, the rear harness, the harness for the dashboard, and the harness for the doors.

By applying these three methods, when considering the case for "Vehicle W", the total number of designed part numbers reduces from 30,000 to around 2000 with an acceptance of a certain level of giveaway costs.

Even though the total part numbers are reduced to about 2000 during the design phase, from an assembly plant point of view, this number is still large and could result in generating costs that are not necessary, which this work will explore.

Table 3-2 shows the usage of front and rear harnesses in the year 2010 for “Vehicle W”. From the table, it can be seen that for the front harnesses wiring family, only about half of the part numbers had been used that year, and the other half were never used in production. Also of note, among the part numbers which were used, only 23% of these part numbers had been used for a volume larger than 500 for that year. The remaining nearly 80% part numbers were used for extremely low volumes. A similar condition can be found in when assessing the rear wire harness usage. This condition indicates that only about 10% of the total part numbers were used frequently (a volume larger than 500 a year). The majority of part numbers were either never used or used in a very low frequency.

Wiring family	Part number usage	Part number usage > 500 times	Part number usage < 500 times
Front harness	53%	23%	77%
Rear harness	46%	23%	77%

Table 3-2: Part number usage of “Vehicle W” in 2010. (Internal correspondence)

On one hand, plant personnel would like to reduce the number of individual part numbers as much as possible as the plant has to keep a certain volume of part numbers for safety stock. When a new model launched, these wire harnesses stored as safety stock will become obsolete. For the part numbers used in a low quantity, the plant has to spend extra costs on storage, internal material handling, and sequencing operations in comparison to the higher volume part numbers.

On the other hand, reducing the wiring harness complexity impacts the product costs. As the part numbers are reduced, the average giveaway cost would increase since the costs associated with the rich cable approach need to be considered. This introduces material waste into the final vehicle.

So it is necessary to develop a cost model that considers both product cost and manufacturing costs so that an optimum complexity level can be found through analysing the trade-off between these two conflicting requirements.

3.3 Benchmark between car makers in managing wiring harness complexity

3.3.1 Wiring harness complexity management in car maker A

For models of car maker A, the complete set of wiring harnesses are divided into four families: the front and rear wiring, wiring for dashboard, and wiring for the doors respectively. Within each family, a certain amount of part numbers is designed.

In the past, the primary design driver was to keep product cost at a minimum level by accepting a minimum level of a giveaway cost (typically at this time the cost of manufacturing is not considered).

When the number of electric devices on a vehicle is limited, this approach is acceptable as in this case, the total number of individual part numbers is low and plant can manage this. But as the product content become more and more complex as car makers try to present more features and feature choices to their customers, more part numbers are needed as most of newly introduced features impact wire harness designs, which introduces problems for the vehicle assembly plants.

To solve this issue, under the leadership of WCM experts, both product development and manufacturing departments are involved to discuss a new standard solution.

As previously stated, a cost model needs to be developed to perform a trade-off analysis for effective clustering and rich cable substitution in the design phase according to forecasted volumes and product costs for each part number.

In reality, determining which part number can be substituted is a challenge when designing the wiring harnesses for a new model. The design department has to rely on either the forecasted data for the new model or refer to the sales data of older generations. Neither of these methods is accurate enough to make decisions with certainty as the launching of the new model is usually one or two years later after the wire harness design cycle, and during this time, the taste of the customer might change significantly.

Another consideration is the determination of the "substitution time window". For instance, suppose that according to the trade-off between product and manufacturing costs, if the total volume for a specific part number is less than 500 per year, then this part number could be substituted by another richer part number to reduce the total costs. If the total volume of this part number is 530 this year, it cannot be substituted in this case.

However, if "substitution time window" is changed to be reviewed weekly, the situation might be different. Using the same example, suppose the total volume of that part number is still 530 in a year, but from week 1 to week 5, the volume is 100, 100, 100, 100, and 30 with no demand in the remaining weeks of the year being considered. According to the trade-off analysis, if the demand is less than 10 per week (assume 50 production weeks per year, and 500/50=10), substitution can be done. So in this case, the substitution can be done in the 45 weeks of the year except the first 5 weeks. Thus the total cost can be further decreased as compared to the previous case.

Theoretically, the best approach is to increase the complexity to the maximum level on the supplier side, then according to the weekly demand or forecast, select a subset of the total designed part numbers and perform the trade-off between product cost and manufacturing cost. If the product cost increase due to the part number substitution is less than the saving by reducing this part number, substitution can be done. Thus the part numbers managed in the plant at a given time window can be kept at a relatively low level and the related product cost increase is not too much. Obviously, the robustness of this approach needs to be analysed in detail since the input is a forecasted demand; therefore, the savings might be much lower than expected if the forecast error is significant.

This thesis focuses on this new approach by using a MATLAB simulation with the Monte Carlo Method, and further details will be given in the later chapters.

3.3.2 Wiring harness complexity management in car maker B

For a vehicle model of car maker B, and taking a model called “Vehicle M” as an example, the wiring harnesses are divided into 10 families, as summarized in Table 3-3. Some wiring families can be further divided into a sub-family according to the market it served or installed position in vehicle.

Number	Wiring Family
1	Body
2	FEL (Front End Lighting)
3	Left body
4	Powertrain
5	ABS (Anti-locked Braking System)
6	IP (Instrument Panel)
7	Doors
8	Lift gate
9	Headliner
10	O/V console

Table 3-3: Wiring families classification of “Vehicle M” of car maker B.

For each family of wiring harnesses, a certain quantity of part numbers will be designed. The product features can be classified into several different designations, as summarized below:

1) A ‘Standard feature’ (the circuits and connectors are always used in production for this part number), which is indicated with an “S”;

2) A ‘Giveaway’ feature (the circuits and connectors are always in the part number but are not always used), which is indicated using a “G”;

3) A feature not present (the option is not present in this part number), which is indicated as blank in the table;

4) A sales code condition which means the product feature is present in the sales codes of this part number. A sales code is used to select the correct part number in the harness family, and is indicated with “+/-”; and

5) A ‘Feature present’ but not driven by sales code, which means the product content is present in the part number but not in the sales code part number.

For determining whether a product feature could be a giveaway or not in a wiring harness, several factors need to be considered including: cost, volume, Buzz/Squeak/Rattle (BSR), sealing unused connectors, Electric Equipment (EE) feasibility, and the assembly line speed although there is no quantified cost information for carrying additional part numbers (the manufacturing cost is not evaluated). This is described in more detail below:

1) Cost: the wiring for the giveaway feature must have a relatively low cost. For instance, some kinds of audio cables, like antenna cables, are costly so they should not be considered as giveaway elements.

2) Production volume for a part number: the low volume part numbers may have more giveaway features.

3) BSR: Buzz/Squeak/Rattle noises generated by wire harnesses are not acceptable. Therefore, actions need to be taken to prevent BSR before providing any unused features (i.e., loose hanging cables are not acceptable).

4) Unused connectors: connectors can only be given away in non-wet area of vehicle.

5) EE feasibility: there are specific conditions where bus circuits and safety circuits cannot be given away.

6) Line speed: the typical line speed in an assembly plant is about 1 minute per vehicle, which may not allow operators to perform additional operations in some stations thus preventing the use of giveaway features.

To reduce the wiring harnesses complexity, giveaway features need to be used for each part number, but they must be designed appropriately. For instance, inside the

“Body” wiring harness family used in a major market for that model, the percentage of average giveaway features per part number is more than 20% (Internal personal correspondence 2012).

At car maker B, when designing the wiring harnesses, the first drive is to reduce the wiring harness complexity via reducing variants, although the manufacturing cost is not quantified. They could tolerate a relatively large giveaway cost to lower the manufacturing complexity problems. The result is that the total part numbers designed in car maker B is much less than that in car maker A (can be 1/10 difference). However, it is not known whether an optimum balance is achieved. Developing a model to achieve an optimal design set of wire harnesses is the goal of this research.

CHAPTER

4. WIRING HARNESS COMPLEXITY COST MODEL

In this chapter, a cost model will be developed to perform the trade-off analysis between manufacturing cost and wiring harness product cost.

The cost model consists of two parts, one part for evaluating the manufacturing cost while the other part for calculating the product cost.

4.1 Manufacturing cost deployment

The purpose of the manufacturing cost deployment analysis is to quantity the manufacturing cost related to the wiring harness component that occur in the plant.

Figure 4-1 shows the layout of the plant that being studied together with the processes that generate the wiring harness manufacturing cost.

When the truck arrives at the plant from the supplier, the first operation is to unload the wiring harnesses, and place the unloaded harnesses into a buffer area on the floor, where they await transport to the warehouse. According to their volume, harnesses will be classified as high runners (HR) and low runners (LR) and they will be transported and stocked separately. The stored harnesses will be transferred to the sequencing area at a certain time before production and will be sequenced according to the production plan. When the correct time occurs, the harnesses will be transported by AGVs (Automatic Guided Vehicle) to the assembly line.

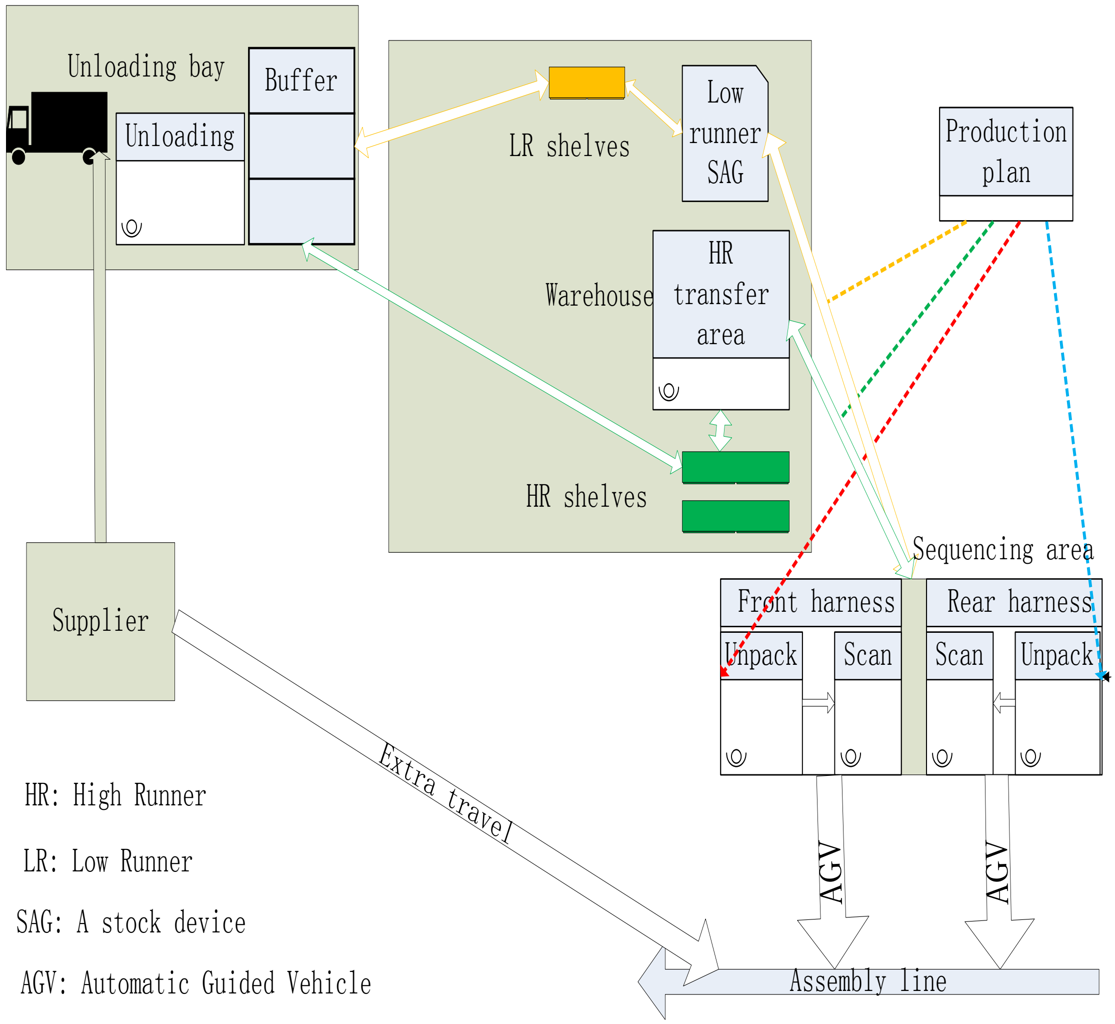

Figure 4-1: Plant layout and major operations for wiring harness management including: unloading wiring harness at unloading bay, transporting harness from buffer to warehouse, from warehouse to sequencing area, sequencing and transporting to assembly line.

The total wiring harness manufacturing cost can be divided into the following elements when considering the process flow and the related operations: 1) administrative cost, 2) plant internal handling cost, 3) cost for the sequencing area, 4) cost for extra assembly process, 5) cost related to warehousing and stocking, and 6) extra travel and obsolescence cost.

For each part, it can be further divided according to whether it is a high runner or low runner and the detailed process flows that occur for each type.

Most of these costs are difficult to evaluate directly because in a plant, the operating cost calculations are often considered according to specific operations and function units, not according to the different vehicle parts. For example, consider operators who are responsible for unloading components: those operators will not only be unloading wiring harnesses, but also other components coming from suppliers such as seats, mirrors and so on. Unloading the wiring harnesses is only a portion of their daily job. The same situation exists in many other operations. This means the total manufacturing cost for a whole unloading function unit is easy to obtain, but the cost related to unloading wiring harnesses specifically is difficult to quantify. To solve the problem, a method called FTE (Full Time Equivalent) can be used here.

FTE is an indicator that represents the workload of an operation or a project relative to the full time workload.

In this chapter, FTE is used to represent the equivalent people needed to perform an operation using a full working time period. The full working time here is the working hours for a shift or for a working day.

FTE can be calculated as follows:

$$\mathbf{FTE} = \frac{\sum_{i=1}^{n} \boldsymbol{Hi}}{\boldsymbol{Hs}} \tag{4.1}$$

Where for a general operation:

“n” is the total number of operators that participate the operation

“Hi” is the working time for operator i for this particular operation (units in hours).

“Hs” is the full working time of a shift (units in hours).

For instance, consider a working period that is one shift which is 8 hours. If a particular operation such as unloading wiring harnesses needs 6 operators working together for 2 hours, the total working time will be 6*2=12 hours. The FTE in this case is calculated through dividing total working hours by the period time, which means the FTE per shift is 12 hours divided by 8 hours, which equals to 1.5. In another words, 1.5 operators are needed to perform this operation during the whole shift. Then according to how many shifts per day, the FTE per day can be calculated for this operation. The total cost for this operation per year thus is easily obtained by multiplying the FTE per day with the unit annual salary for the related employee or operator.

4.1.1 Administrative cost

The administrative cost can be divided into two parts: one for planning and the other one for inventory management.

1) Administrative cost (planning)

This part of cost is related to the wiring harness planning in the plant, which includes operations such as generating orders to the supplier, monitoring the wiring harness supply condition, receiving the harnesses, checking the quantity and quality when they arrive from the supplier, and sign the related documents. As these jobs are performed by salaried employees (or white collars), the cost is calculated in terms of FTE per day as follows:

$$FTE_{adpd} = \frac{\sum_{i=1}^{n} Hi}{H_d} \tag{4.2}$$

$$C_{adp} = FTE_{adpd} * S_{adp} \tag{4.3}$$

Where:

“FTE_{adpd}” is the FTE per day for administrative planning.

“n” is the total number of employees that participate the planning

“H_i” is the working time for employee i for this particular operation (units in hours).

“H_d” is the full daily working time (units in hours).

“C_{adp}” is the cost for administrative planning.

“S_{adp}” is the annual salary of the related employee.

This cost will change if the number of wiring harnesses individual part numbers changes. This shows that more part numbers will result in more administrative working to perform the job.

2) Administrative cost (inventory management)

This part is the administrative cost for wiring harness inventory management. Main operations include monitoring the quantity of each part number in the warehouse, and making emergency orders. As those jobs are performed by salaried employees, FTE per day is used here.

$$\boldsymbol{FTE_{adid}} = \frac{\sum_{i=1}^{n} \boldsymbol{Hi}}{\boldsymbol{H_d}} \tag{4.4}$$

$$\boldsymbol{C_{adi}} = \boldsymbol{FTE_{adid}} * \boldsymbol{S_{adi}} \tag{4.5}$$

Where:

“FTE_{adid}” is the FTE per day for administrative inventory management.

“n” is the total number of employees that participate the operation

“H_i” is the working time for employee i for this particular operation (units in hours).

“H_d” is the full daily working time (units in hours).

“C_{adi}” is the cost for administrative inventory management.

“S_{adi}” is the annual salary for the related employee.

Also this cost is variable if number of individual part numbers changed.

3) Total administrative cost

Total administrative cost is the sum of planning cost and inventory management cost.

$$\boldsymbol{C_{ad}} = \boldsymbol{C_{adp}} + \boldsymbol{C_{adi}} \tag{4.6}$$

Where:

“C_{ad}” is total administrative cost.

4.1.2 Plant internal handling cost

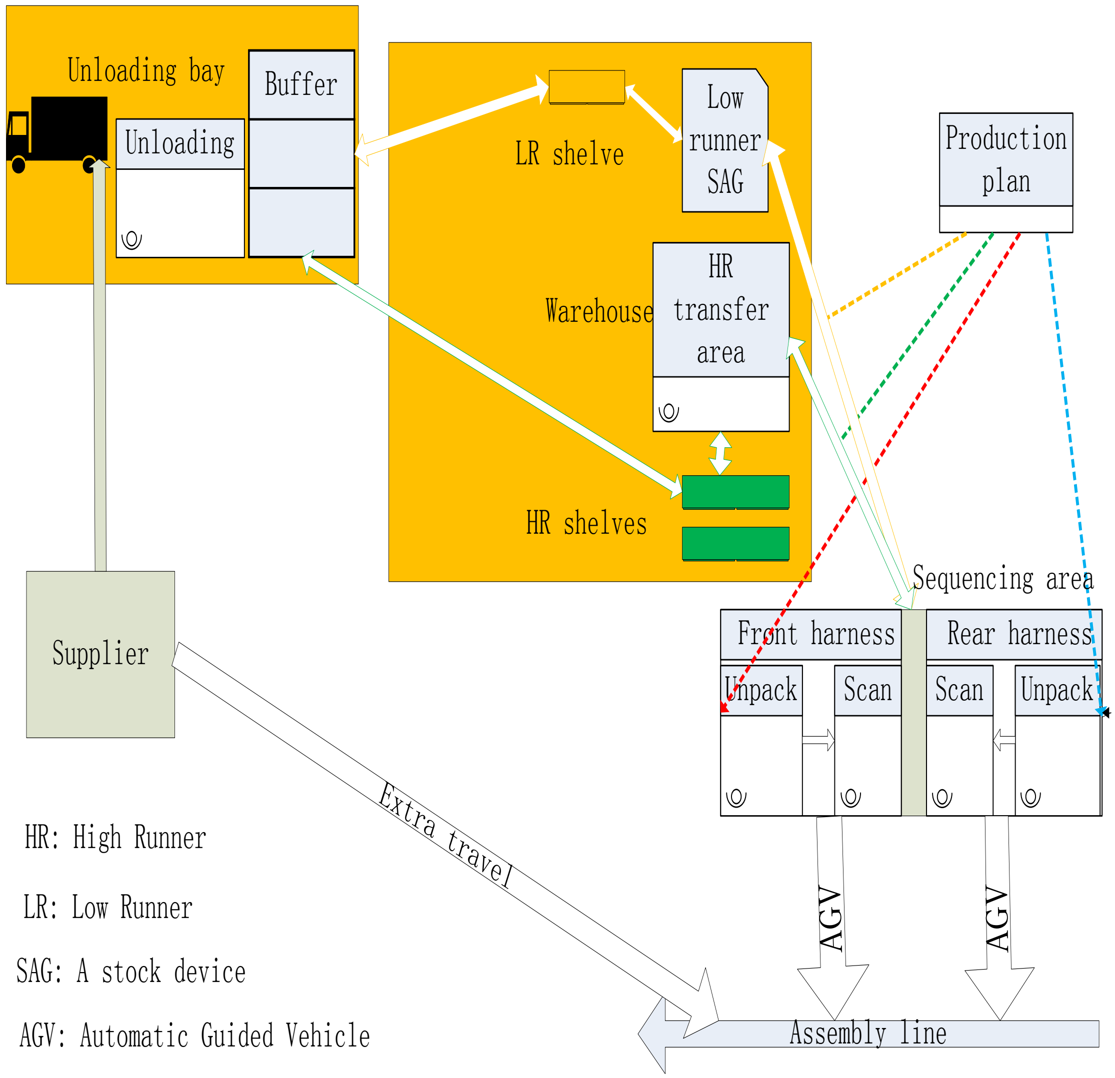

Figure 4-2: Plant internal handling process and operations highlighted in orange. The costs are generated in unloading bay and warehouse due to unloading operation and transportation of wiring harness to stock devices.

The plant internal handling cost is the cost for transporting the harnesses from the unloading bay to and from the warehouse, and then to the sequencing area, which highlighted in orange in Figure 4-2. It can be further divided into following parts:

1) Space cost for the unloading bay

The space cost of the unloading bay is calculated as the following formula:

$$C_{spu} = SPA_{unl} * U_{sunl} \tag{4.7}$$

Where:

"C_{spu}" is the space cost of the unloading bay.

"SPA_{unl}" is the space of the unloading bay.

"U_{sunl}" is the unit space cost of the unloading bay in a year.

The space cost is variable according to the number of individual part numbers as each part number occupies a specific defined space.

2) Cost for unloading

This is the labour cost for the unloading operation.

$$FTE_{unls} = \frac{\sum_{i=1}^{n} Hi}{H_s} \tag{4.8}$$

$$C_{unls} = FTE_{unls} * S_{unl} * N_{shift} \tag{4.9}$$

Where:

"FTE_{unls}" is the FTE per shift for the unloading.

"n" is the total number of operators that participate the operation

"H_i" is the working time for operator i for this particular operation (units in hours).

"H_s" is the full shift working time (units in hours).

"C_{unls}" is the cost for the unloading.

"S_{unl}" is the annual salary for a related operator.

"N_{shift}" is the number of shifts per day.

This cost will not vary according to number of individual part numbers as the total unloading time should not change if the total quantity of harnesses is kept the same.

3) Operating cost of fork lift for unloading

This is the operating cost for the fork lift used for the wiring harnesses unloading process:

$$C_{fokl} = N_{fokl} * CU_{fokl} \tag{4.10}$$

Where:

"C_{fokl}" is the operating cost of the fork lift

"N_{fokl}" is the equivalent number of fork lifts used for wiring harness unloading.

"CU_{fokl}" is the unit annual operating cost for a fork lift.

This cost will not vary when changing the number of individual part numbers.

4) Cost for high runners (HR) to warehouse

This part of the cost includes the transportation of HRs from the buffer to the shelves and placing the harnesses onto the shelves.

$$FTE_{HRWRS} = \frac{\sum_{i=1}^{n} Hi}{H_s} \tag{4.11}$$

$$C_{HRWR} = FTE_{HRWRS} * S_{HRWR} * N_{shift} \tag{4.12}$$

Where:

"FTE_{HRWRS}" is the FTE per shift for transporting HRs to the shelves.

"n" is the total number of operators that participate the operation.

"H_i" is the working time for operator i for this particular operation (units in hours).

"H_s" is the full shift working time (units in hours).

"C_{HRWR}" is the cost for the HR transportation.

"S_{HRWR}" is the annual salary for a related operator.

"N_{shift}" is the number of shifts per day.

The total cost should vary when the number of individual part numbers is changing. This will change the total working hours of this operation as different part numbers have their own stock position on the shelves.

5) Cost for High Runner (HR) repack

This is the cost for repacking the high runners before transporting them to the sequencing area.

$$\boldsymbol{FTE_{HRRPS}} = \frac{\sum_{i=1}^{n} \boldsymbol{Hi}}{\boldsymbol{H_s}} \tag{4.13}$$

$$\boldsymbol{C_{HRRP}} = \boldsymbol{FTE_{HRRPS}} * \boldsymbol{S_{HRRP}} * \boldsymbol{N_{shift}} \tag{4.14}$$

Where:

"FTE_{HRRPS}" is the FTE per shift for repacking the high runners.

"n" is the total number of operators that participate the operation.

"H_i" is the working time for operator i for this particular operation (units in hours).

"H_s" is the full shift working time (units in hours).

"C_{HRRP}" is the cost for the HR repackaging.

"S_{HRRP}" is the annual salary for a related operator.

"N_{shift}" is the number of shifts per day.

The HR repacking cost does not vary according to the number of individual part numbers.

6) Cost of feeding HR to sequencing area.

This is the related cost from taking the correct quantity of each higher runner harness from the shelves according to the production plan to their arriving to the sequencing area.

$$FTE_{HRFSS} = \frac{\sum_{i=1}^{n} Hi}{H_s} \quad (4.15)$$

$$C_{HRFS} = FTE_{HRFSS} * S_{HRFS} * N_{shift} \quad (4.16)$$

Where:

"FTE_{HRFSS}" is the FTE per shift for feeding high runners to the sequencing area.

"n" is the total number of operators that participate the operation.

"H_i" is the working time for operator i for this particular operation (units in hours).

"H_s" is the full shift working time (units in hours).

"C_{HRFS}" is the cost for feeding high runners to the sequencing area.

"S_{HRFS}" is the annual salary for a related operator.

"N_{shift}" is the number of shifts per day.

This part of the cost will not vary according to the change of part numbers as the total volume feeding to the sequencing area is fixed by the production plan.

7) Cost for low runners (LR) to warehouse

This part of the cost includes the transportation of LRs from the buffer to the shelves and putting the harnesses onto the shelves.

$$FTE_{LRWRS} = \frac{\sum_{i=1}^{n} Hi}{H_s} \quad (4.17)$$

$$C_{LRWR} = FTE_{LRWRS} * S_{LRWR} * N_{shift} \quad (4.18)$$

Where:

"FTE_{LRWRS}" is the FTE per shift for transporting LRs to the shelves.

"n" is the total number of operators that participate the operation.

"H_i" is the working time for operator i for this particular operation (units in hours).

"H_s" is the full shift working time (units in hours).

"C_{LRWR}" is the cost for LR transportation to the shelves.

"S_{LRWR}" is the annual salary for a related operator.

"N_{shift}" is the number of shifts per day.

The total cost should vary when the number of individual part numbers is changing. The total working hours of this operation will change as different part numbers have their own stock position on the shelves.

8) Cost for low runners (LR) from shelves to SAG (a temporary stock device)

This part includes the cost of transferring low runners from shelves to SAG (the SAG is a temporary stock device placed just nearby the high runner transfer area).

$$FTE_{LRSAGS} = \frac{\sum_{i=1}^{n} Hi}{H_s} \tag{4.19}$$

$$C_{LRSAG} = FTE_{LRSAGS} * S_{LRSAG} * N_{shift} \tag{4.20}$$

Where:

"FTE_{LRSAGS}" is the FTE per shift for the LR transport to the SAG.

"n" is the total number of operators that participate the operation.

"H_i" is the working time for operator i for this particular operation (units in hours).

"H_s" is the full shift working time (units in hours).

"C_{LRSAG}" is the cost for the LR transportation to the SAG.

"S_{LRSAG}" is the annual salary for a related operator.

"N_{shift}" is the number of shifts per day.

The total cost should vary when the number of individual part numbers is changing.

9) Cost of feeding LR to sequencing area.

This is the related cost from taking the correct quantity of each low runner part number from the SAG according to the production plan to arriving to the sequencing area.

$$\boldsymbol{FTE_{LRFSS}} = \frac{\sum_{i=1}^{n} \boldsymbol{Hi}}{\boldsymbol{H_s}} \tag{4.21}$$

$$\boldsymbol{C_{LRFS}} = \boldsymbol{FTE_{LRFSS}} * \boldsymbol{S_{LRFS}} * \boldsymbol{N_{shift}} \tag{4.22}$$

Where:

"FTE_{LRFSS}" is the FTE per shift for feeding low runners to the sequencing area.

"n" is the total number of operators that participate the operation.

"H_i" is the working time for operator i for this particular operation (units in hours).

"H_s" is the full shift working time (units in hours).

"C_{LRFS}" is the cost for feeding low runners to the sequencing area.

"S_{LRFS}" is the annual salary for a related operator.

"N_{shift}" is the number of shifts per day.

This part of the cost will not vary according to the change of part numbers as the total volume feeding to sequencing area is fixed by the production plan.

10) Total cost for plant internal handling

The total cost for plant internal handling is calculated as the sum of previous nine items:

$$\begin{aligned} \boldsymbol{C_{PLI}} &= \boldsymbol{C_{spu}} + \boldsymbol{C_{unls}} + \boldsymbol{C_{fokl}} + \boldsymbol{C_{HRWR}} + \boldsymbol{C_{HRRP}} + \boldsymbol{C_{HRFS}} \\ &+ \boldsymbol{C_{LRWR}} + \boldsymbol{C_{LRSAG}} + \boldsymbol{C_{LRFS}} \end{aligned} \tag{4.23}$$

Where:

"C_{PLI}" is the total cost for plant internal handling.

4.1.3 Cost for sequencing area

The function of the sequencing area is related to sequencing the different part numbers according to the production plan so that each car on the assembly line is correlated with its wiring harnesses. The sequencing area in the plant is highlighted in blue in Figure 4-3.

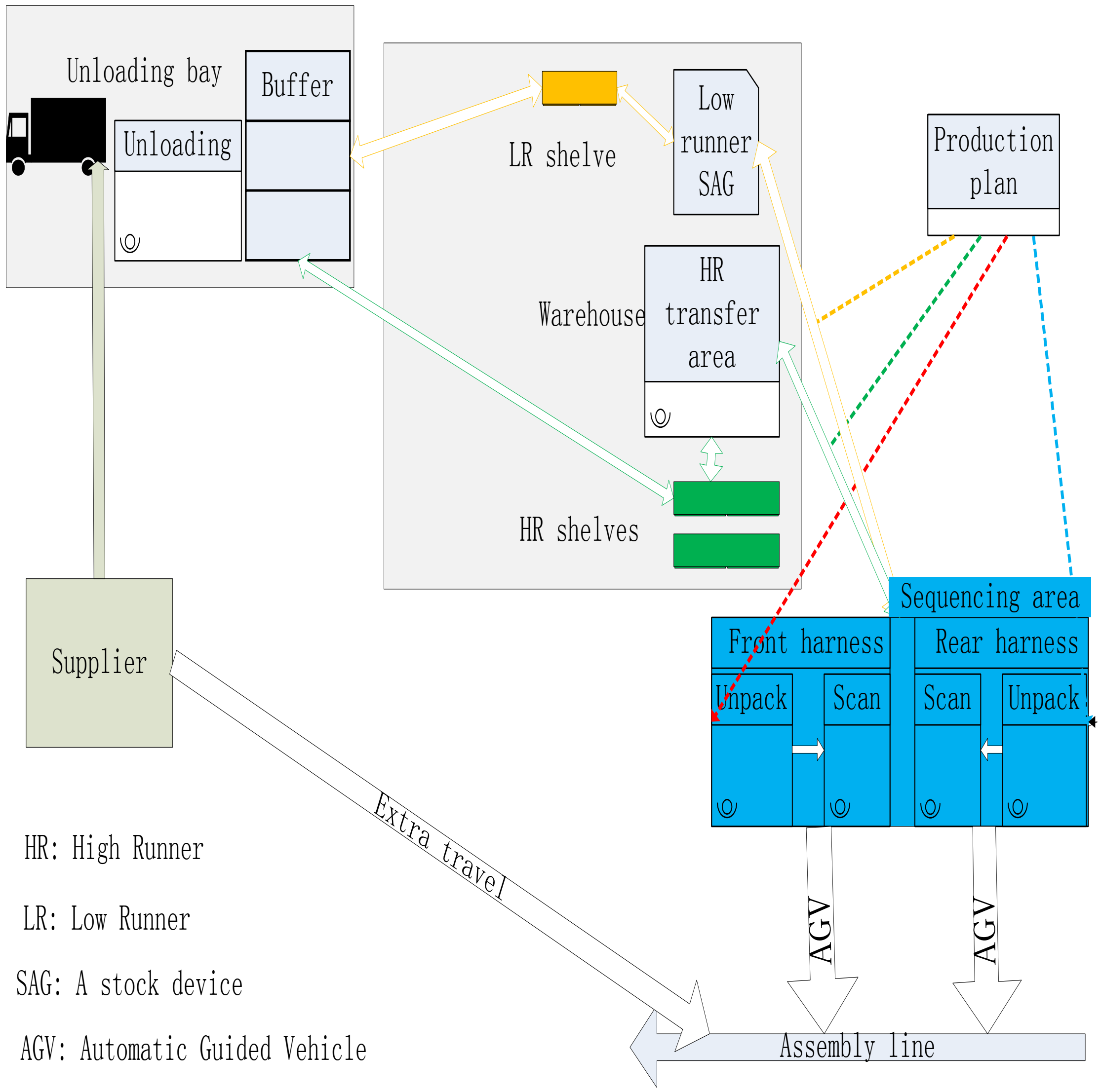

Figure 4-3: Process and operations in sequencing area highlighted in blue. Major operations in sequencing area including: unpacking, scanning and using AGV transport wiring harness to assembly line.

The costs for the sequencing area are listed as follows:

1) Sequencing area space cost:

The space cost of the sequencing area can be calculated in a same way as the space cost of the unloading bay.

$$C_{spsa} = SPA_{sa} * U_{sa} \tag{4.24}$$

Where:

"C_{spsa}" is the space cost for the sequencing area.

"SPA_{sa}" is the space of the sequencing area.

"U_{sa}" is unit space cost for the sequencing area in a year.

The space cost is variable according to the number of individual part numbers as each part number occupies a defined space.

2) Cost for unpacking

This cost is part of the handling cost, and is due to opening the box of wiring harnesses and taking out the correct quantity of each part number according to the production plan.

$$FTE_{unps} = \frac{\sum_{i=1}^{n} Hi}{H_s} \tag{4.25}$$

$$C_{unp} = FTE_{unps} * S_{unp} * N_{shift} \tag{4.26}$$

Where:

"FTE_{unps}" is the FTE per shift for unpacking in the sequencing area.

"n" is the total number of operators that participate the operation.

"H_i" is the working time for operator i for this particular operation (units in hours).

"H_s" is the full shift working time (units in hours).

"C_{unp}" is the cost for unpacking in the sequencing area.

"S_{unp}" is the annual salary for a related operator.

"N_{shift}" is the number of shifts per day.

As the total unpack quantity will not change, the cost will not be affected by the variation of number of individual part numbers.

3) Cost of sequencing

This is the cost for picking the correct part number according to the production plan and putting them in the correct sequencing order, one by one.

$$\boldsymbol{FTE_{SEQS}} = \frac{\sum_{i=1}^{n} \boldsymbol{Hi}}{\boldsymbol{H_s}} \tag{4.27}$$

$$\boldsymbol{C_{SEQ}} = \boldsymbol{FTE_{SEQS}} * \boldsymbol{S_{SEQ}} * \boldsymbol{N_{shift}} \tag{4.28}$$

Where:

“FTE_{SEQS}” is the FTE per shift for sequencing the harnesses.

“n” is the total number of operators that participate the operation.

“H_i” is the working time for operator i for this particular operation (units in hours).

“H_s” is the full shift working time (units in hours).

“C_{SEQ}” is the cost for sequencing the harnesses.

“S_{SEQ}” is the annual salary for a related operator.

“N_{shift}” is the number of shifts per day.

The cost should increase with increasing part numbers because more part numbers will lead to using more time being required for sequencing.

4) Cost for scanning and labeling

This part of the cost is related to the operation of scanning the related harness data into the production system and labeling them with a serial number so that the relationship between the car body and the wiring harness can be established.

$$FTE_{SCANS} = \frac{\sum_{i=1}^{n} Hi}{H_s} \tag{4.29}$$

$$C_{SCAN} = FTE_{SCANS} * S_{SCAN} * N_{shift} \tag{4.30}$$

Where:

"FTE_{SCANS}" is the FTE per shift for scanning and labeling the harnesses.

"n" is the total number of operators that participate the operation.

"H_i" is the working time for operator i for this particular operation (units in hours).

"H_s" is the full shift working time (units in hours).

"C_{SCAN}" is the cost for scanning and labeling the harnesses.

"S_{SCAN}" is the annual salary for a related operator.

"N_{shift}" is the number of shifts per day.

As the total scanning and labeling quantity will not change, the cost will not be affected by the variation of the number of individual part numbers.

5) Cost for feeding assembly line

This part of the cost is related to the operation of putting the sequenced wiring harnesses onto the AGV, so that the AGV can transport the harnesses to the corresponding assembly stations.

$$FTE_{AGVS} = \frac{\sum_{i=1}^{n} Hi}{H_s} \tag{4.31}$$

$$C_{AGV} = FTE_{AGVS} * S_{SCAN} * N_{shift} \tag{4.32}$$

Where:

"FTE_{AGVS}" is the FTE per shift for loading harnesses into the AGV.

"n" is the total number of operators that participate the operation.

"H_i" is the working time for operator i for this particular operation (units in hours).

"H_s" is the full shift working time (units in hours).

"C_{AGV}" is the cost for loading harnesses into the AGV.

"S_{AGV}" is the annual salary for a related operator.

"N_{shift}" is the number of shifts per day.

As the total loading quantity will not change, the cost will not be affected by the variation of the number of individual part numbers.

6) Total cost for sequencing area

The total cost of sequencing area is the sum of previous 5 items.

$$\boldsymbol{C_{SEQAREA} = C_{spsa} + C_{unp} + C_{SEQ} + C_{SCAN} + C_{AGV}} \tag{4.33}$$

Where:

"$C_{SEQAREA}$" is the total cost of sequencing area.

4.1.4 Cost for extra assembly process

This part is the extra assembly cost occurred during the wiring harness assembly process at the assembly line due to unpredictable mistakes, which is highlighted in red in Figure 4-4.

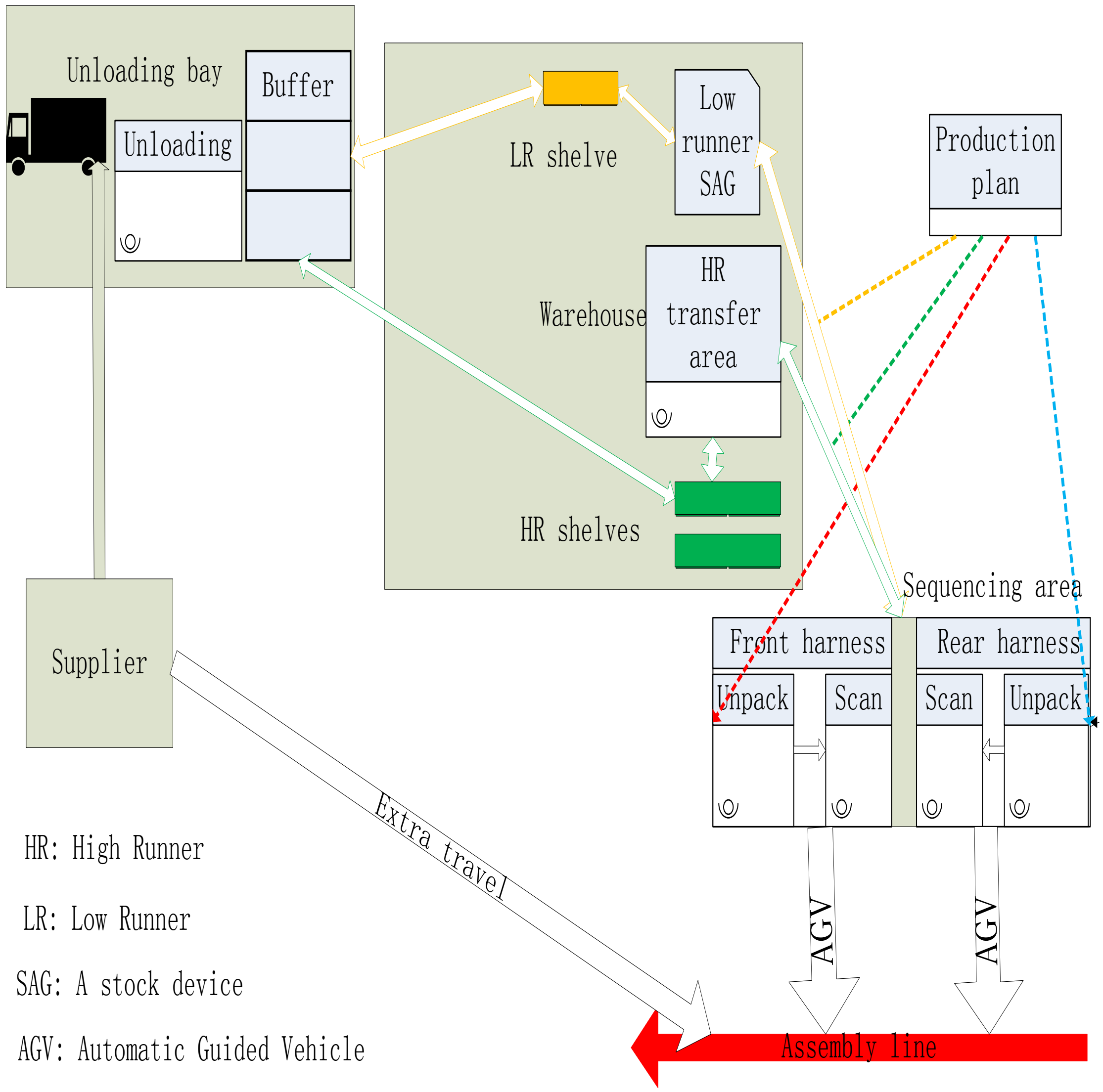

Figure 4-4: Position of assembly line in the plant layout highlighted in red.

The cost of the extra assembly process can be split as follows:

1) Substitution cost due to a quality issue

The substitution cost means using the same part number or a richer cable when quality issues in the original harness have occurred. This cost includes taking the original harness out of the vehicle, transferring the substitution harness from the warehouse to the assembly line and installing it on the vehicle, and the material waste of original harness.

As this is not a standard operation during the vehicle manufacturing, which means the occurrence is unexpected, it can be calculated as the product of the substitution quantity in a year and a unit substitution cost:

$$\boldsymbol{C_{subs}} = \boldsymbol{N_{subs}} * \boldsymbol{U_{subs}} \tag{4.34}$$

$$\boldsymbol{C_{subs}} = \boldsymbol{N_{subs}} * \boldsymbol{U_{subs}} \tag{4.35}$$

Where:

"C_{subs}" is the substitution cost due to a quality issue.

"N_{subs}" is the quantity of substitutions a year.

"U_{subs}" is the cost for each substitution.

This cost should vary with the number of individual part numbers, as more part numbers will increase the probability of having quality issues.

2) Cost of line stoppage due to the lack of a cable.

As wiring harnesses are one of the first components to be assembled on a vehicle, if a no-cable-condition occurs, it will influence all the remaining operations. In this case, the related vehicle and its components that are waiting to be assembled need to be taken out of the line, so assembly line has to stop for some time. This is expensive. The cost can be calculated as follows:

$$\boldsymbol{C_{stop}} = \boldsymbol{N_{stop}} * \boldsymbol{U_{stop}} \tag{4.36}$$

Where:

"C_{stop}" is the stoppage cost due to the lack of a cable.

"N_{stop}" is the quantity of stops in a year.

"U_{stop}" is the cost for each stoppage cost due to the lack of a cable.

The stoppage cost should vary according to the number of individual part numbers, as the more part numbers, the easier it is for the stock to be out of harnesses.

3) Rework due to wrong cable being installed.

This includes the related labour cost and material cost.

$$\boldsymbol{C_{rewo} = N_{rewo} * U_{rewo}} \tag{4.37}$$

Where:

"C_{rewo}" is the reworking cost due to a wrong cable.

"N_{rewo}" is the quantity of reworks a year.

"U_{rewo}" is the cost for each rework due to a wrong cable.

The reworking cost should vary according to the number of individual part numbers as the more part numbers, the higher the chances for reworking situations to happen.

4) Total manufacturing process related cost

The total manufacturing process related cost is calculated as the sum of previous 4 items:

$$\boldsymbol{C_{manu} = C_{subs} + C_{stop} + C_{rewo}} \tag{4.38}$$

Where:

"C_{manu}" is the total manufacturing process related cost

4.1.5 Cost of inventory and extra travel cost.

This part is related to the cost of inventory including the spacing cost, handling cost, obsolescence cost, and the cost of extra travel, which is highlighted in green in Figure 4-5. It can be calculated as follows:

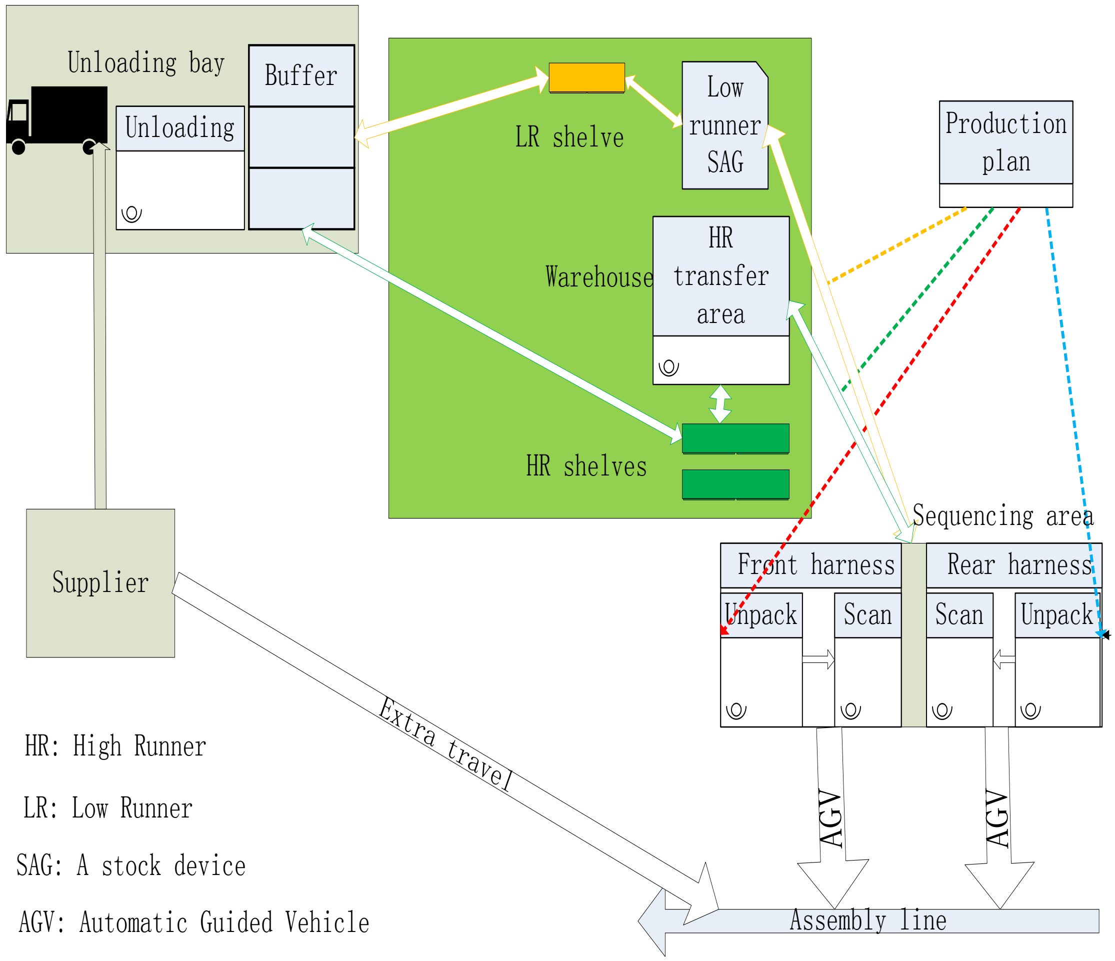

Figure 4-5: Warehouse location in the plant layout highlighted in green and the location of wiring harness stock area and transfer area in the warehouse.

1) Space cost of inventory

The space cost of the warehouse is calculated using the following formula:

$$C_{spi} = SPA_{inv} * U_{sinv} \tag{4.39}$$

Where:

"C_{spi}" is the space cost of inventory.

"SPA_{inv}" is the space occupied by wiring harnesses in inventory.

"U_{sinv}" is the unit space cost of inventory.

The space cost is variable according to the number of individual part numbers as each part number occupy certain space in the inventory.

2) Inventory holding cost

This is the cost related to holding the wiring harnesses in the warehouse, it can be calculated as certain percentage of total value of wiring harnesses in the warehouse.

$$\boldsymbol{C_{inho}} = \boldsymbol{V_{inho}} * \boldsymbol{H_{inho}} \tag{4.40}$$

Where:

"C_{inho}" is the inventory holding cost.

"V_{inho}" is the total wiring harness value in the inventory.

"H_{inho}" is the coefficient of holding cost which is expressed as a percentage.

The inventory holding cost is variable according to the number of individual part numbers as the value in the inventory should change.

3) Obsolescence cost

The obsolescence cost is calculated as follows:

$$\boldsymbol{C_{obso}} = \sum_{\boldsymbol{i}=1}^{\boldsymbol{N_{ob}}} \boldsymbol{C_i} * \boldsymbol{Q_i} \tag{4.41}$$

Where:

"C_{obso}" is the cost of the wiring harnesses obsolescence.

"C_i" is the unit cost for part number i.

"Q_i" is the quantity to be obsolesced for part number i.

"N_{ob}" is the number of individual part numbers need to be made obsolete.

The cost of obsolescence should vary according to the change of the number of individual part numbers.

4) Extra travel cost

The extra travel cost is the cost of requiring the supplier to ship harnesses using air travel immediately to the assembly plant.

$$C_{extr} = Q_{extr} * U_{extr} \tag{4.42}$$

Where:

"C_{extr}" is the wiring harness extra travel cost.

"U_{extr}" is the unit cost for extra travel.

"Q_{extr}" is the quantity of wiring harnesses used in extra travel.

The cost of extra travel should vary according to the change of number of individual part numbers.

5) Total cost of inventory and extra travel

The total cost of inventory and extra travel can be calculated as the sum of previous four items:

$$C_{inex} = C_{spi} + C_{inho} + C_{obso} + C_{extr} \tag{4.43}$$

Where:

"C_{inex}" is the total cost of inventory and extra travel.

4.1.6 Total manufacturing cost

The total manufacturing cost for wiring harnesses is the sum of the administrative cost, plant internal handling cost, cost for sequencing area, cost for extra assembly processes, cost of inventory and extra travel cost.

$$C_{malo} = C_{ad} + C_{PLI} + C_{SEQAREA} + C_{manu} + C_{inex} \tag{4.44}$$

Where:

"C_{malo}" is the Total manufacturing cost.

Thus the manufacturing cost per year per part number is obtained through dividing the total manufacturing cost by the number of individual part numbers managed in the plant.

$$C_{pn} = C_{malo} / N_{pn} \tag{4.45}$$

Where:

"C_{pn}" is the manufacturing cost per year per part number.

"N_{pn}" is the number of individual part numbers.

4.2 Product cost model

The product cost of a wiring harness is the cost of the wiring harnesses that are assembled on the vehicle according to the customer order. It is calculated as the product of cost of the part number and the volume that part number assembled during production.

The total product cost is calculated using the following formula:

$$C_{PROD} = \sum_{pni=1}^{PN} CU_{pni} * V_{pni} \tag{4.46}$$

Where:

"C_{PROD}" is the total wiring harness product cost

"CU_{pni}" is the product cost for part number "pni"

"V_{pni}" is the production volume for part number "pni"

"PN" is the total number of individual part numbers used in production.

4.3 Trade-off cost model

The trade-off cost model is obtained by combining the manufacturing cost model and the product cost model, and expressing it in terms of cost per vehicle.

$$C_{totpv} = \frac{C_{pn} * N_{pn} + C_{PROD}}{N_{veh}} \tag{4.47}$$

Where:

"C_{totpv}" is the total cost of the wiring harnesses per vehicle.

"N_{veh}" is the total production volume of vehicle.

Through this trade-off model developed in this research, it is possible to compute the total cost difference due to the variation of the number of individual part numbers managed in the plant so that an optimum wiring harness complexity level can be found.

CHAPTER

5. CASE STUDY

In this chapter, a case study of an existing model called "Vehicle W" is presented to show the potential benefits that can be obtained by using the trade-off cost model. The analysis presented here is based on data from the year 2010. As it is impossible to obtain the data during the design phase, the analysis is done using the actual production data.

5.1 Case study inputs

The case study is focused on two wiring harness families (front harnesses, rear harnesses) out of four (wiring harnesses for doors and the dashboard are not considered here). The analyses of the two families are done separately. The inputs of the case study are as follows:

1) Part number production volume table. This table shows the production volume for each part number in year 2010 that was used in "Vehicle W". Table 5-1 shows a small portion of the part number volume table for front harnesses.

Year	Model	Family	Part number	Production volume
2010	Vehicle W	Front	66	135
2010	Vehicle W	Front	67	100
2010	Vehicle W	Front	69	1200
2010	Vehicle W	Front	70	1900

Table 5-1: Example of part number production volume table in the year 2010 for model "Vehicle W" front wiring family.

2) Part number cost table. This table shows the product cost of all part numbers that were used in "Vehicle W". Table 5-2 shows a small portion of the part number cost

table. Suppose that the unit product cost for part number 66 is A. The product cost of part number 67 is €1.2 higher than 66. The cost of part number 70 is €6.6 higher than 66.

Year	Model	Family	Part number	Part number cost (€)
2010	Vehicle W	Front	66	A
2010	Vehicle W	Front	67	A+1.2
2010	Vehicle W	Front	69	A+5.6
2010	Vehicle W	Front	70	A+6.6

Table 5-2: Example of part number cost table in the year 2010 for model "Vehicle W" front wiring family.

3) Part number compatibility table. Given a part number, the part number compatibility table lists all the possible part numbers that could be substituted for the original part number. Table 5-3 shows a small portion of a part number compatibility table. For instance, part number 66 can be replaced by 70, 69 or 67 according to the table, while for part number 70 no substitution can be made.

Part number	Replaced by	Replaced by	Replaced by
66	70	69	67
67	70	69	
69	70		

Table 5-3: Example of part number compatibility table.

4) Manufacturing cost. The manufacturing used here is €1500 per year per part number, as this is the result obtained using the manufacturing cost deployment from the previous chapter. To simplify the analysis, the manufacturing cost per part number per year is assumed to be constant regardless of the variation of the number of wiring harness part numbers.

5.2 Case study analysis

To perform the trade-off, it is necessary to compare the manufacturing cost per part number per year with the cost of each substitution.

The cost of each substitution is obtained from the product cost table, product volume table and compatibility table.

The first thing to do is to combine the compatibility table and the product cost table together so that for each part number, the cost of part number that can be used for substitution can be shown.

For example, in Table 5-4, in terms of column “Replaced cost 1”, “A+6.6” is the cost of part number 70, as this part number can substitute all the other part numbers according to the compatibility table, “A+6.6” occupied the part number code in the new table.

Part number	Origin cost (€)	Replaced cost 1 (€)	Replaced cost 2 (€)	Replaced cost 3 (€)
66	A	A+6.6	A+5.6	A+1.2
67	A+1.2	A+6.6	A+5.6	
69	A+5.6	A+6.6		
70	A+6.6			

Table 5-4: Origin cost and substitution part number cost.

The next step is to calculate the unit substitution cost for each case. It can be easily obtained from Table 5-4, by calculating the product cost difference.

For instance, in Table 5-5, the cost for substituting part number 66 with part number 70 is €6.6 each.

Part number		70	69	67
	Origin cost (€)	**Delta cost 1 (€)**	**Delta cost 2 (€)**	**Delta cost 3 (€)**
66	A	6.6	5.6	1.2
67	A+1.2	5.4	4.4	
69	A+5.6	1		
70	A+6.6			
Delta cost: Cost difference between different part numbers				

Table 5-5: Unit substitution cost for each part number.

The next step is to calculate the total cost for each possible substitution by multiplying the unit cost difference with the total production volume of the original part number.

For instance, as shown in Table 5-6, if part number 70 is used as a substitution for part number 67, the total cost for that year is €162. As the manufacturing cost is €1500 per year per part number, by doing this substitution, the total saving is €1500-€162= €1338.

It can be found that in some cases, for one part number, there is more than one substitution choice. The part number 66 can be replaced not only by 67, but also part number 69 or 70, with total substitution costs that are €756 and €891 respectively.

Generally speaking, if there is more than one option such that the total substitution cost is lower than manufacturing cost, the part number with the lowest total substitution cost should be chosen, as this would save the most money.

However, sometimes there are exceptions, once again, using Table 5-6 as an example. Notice that part number 70 can substitute for all the other three part numbers and the costs for substitutions are all lower than €1500, in this situation, the best choice is to use only part number 70 to replace part numbers 66, 67 and 69 as in this case, the number of individual part numbers is the minimum; only one part number exists, while before substitution there were four part numbers.

Part number	70		69		67	
	Delta cost 1	**Total**	**Delta cost 2**	**Total**	**Delta cost 3**	**Total**
66	€ 6.6	€ 891.0	€ 5.6	€ 756.0	€ 1.2	€ 162.0
67	€ 5.4	€ 540.0	€ 4.4	€ 440.0		
69	€ 1.0	€ 1,200.0				
70						
Delta cost: Cost difference between different part numbers						

Table 5-6: Unit and total substitution cost for each part number.

Table 5-7 represents the results of performing a trade-off analysis. The table shows that the total product cost increase is €2631, since totally reducing three part numbers is achieved, the saving from manufacturing cost is 3*1500, which is €4500. This needs to be converted in terms of the cost per vehicle: the product cost is €0.79 per vehicle, the manufacturing saving is €1.35 per vehicle, so the total saving is €0.56 per vehicle.

Part number	PN after substitution	Product cost increase	Volume	# of PN	Manufacturing saving
66	70	€ 891.00	135	1	€ 0.00
67	70	€ 540.00	100	0	€ 1,500.00
69	70	€ 1,200.00	1200	0	€ 1,500.00
70	70	€ 0.00	1900	0	€ 1,500.00
Sum		€ 2,631.00	3335	1	€ 4,500.00
Cost per vehicle		€ 0.79			€ 1.35
Total saving per vehicle		€ 0.56			
PN: Part number					

Table 5-7: Example of results showing total saving per vehicle.

The analysis is performed for the entire front and rear wiring harness families.

5.3 Case study results

Number of individual part numbers	96	134	148	173
Product cost increase (€)	6.114	0.073	0.066	0.000
Manufacturing cost difference (€)	-0.588	-0.298	-0.191	0.000
Total cost difference (€)	5.526	-0.225	-0.125	0.000

Table 5-8: Case study results of front wiring harness of "Vehicle W".

Table 5-8 presents the results of case study for front wiring harness family. The total part numbers before substitution is 173, as this is the maximum complexity level for the front harness. This group of data is used as a reference for subsequent discussions. The optimum complexity level for this case is 134 part numbers, and the total saving compared to the reference is €0.225 per vehicle. The condition of 148 part numbers is obtained considering partial substitution. The total savings for that condition is €0.125 per vehicle. The condition of 96 part numbers is obtained through reducing the part numbers to a minimum level regardless of the trade-off. In this case, no savings can be obtained. The total cost is €5.526 per vehicle, and this result is due to increasing product costs based on reducing complexity without any limitation.

Figure 5-1 represents the product costs for the above four cases. It can be seen that as the number of individual part numbers decreases, the product cost increases. If the substitution is performed according to the trade-off analysis, which means implementing a substitution only if the product cost increase is less than manufacturing cost, the increase of the product cost can be maintained at a low level. Otherwise the product cost would increase as some substitutions could generate huge costs because of the large production volumes.

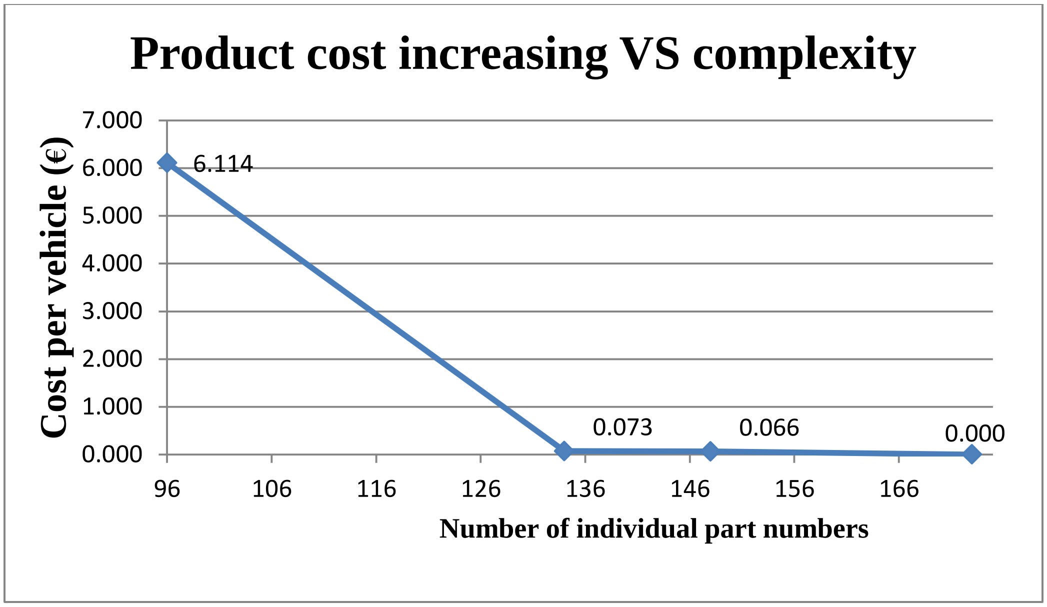

Figure 5-1: Product costs difference based on the variation of part number quantity compared to the case of using 173 part numbers.

Figure 5-2 illustrates the manufacturing cost difference in terms of cost per vehicle as a function of number of individual part numbers. Note that the negative value means saving in this case. It can be seen that by decreasing the number of individual part numbers, the manufacturing cost will decrease.

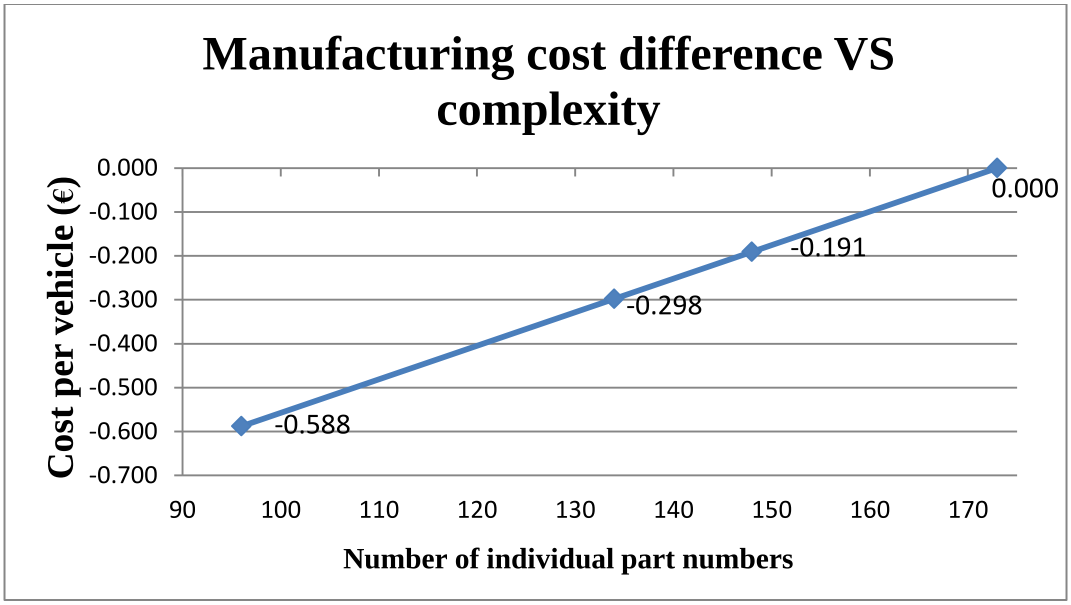

Figure 5-2: Manufacturing cost difference in terms of cost per vehicle as variation of number of individual part numbers compared to the case of using 173 part numbers.

Figure 5-3 shows the total cost difference in terms of cost per vehicle for the four cases. Note that negative values indicates a situation where there is a saving while positive values indicates that there are additional costs as compared to the reference.

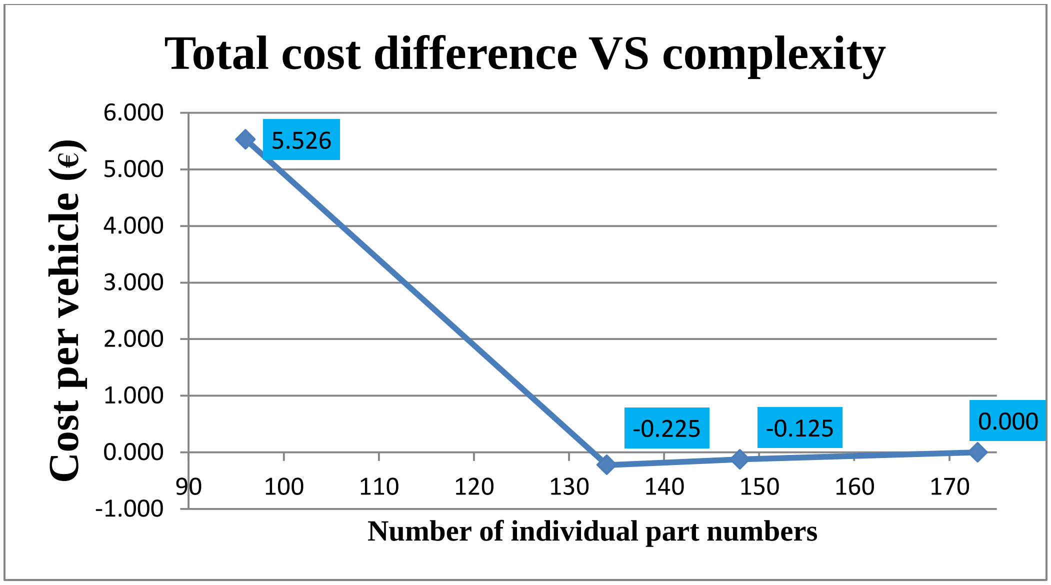

Figure 5-3: Total cost difference per vehicle as variation of number of individual part numbers compared to the case of using 173 part numbers.

From the data set being analysed, the optimum complexity for the front wiring harnesses is 134 part numbers and this would save €0.225 per vehicle.

Similar results are obtained for the rear harness family. As shown in Table 5-9, for the rear wiring harness family, the optimum complexity level consists of 155 part numbers, and this will result in a saving of €0.648 per vehicle.

Number of individual part numbers	**90**	**155**	**165**	**222**
Product cost increase (€)	34.19	-0.136	-0.122	0
Logistic cost difference (€)	-1.008	-0.512	-0.435	0
Total cost difference (€)	33.182	-0.648	-0.557	0

Table 5-9: Case study results of rear wiring harness of "Vehicle W"

Figure 5-4 represents the product cost increase for the four cases of the rear harness family. Note that for the case using 155 part numbers and 165 part numbers, the product increase is negative which is unusual. This is due to the fact in some substitution scenarios, the cost of the original harness is higher than that used for substitution, so that after this substitution, the product cost decreases if the production volume is high.

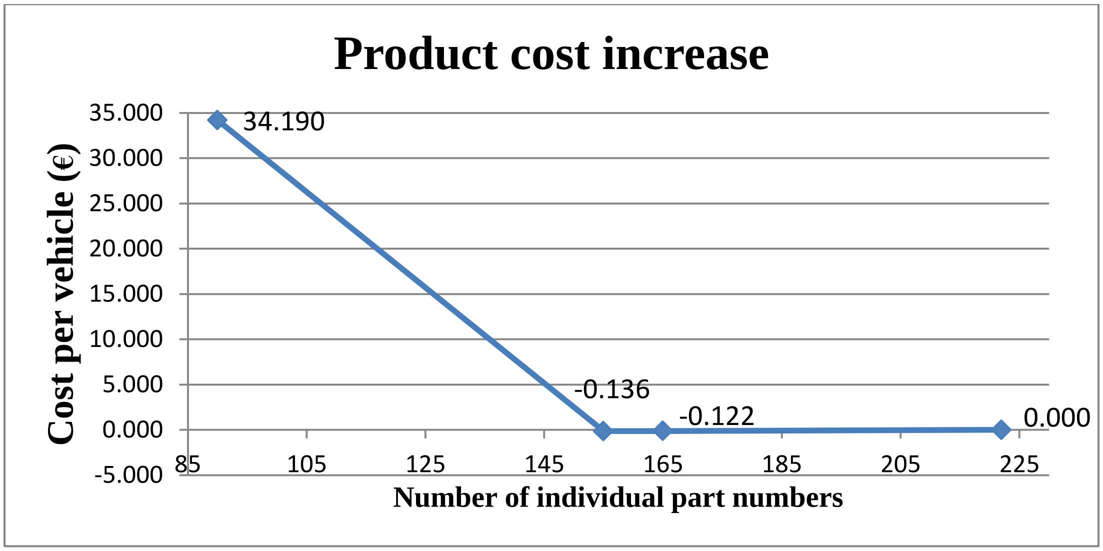

Figure 5-4: Product cost increasing as variation of number of individual part numbers for rear harnesses compared to the case of using 225 part numbers.

Figure 5-5 illustrates the manufacturing cost difference in terms of cost per vehicle as a function of number of individual part numbers for rear harness family. Note that the negative value indicates savings in this case. It can be seen that decreasing the number of individual part numbers, the manufacturing cost will decrease.

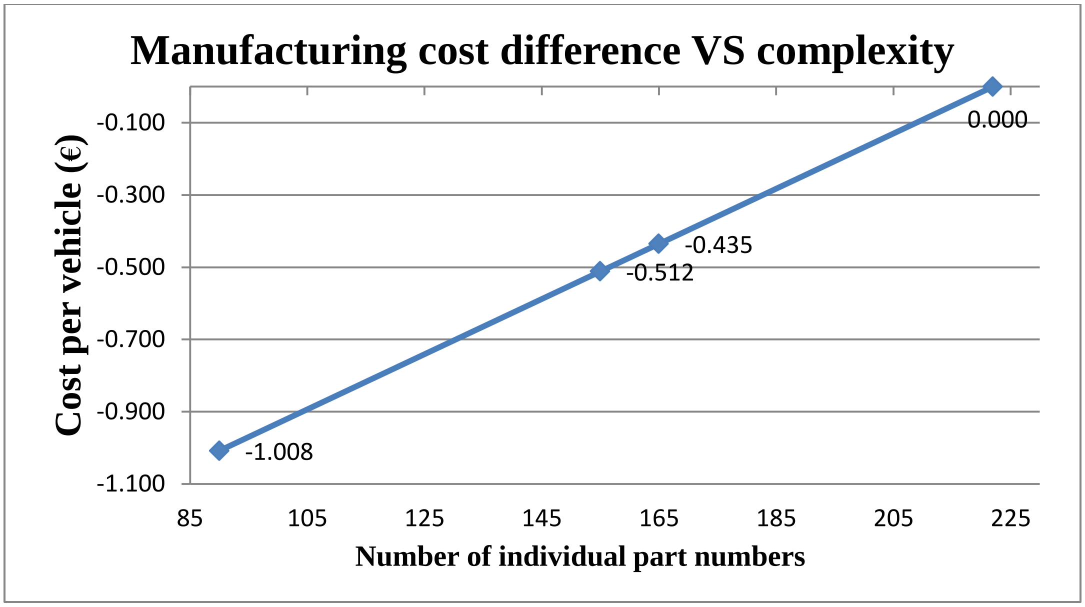

Figure 5-5: Manufacturing cost difference in terms of cost per vehicle as variation of number of individual part numbers for rear harnesses compared to the case of using 225 part numbers.

Figure 5-6 shows the total cost difference in terms of cost per vehicle for the four cases. Note that negative values indicate a savings situation while positive values indicate an additional cost as compared to the reference data.

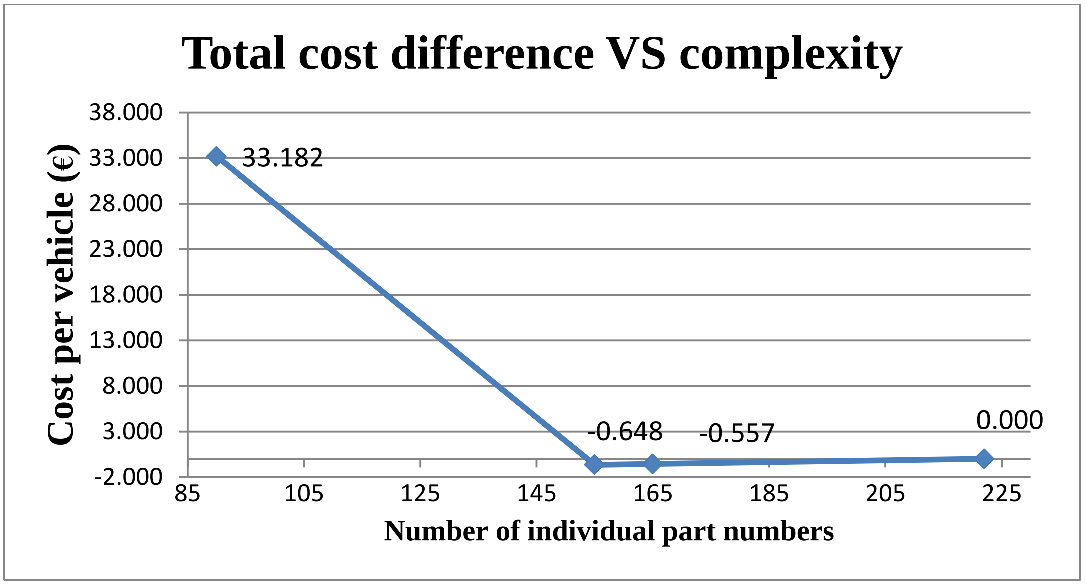

Figure 5-6: Total cost difference per vehicle as variation of number of individual part numbers for rear harnesses compared to the case of using 225 part numbers.

The optimum complexity for the rear harnesses is 155 part numbers and this could save €0.648 per vehicle.

5.4 Case study conclusion

The case study shows that even if only considering half the wiring harness families, the total saving per vehicle could reach nearly €0.9 per vehicle through the implementation of a trade-off model, which is a significant savings.

Although the case study shows benefits when using this trade-off cost model, the case study also has some drawbacks.

1) The analysis is performed according to the real production volume, not the forecasted one, but in reality, the plant makes orders according to the forecasted data. Between the forecasted and real data, errors always exist. If the trade-off analysis is done

on the basis of forecasted data, the actual benefits will change, and this depends on the accuracy of the forecasting.

2) The trade-off between the product cost and manufacturing cost is based on the data for a year which means the part numbers that have low production volumes for this period can be replaced by other part numbers. But if a shorter time duration is considered for the trade-off analysis, for instance, one week or one month, the benefits should be larger. Realistically, for a general part number, the demand is not evenly distributed every week in the year, which means for some weeks the volume is high while in others the required quantity is low or even without demand. For the latter case, that part number could have the opportunity to be substituted according to the weekly trade-off.

Theoretically, the best approach for managing wiring harness complexity is to first maintain the complexity at maximum level at supplier side, then perform a trade-off between product cost and manufacturing cost week by week according to the forecasted data, i.e., select a subset of total part numbers to be managed in the plant, so that both the complexity level and the product cost increase can be kept at a relatively low level.

CHAPTER

6. MATLAB SIMULATION

In this chapter, a MATLAB simulation using the Monte Carlo method is presented. The aim of the MATLAB model is to simulate the best approach in concept for managing wire harness complexity. The first goal is to maintain the complexity at the highest level at the supplier side, then according to the demand forecast, choose the appropriate subsets of wiring harnesses week by week. In other words, for each week, only a portion of the potential part numbers will be selected according to the trade-off between the product cost and manufacturing cost.

Since the demand forecast data is difficult to get, the Monte Carlo method is used to generate random numbers to simulate the forecast process. The Monte Carlo method is a class of computational algorithms that rely on repeated random sampling to compute the results. As the number of repetitions increases, the results will be closer to real conditions.

Of course, since the forecast data is never accurate, a certain amount of differences between the forecast volume and the real demand will also need to be considered in the model.

6.1 Simulation model development

As the wiring harness complexity is generated from both “variants” coming from mandatory features and “additional free options” from the option features, this model will only focus on the “additional free options” to simplify the model.

In the model, two scenarios will be simulated at the same time: the first one is a scenario without using a trade-off approach to reduce complexity, or no substitution of rich cables is performed; the second scenario is the theoretical best approach, that is the trade-off between the product cost and the manufacturing cost will be implemented. A comparison of the results will be made between the two scenarios.

6.1.1 Simulation process flow

The simulation process flow of the first scenario is shown in Figure 6-1. For each week, starting from the total designed part numbers, given the forecast of demand of each part number, assuming a certain level of forecast error, plus the quantity for safety stock, the order quantity can be derived so that the orders will go to the supplier to build the harnesses.

The part numbers that arrive from the supplier will first go into inventory. As in real conditions, the customer might change his idea about the product content so a certain level of customer order changes will be assumed. Thus the production plan can be obtained by combining the ordered quantity and the customer order changes.

Then according to the production plan, the correct quantity of part numbers will be taken out from the warehouse to the assembly line. After this step, the new inventory level needs to be determined. If the remaining inventory level is higher than the required safety stock, no additional action is needed. If the remaining inventory level is larger than zero but smaller than the safety stock required, the quantity difference must be ordered for the next week to ensure the safety stock level. If the inventory level is smaller than zero, which means stock was run out for that part number, the plant has to place an emergency order so that the extra travel can be performed; also the required safety stock quantity needs to be ordered for next week.

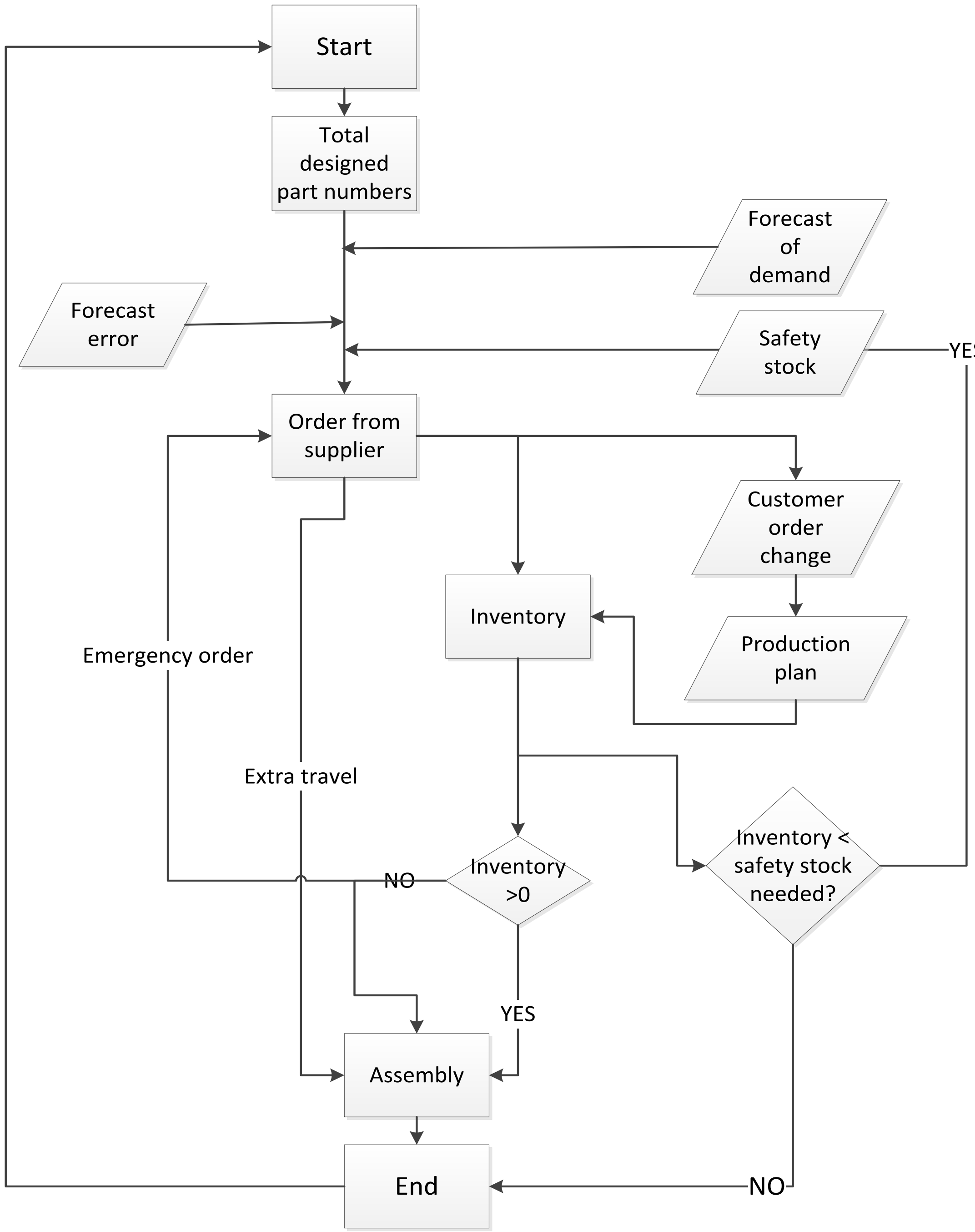

Figure 6-1: Simulation process flow for scenario one, major processes including: making orders according to forecast data, manage warehouse flow according to production plan.

The simulation process flow of the second scenario is shown in Figure 6-2. The majority is similar to the first scenario, the main difference is: before making an order to the supplier, a trade-off between the product cost and manufacturing cost is performed, so that some part numbers with low forecasted volumes will be substituted by richer part numbers. In this way, the plant only needs to manage a subset of the total part numbers, thus reducing its local costs.

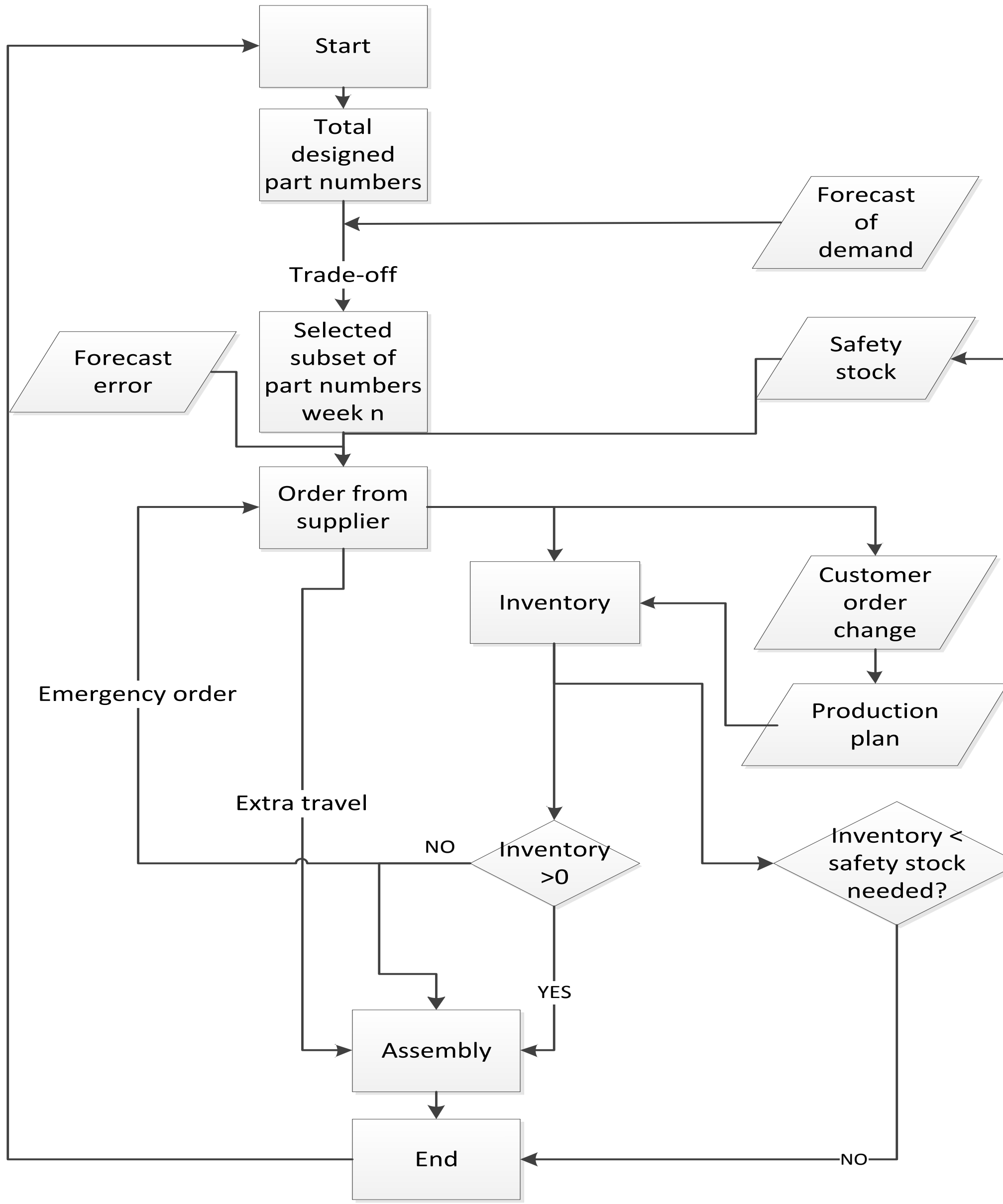

Figure 6-2: Simulation process flow for new scenario. Compared to Figure 6-1, the major difference is performing a trade-off to select a subset of total part numbers before making orders.

6.1.2 Simulation calculation flow for trade-off

Figure 6-3 shows the calculation flow of the simulation model for the trade-off analysis. It can be divided into 16 steps, which are described in detail.

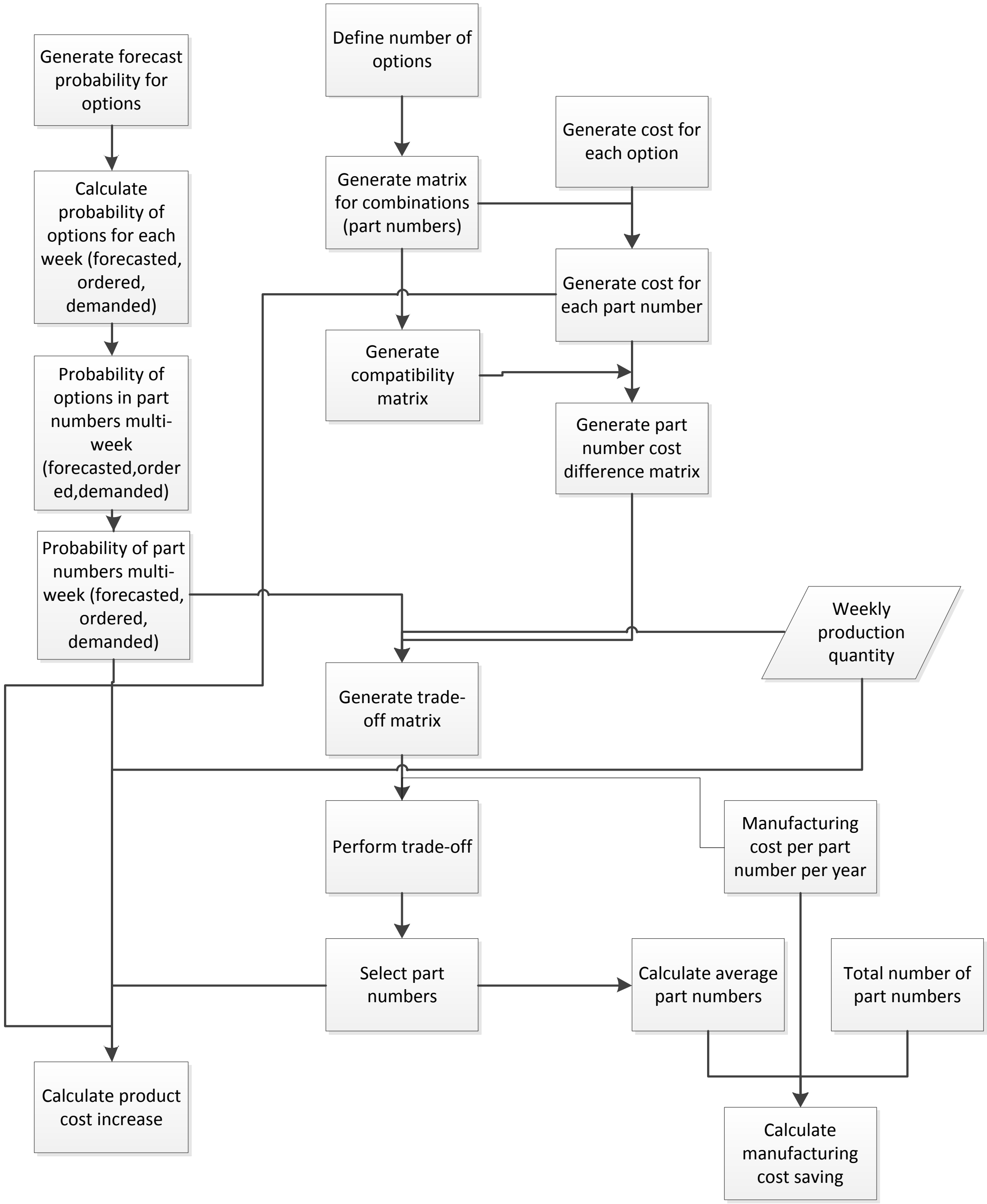

Figure 6-3: Calculation flow for performing trade-off analysis, major information needed including: manufacturing cost per part number per year, cost of part numbers and forecast volume of part numbers.

1) Define number of options. The first step is to choose the number of options for simulation. Here three options are used as an example.

2) Generate the matrix for combinations (part numbers). As the approach is to first maintain maximum complexity level at the supplier side, the designed part numbers should be as many as possible. Since the number of options is three, the total combinations are $2^3=8$, this means the designed number of individual part numbers are eight.

Table 6-1 shows the matrix for combinations (part numbers). It displays the presence of options in each part number; “0” means the option is not present, “1” means the option is present. Each column represents one combination (part number).

Option/Part number	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
1	0	1	0	1	0	1	0	1
2	0	0	1	1	0	0	1	1
3	0	0	0	0	1	1	1	1

Table 6-1: Matrix for combinations showing the presence of options. “0” means the option is not present in the combination, “1” means the option is present in the combination.

3) Generate compatibility matrix

Table 6-2 shows the compatibility matrix for each part number, If “1” is present in the position (I,J), it means part number I can be substituted by part number J.

Part number	1	2	3	4	5	6	7	8
1	1	1	1	1	1	1	1	1
2	0	1	0	1	0	1	0	1
3	0	0	1	1	0	0	1	1
4	0	0	0	1	0	0	0	1
5	0	0	0	0	1	1	1	1
6	0	0	0	0	0	1	0	1
7	0	0	0	0	0	0	1	1
8	0	0	0	0	0	0	0	1

Table 6-2: Compatibility matrix, "0" means the part number on the row cannot be replaced by part number on the column; "1" means the part number on the row can be replaced by part number on the column.

4) Generate cost for the options. The cost of each option is generated by assuming values based on prior experience. For this work, the cost of each option can be assumed as €7.1, €4.2, €1 respectively.

5) Generate part number cost matrix. This matrix is obtained from the matrix of combinations which indicates the presence of each option in each part number and the cost of the option. In addition, a base cost of €20 is assumed for each part number. Table 6-3 shows the matrix of costs for part numbers.

Part number	Cost (€)
1	20.0
2	27.1
3	24.2
4	31.3
5	21.0
6	28.1
7	25.2
8	32.3

Table 6-3: Matrix of part number cost.

6) Generate the matrix of the unit substitution cost. The matrix in Table 6-4 shows the unit substitution cost between part numbers. For instance, position (1,2) means the cost of part number 2 is €7.1 higher than cost of part number 1. The value 0 means that substitutions between the two part numbers are not feasible for compatibility reasons.

Part number	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
1	0.0	7.1	4.2	11.3	1.0	8.1	5.2	12.3
2	0.0	0.0	0.0	4.2	0.0	1.0	0.0	5.2
3	0.0	0.0	0.0	7.1	0.0	0.0	1.0	8.1
4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0
5	0.0	0.0	0.0	0.0	0.0	7.1	4.2	11.3
6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	4.2
7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	7.1
8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table 6-4: Matrix of unit substitution cost. A value other than zero indicates the unit substitution cost for using part number of the column replacing the part number of the row, unit is Euro.

7) Generate forecasting data for the options. The forecasting data of options will be generated by MATLAB randomly which creates three numbers (one for each option) that are between zero and one describing the percentage of customers who would like to have that option. As the marketing condition often changes frequently, in the model, the forecast data is updated every four weeks to simulate the dynamics of marketing. The three groups of random numbers (assuming simulation covers twelve weeks and one group covers four weeks) generated in the example are: 0.3470, 0.3182, 0.4599; 0.4774, 0.8899, 0.0651; 0.1800, 0.8037, 0.5140.

8) Calculate the probability of the options for each week (forecast, ordered, and demand).

Table 6-5 shows the forecasted condition, the probability changes for every four weeks.

Option/Week	1	2	3	4	5	6	7	8	9	10	11	12
1	0.347	0.347	0.347	0.347	0.477	0.477	0.477	0.477	0.180	0.180	0.180	0.180
2	0.318	0.318	0.318	0.318	0.890	0.890	0.890	0.890	0.804	0.804	0.804	0.804
3	0.460	0.460	0.460	0.460	0.065	0.065	0.065	0.065	0.514	0.514	0.514	0.514

Table 6-5: Forecasted probability of each option in different weeks.

Table 6-6 represents the ordered condition, and it is obtained on the basis of the forecast condition by adding a certain level of uncertainty generated randomly within certain limits to represent the forecast error.

Option/Week	1	2	3	4	5	6	7	8	9	10	11	12
1	0.329	0.335	0.356	0.327	0.478	0.503	0.466	0.444	0.182	0.188	0.173	0.178
2	0.288	0.334	0.340	0.342	0.911	0.973	0.901	0.825	0.757	0.735	0.821	0.797
3	0.474	0.483	0.461	0.433	0.068	0.064	0.067	0.068	0.543	0.524	0.491	0.524

Table 6-6: Probability of each option for ordered condition.

Table 6-7 shows the demand condition, and it is obtained on the basis of the ordered condition by adding a certain level of uncertainty generated randomly within certain limits which represents the customer order change.

Option/Week	1	2	3	4	5	6	7	8	9	10	11	12
1	0.324	0.331	0.351	0.332	0.473	0.513	0.467	0.444	0.182	0.191	0.175	0.180
2	0.292	0.329	0.343	0.347	0.894	0.967	0.894	0.813	0.759	0.734	0.831	0.782
3	0.473	0.476	0.468	0.434	0.067	0.063	0.066	0.068	0.542	0.527	0.500	0.518

Table 6-7: Probability of each option for actual condition.

9) Calculate the probability of the options in part numbers for each week (forecast, ordered, and demand).

These three matrices are obtained from the related matrix in step 8) by considering the presence of options in a part number. For instance, supposing the probability of choosing option 1 is 0.3470, in part number 1, this option does not exist, the probability of not choosing option 1 is 1-0.3470=0.6530

10) Calculate the probability of occurrence of each part number for each week (forecast, ordered, demand).

This matrix is obtained through multiplying the three option probabilities for a part number.

Table 6-8 represents the forecast condition, note that the probabilities change every 4 weeks.

Part number/Week	1	2	3	4	5	6	7	8	9	10	11	12
1	0.240	0.240	0.240	0.240	0.054	0.054	0.054	0.054	0.078	0.078	0.078	0.078
2	0.128	0.128	0.128	0.128	0.049	0.049	0.049	0.049	0.017	0.017	0.017	0.017
3	0.112	0.112	0.112	0.112	0.435	0.435	0.435	0.435	0.320	0.320	0.320	0.320
4	0.060	0.060	0.060	0.060	0.397	0.397	0.397	0.397	0.070	0.070	0.070	0.070
5	0.205	0.205	0.205	0.205	0.004	0.004	0.004	0.004	0.083	0.083	0.083	0.083
6	0.109	0.109	0.109	0.109	0.003	0.003	0.003	0.003	0.018	0.018	0.018	0.018
7	0.096	0.096	0.096	0.096	0.030	0.030	0.030	0.030	0.339	0.339	0.339	0.339
8	0.051	0.051	0.051	0.051	0.028	0.028	0.028	0.028	0.074	0.074	0.074	0.074

Table 6-8: Forecasted probabilities of eight part numbers in twelve different weeks.

Table 6-9 shows the ordered condition, note that in this case, the probability is different for each week due to the forecast error.

Part number/Week	1	2	3	4	5	6	7	8	9	10	11	12
1	0.251	0.229	0.229	0.251	0.043	0.012	0.049	0.091	0.091	0.102	0.075	0.079
2	0.123	0.115	0.127	0.122	0.039	0.012	0.043	0.072	0.020	0.024	0.016	0.017
3	0.102	0.115	0.118	0.130	0.443	0.453	0.449	0.428	0.283	0.284	0.345	0.312
4	0.050	0.058	0.065	0.063	0.406	0.459	0.392	0.342	0.063	0.066	0.072	0.067
5	0.227	0.214	0.196	0.192	0.003	0.001	0.004	0.007	0.108	0.113	0.073	0.088
6	0.111	0.108	0.108	0.093	0.003	0.001	0.003	0.005	0.024	0.026	0.015	0.019
7	0.092	0.107	0.101	0.100	0.032	0.031	0.032	0.031	0.336	0.313	0.334	0.343
8	0.045	0.054	0.056	0.049	0.030	0.031	0.028	0.025	0.075	0.072	0.070	0.074

Table 6-9: Ordered probabilities of eight part numbers in twelve different weeks.

Table 6-10 shows demanded condition of probabilities of part numbers. Slightly difference can be found compared to ordered condition due to customer order change.

Part number/Week	1	2	3	4	5	6	7	8	9	10	11	12
1	0.252	0.235	0.227	0.247	0.052	0.015	0.053	0.097	0.090	0.102	0.070	0.086
2	0.121	0.116	0.123	0.123	0.047	0.016	0.046	0.077	0.020	0.024	0.015	0.019
3	0.104	0.115	0.118	0.131	0.439	0.441	0.445	0.421	0.285	0.281	0.343	0.309
4	0.050	0.057	0.064	0.065	0.395	0.465	0.390	0.336	0.063	0.066	0.073	0.068
5	0.226	0.214	0.200	0.189	0.004	0.001	0.004	0.007	0.107	0.114	0.070	0.093
6	0.109	0.106	0.108	0.094	0.003	0.001	0.003	0.006	0.024	0.027	0.015	0.020
7	0.093	0.105	0.104	0.100	0.032	0.030	0.031	0.031	0.336	0.313	0.343	0.332
8	0.045	0.052	0.056	0.050	0.028	0.031	0.028	0.025	0.075	0.074	0.073	0.073

Table 6-10: Actual probabilities of eight part numbers in twelve different weeks.

11) Generate the trade-off matrix. The trade-off matrix is generated by combining the part number probability matrix, the matrix of unit substitution cost and the weekly production quantity.

Figure 6-4 shows the trade-off matrix for week 5 and week 6. The value in position (I,J) means the substitution cost for substituting part number I using part number J; 0 means the substitution cannot be made due to compatibility reasons.

```
matrice_tradeoff_total <8x8x12 double>
val(:,:,5) =

  1.0e+004 *

        0   0.1910   0.1130   0.3040   0.0269   0.2179   0.1399   0.3309
        0        0        0   0.1032        0   0.0246        0   0.1278
        0        0        0   1.5436        0        0   0.2174   1.7610
        0        0        0        0        0        0        0   0.1986
        0        0        0        0        0   0.0133   0.0079   0.0212
        0        0        0        0        0        0        0   0.0072
        0        0        0        0        0        0        0   0.1074
        0        0        0        0        0        0        0        0


val(:,:,6) =

  1.0e+004 *

        0   0.1910   0.1130   0.3040   0.0269   0.2179   0.1399   0.3309
        0        0        0   0.1032        0   0.0246        0   0.1278
        0        0        0   1.5436        0        0   0.2174   1.7610
        0        0        0        0        0        0        0   0.1986
        0        0        0        0        0   0.0133   0.0079   0.0212
        0        0        0        0        0        0        0   0.0072
        0        0        0        0        0        0        0   0.1074
        0        0        0        0        0        0        0        0
```

Figure 6-4: Trade-off matrix for week five and week six, the values other than zero indicate the total substitution cost in a year.

12) Performing the trade-off analysis. To better explain the process, let us use another name "a" for the trade-off matrix and "b" for the part number cost matrix.

Suppose the manufacturing cost is €1500 per year per part number, and the production week period is twelve, so the initial upper bound for the substitution is 1500/12= €125.

If in matrix "a" the element (I,J) is within the interval between zero and an upper bound, it means that in the matrix "b", that is the cost of each part number, the row I can be substituted by row J.

As the case shown in the Figure 6-4, there are two substitutions that can be made for week five because the cost of substitution is €79 in position (5,7), and €72 in position

(6,8), which are both smaller than the manufacturing cost per part number per week (€125).

All the qualified elements in matrix “a” can be seen in the matrix “D”. Figure 6-5 shows a portion of “D” from week five to week eight. For instance, in week five, part number 5 can be substituted by part number 7, and part number 6 can be substituted by part number 8.

```
D <2x19x12 double>
val(:,:,5) =

   5   6   0   0   0   0   0   0   0   0   0
   7   8   0   0   0   0   0   0   0   0   0


val(:,:,6) =

   5   5   6   0   0   0   0   0   0   0   0
   6   7   8   0   0   0   0   0   0   0   0


val(:,:,7) =

   5   5   6   0   0   0   0   0   0   0   0
   6   7   8   0   0   0   0   0   0   0   0


val(:,:,8) =

   5   5   6   0   0   0   0   0   0   0   0
   6   7   8   0   0   0   0   0   0   0   0
```

Figure 6-5: Qualified elements for substitution for week five to week eight, the value of first row represents the part number need to be substituted, the value of second row represents the part number used for substitution.

To simplify the model, several assumptions are made during the calculations.

a) Among all the qualified elements in matrix a, it may happen that one part number can be replaced by more than one other part number, for instance supposing, (1,3), (1,5), (1,7) are all qualified. In this case, only one can be used for substitution, Therefore, compare the values of a(1,3), a(1,5), and a(1,7), and use the smallest resulting condition for the substitution.

b) It may happen that one rich part number can be substituted for another, but later it also needs to be replaced by another part number which is richer; for example, elements (1,5) and (5,7) are both qualified in the same week. This means part number 5 will substitute for part number 1 but part number 5 can also be replaced by part number 7. Without any correction being introduced, two substitutions are made, but this results in only reducing 1 part number (from 1,5,7 to 5,7). The sum of a(1,5) and a(5,7) may be higher than the upper bound. This situation should be avoided as the total substitution cost is already more than the manufacturing cost.

To prevent this, the values in matrix “a” are compared and only the smaller one can be the substitute. For example, if a(1,5)<a(5,7), part number 1 will be substituted by part number 5, if a(5,7) is smaller, part number 5 will be substituted by part number 7. Of course there exists another condition, which is the value of a(1,5)+a(5,7) is within the upper bound; this means both cases can be replaced, but here this condition is not considered because it increases the product cost without leading to further savings. That is to say: the product cost will be increased twice but with only one resulting part number reduction.

c) Consider the upper bound for substitution. Since for each substitution, the increase of the product cost is less than the upper limit for most cases, some bonuses can be obtained and could be used in the following week, so that more part numbers could be substituted.

However, here arises another problem: suppose the upper limit of first week is €125, and two part numbers had been reduced and the cost of substitution is €95 and €85, which means the bonus is €30 and €40 respectively. So the total bonus would be €70 for next week. But if adding this €70 directly to the previous upper limit that is €125, the new upper bound would be €195 for each substitution, but this will lead to unexpected extra costs in some cases.

For instance, for the next week, the upper bound becomes € 195, and the simulation provides two groups which are qualified, and assuming the increase of product cost is €190 for both cases, the total cost is €190+€190, which is €380. But the saving obtained is only €125+€125+€70= €320. This means in this case, by substitution, the company would have €380-€320= €60 losses. This is not acceptable, and it will decrease the upper bound for the third week.

To resolve this issue, the total bonus obtained from the previous week will be distributed according to the number of reduced part numbers. However without knowing the upper bound, the number of individual part numbers used cannot be calculated, and in this case, the number from the previous week is used.

Using the same example, the total bonus €70 will be divided by 2 which results €35. So the new upper bound for each substitution will be €125+€35= €160.

There may be a mathematical problem as no substitution can be found in some cases, so the part number reduction is 0, which leads to the formula in MATLAB becoming invalid. At last, the total bonus will be divided by the number of individual part numbers reduction +0.01 then adding the origin upper bound from previous week to obtain a new upper bound for trade-off.

13) Select the part number. After performing the trade-off analysis according to the part number product cost and the manufacturing cost, the final substitution part numbers can be defined. Figure 6-6 shows the final substitution from week 5 to week 8. For instance, in week 5, part number 5 will be substituted with part number 7 while part number 6 will be substituted by part number 8.

```
IJBTOT <2x19x12 double>

val(:,:,5) =

   5   6   0   0   0   0   0   0   0   0   0   0   0
   7   8   0   0   0   0   0   0   0   0   0   0   0


val(:,:,6) =

   5   6   0   0   0   0   0   0   0   0   0   0   0
   7   8   0   0   0   0   0   0   0   0   0   0   0


val(:,:,7) =

   5   6   0   0   0   0   0   0   0   0   0   0   0
   7   8   0   0   0   0   0   0   0   0   0   0   0


val(:,:,8) =

   5   6   0   0   0   0   0   0   0   0   0   0   0
   7   8   0   0   0   0   0   0   0   0   0   0   0
```

Figure 6-6: Final substitution decision from week five to week eight, the value of first row represents the part number need to be substituted, the value of second row represents the part number used for substitution.

The matrix of the part number cost before and after the substitution is shown in Table 6-11 and Table 6-12. For instance, in week 5, as part number 5 has been replaced by part number 7, at position (5,5) in Table 6-12 the cost is €25.2 which is the cost of part number 7 instead of €21 which is cost of part number 5 shown in Table 6-11.

Week/Part number	1	2	3	4	5	6	7	8
1	20.0	27.1	24.2	31.3	21.0	28.1	25.2	32.3
2	20.0	27.1	24.2	31.3	21.0	28.1	25.2	32.3
3	20.0	27.1	24.2	31.3	21.0	28.1	25.2	32.3
4	20.0	27.1	24.2	31.3	21.0	28.1	25.2	32.3
5	20.0	27.1	24.2	31.3	21.0	28.1	25.2	32.3
6	20.0	27.1	24.2	31.3	21.0	28.1	25.2	32.3
7	20.0	27.1	24.2	31.3	21.0	28.1	25.2	32.3
8	20.0	27.1	24.2	31.3	21.0	28.1	25.2	32.3
9	20.0	27.1	24.2	31.3	21.0	28.1	25.2	32.3
10	20.0	27.1	24.2	31.3	21.0	28.1	25.2	32.3
11	20.0	27.1	24.2	31.3	21.0	28.1	25.2	32.3
12	20.0	27.1	24.2	31.3	21.0	28.1	25.2	32.3

Table 6-11: Cost of each part number before substitution in twelve weeks, unit is Euro.

Week/Part number	1	2	3	4	5	6	7	8
1	20.0	27.1	24.2	31.3	21.0	28.1	25.2	32.3
2	20.0	27.1	24.2	31.3	21.0	28.1	25.2	32.3
3	20.0	27.1	24.2	31.3	21.0	28.1	25.2	32.3
4	20.0	27.1	24.2	31.3	21.0	28.1	25.2	32.3
5	20.0	27.1	24.2	31.3	25.2	32.3	25.2	32.3
6	20.0	27.1	24.2	31.3	25.2	32.3	25.2	32.3
7	20.0	27.1	24.2	31.3	25.2	32.3	25.2	32.3
8	20.0	27.1	24.2	31.3	25.2	32.3	25.2	32.3
9	20.0	28.1	24.2	31.3	21.0	28.1	25.2	32.3
10	20.0	28.1	24.2	31.3	21.0	28.1	25.2	32.3
11	20.0	28.1	24.2	31.3	21.0	28.1	25.2	32.3
12	20.0	28.1	24.2	31.3	21.0	28.1	25.2	32.3

Table 6-12: Cost of part number (product version) after substitution in twelve weeks, unit is Euro.

14) Calculate average number of individual part numbers. The average number of individual part numbers used is calculated through evaluating the average number of individual part numbers used in each week. Table 6-13 shows the number of individual

part numbers used after substitution for each week, thus according to this example, the average number of individual part numbers is 7.

Week	**Number of individual part numbers**
1	8
2	8
3	8
4	8
5	6
6	6
7	6
8	6
9	7
10	7
11	7
12	7

Table 6-13: Number of individual part numbers used after substitution for each week.

15) Calculate the yearly manufacturing cost saving. The manufacturing cost saving is calculated given the total part numbers, and the average part numbers used after substitution and the manufacturing cost per year per part number. In this example, the manufacturing saving is €1500 a year because the average saving is 1 part number.

16) Calculate product cost increase (total substitution cost). The product cost increase is calculated as the difference between the total product cost after substitution and the total product cost before substitution. Figure 6-7 shows the product cost increase based on the forecast data. This means when using substitution parts, the total product cost increase is €945 without considering any forecast error and the change of customer orders. If consider the forecasting error and the customer order change, which means using real production data when performing the calculation, the total product cost

increase due to substitution is €998, as shown in Figure 6-8. In this case, due to the forecast error and the customer order change, the benefit from using a substitution approach is reduced.

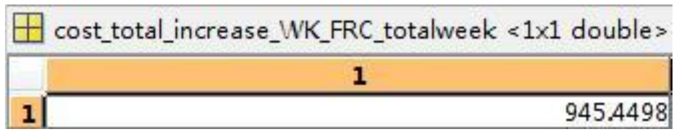

Figure 6-7: Product cost increasing according to forecasted production volume.

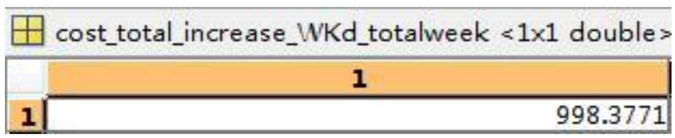

Figure 6-8: Product cost increasing according to actual production volume.

<u>6.1.3 Simulation calculation for warehouse flow in scenario one.</u>

As the obsolescence cost and the extra travel cost are two major losses related to wiring harness management, in the simulation model, these two costs will be calculated out of the manufacturing cost to see how much cost reduction can be achieved through the strategy of using substitutions.

Figure 6-9 represents the warehouse calculation flow of first scenario.

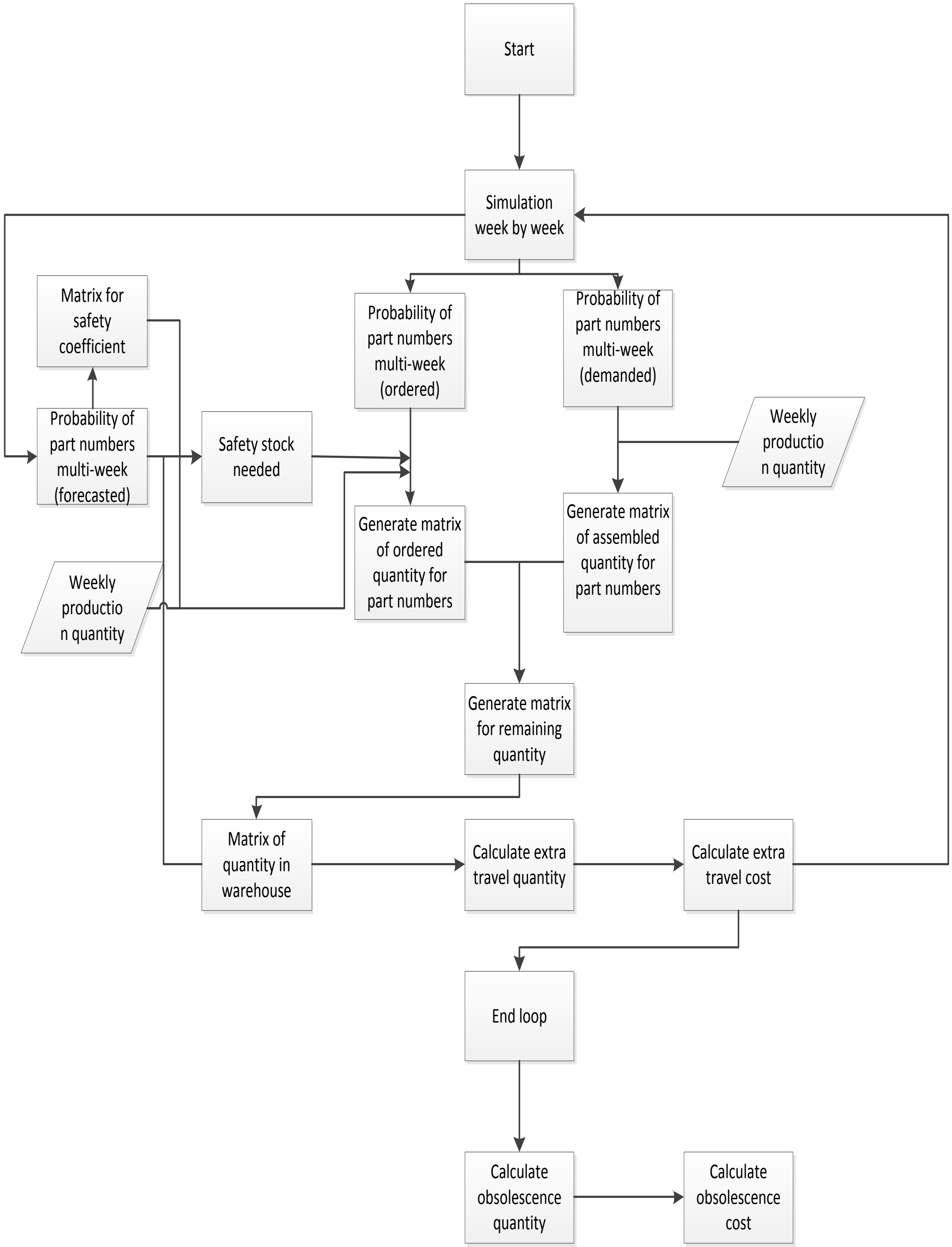

Figure 6-9: Calculation of warehouse flow of scenario one, major steps including: calculate ordered, assembled, remaining and warehouse quantity.

The calculation can be processed week by week as the following steps:

1) Calculate safety stock needed. The quantity of safety stock needed is calculated by the difference of the required safety stock quantity and the remaining quantity in the warehouse left from the previous week. If the difference is equal or less than 0, no additional safety stock needs to be ordered. The required safety stock quantity is calculated in this way, if the forecast volume of a part number is less than a percentage of total volume (2% for example), the required safety stock is set to 0 as in this case, the risk for a stock out condition is relatively low and by doing this, the obsolescence quantity can be reduced. If not, a safety stock coefficient will be assigned (a percentage), and by combining the safety coefficient with the forecast probability and a weekly production quantity, the required safety stock quantity can be determined.

Table 6-14 shows the matrix of safety coefficients for each part number. The safety coefficient in this case is 2% or 0 if forecasted volume is low.

Part number/Week	1	2	3	4	5	6	7	8	9	10	11	12
1	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
2	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
3	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
4	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
5	0.02	0.02	0.02	0.02	0.00	0.00	0.00	0.00	0.02	0.02	0.02	0.02
6	0.02	0.02	0.02	0.02	0.00	0.00	0.00	0.00	0.02	0.02	0.02	0.02
7	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
8	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02

Table 6-14: Matrix of safety coefficient for each part number in twelve weeks.

Table 6-15 shows the quantity of safety stock needed for each part number in each week.

Part number/Week	1	2	3	4	5	6	7	8	9	10	11	12
1	4	6	24	0	0	0	5	5	8	0	0	0
2	0	0	0	0	0	0	5	5	2	0	1	0
3	0	3	2	1	37	0	0	0	0	0	0	0
4	0	0	0	0	18	0	0	0	0	0	0	0
5	0	0	0	18	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0	0	0	0	0
7	0	0	0	1	0	0	0	0	14	0	0	34
8	0	0	0	0	0	0	0	0	0	0	0	0

Table 6-15: Matrix of safety stock needed for each part number in twelve weeks.

2) Generate a matrix for the ordered quantity. This matrix shows the quantity ordered for each part number, and it is obtained by adding the safety stock needed to the order quantity for each wire harness part number. Figure 6-10 shows the ordered quantity for each part number in each week. Note that due to a forecast update of every 4 weeks, the quantity of an individual part number has a large fluctuation at this interval change.

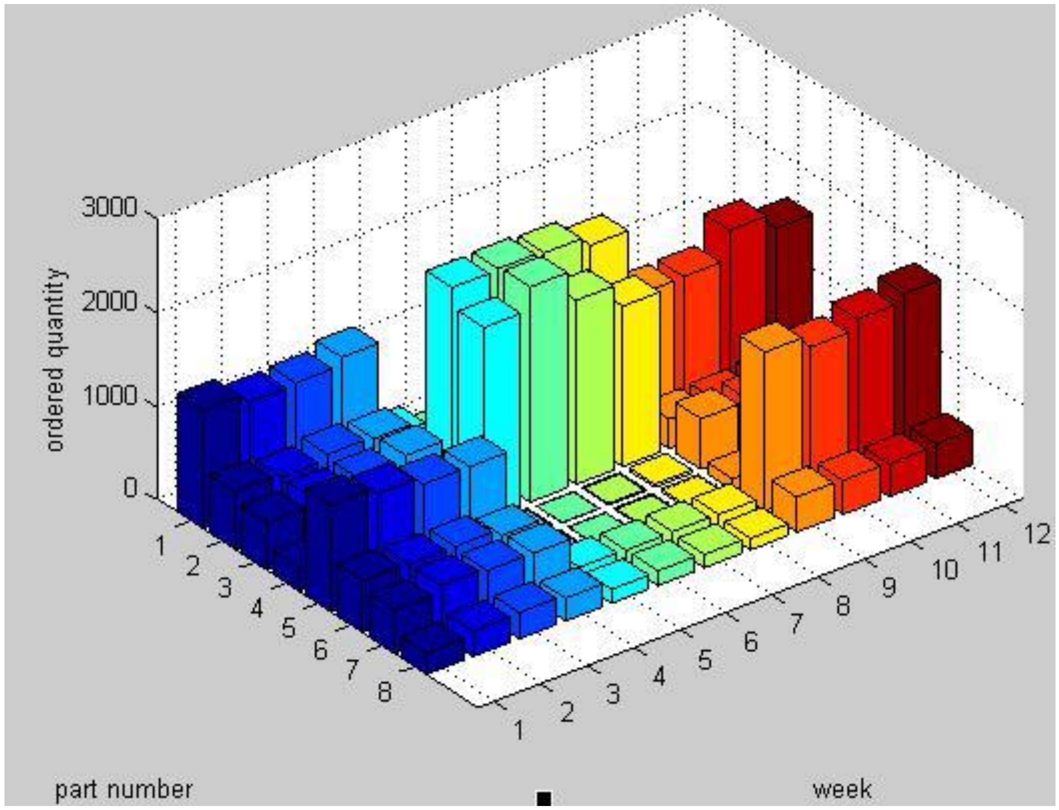

Figure 6-10: Bar graph of ordered quantity for eight part numbers in twelve weeks.

3) Generate matrix for the assembled quantity. The assembled quantity is the production plan for each part number, and it is calculated by multiplying the demand part number probability with the weekly production quantity. Figure 6-11 shows the assembled quantity for each part number in each week.

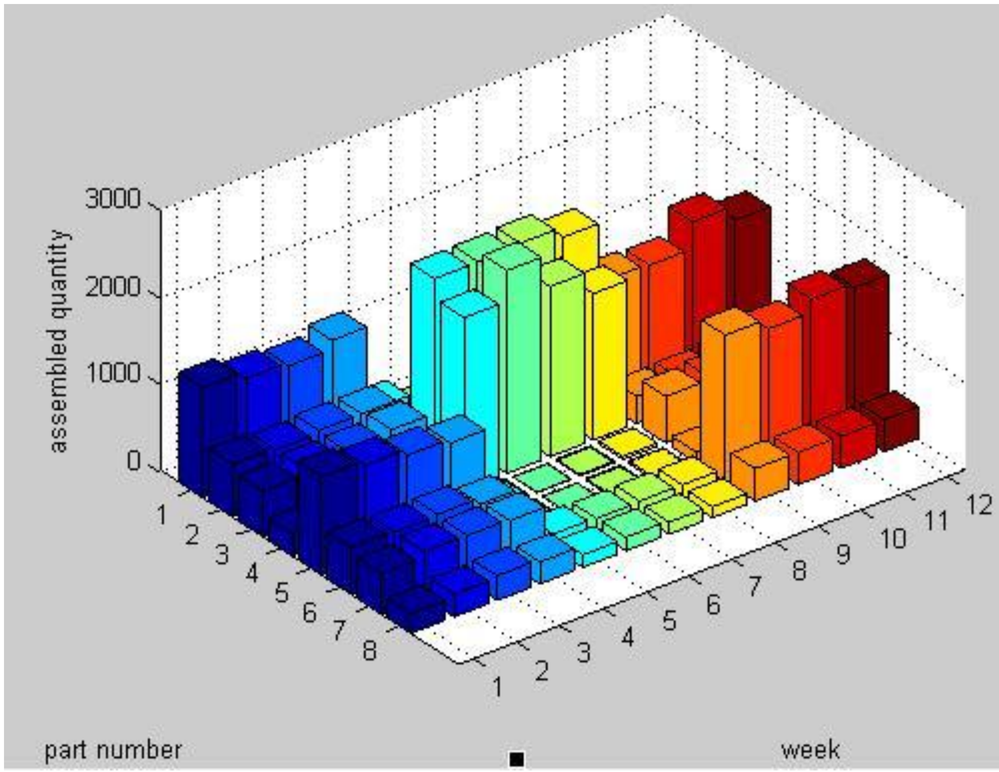

Figure 6-11: Bar graph of assembled quantity for eight part numbers in twelve weeks.

4) Generate matrix for the remaining quantity. The remaining quantity is the difference between the ordered quantity and the assembled quantity for each part number. A positive value indicates that what was ordered is more than what was assembled; therefore, the remaining quantity of that part number will stay in inventory. A negative value indicates that what is ordered is less than what is needed on the assembly line, so that inventory is needed. In reality, the warehouse flow should follow the FIFO principal, and in terms of the part number quantity, there is no difference considering the calculation results. Figure 6-12 shows the remaining quantity for each part number.

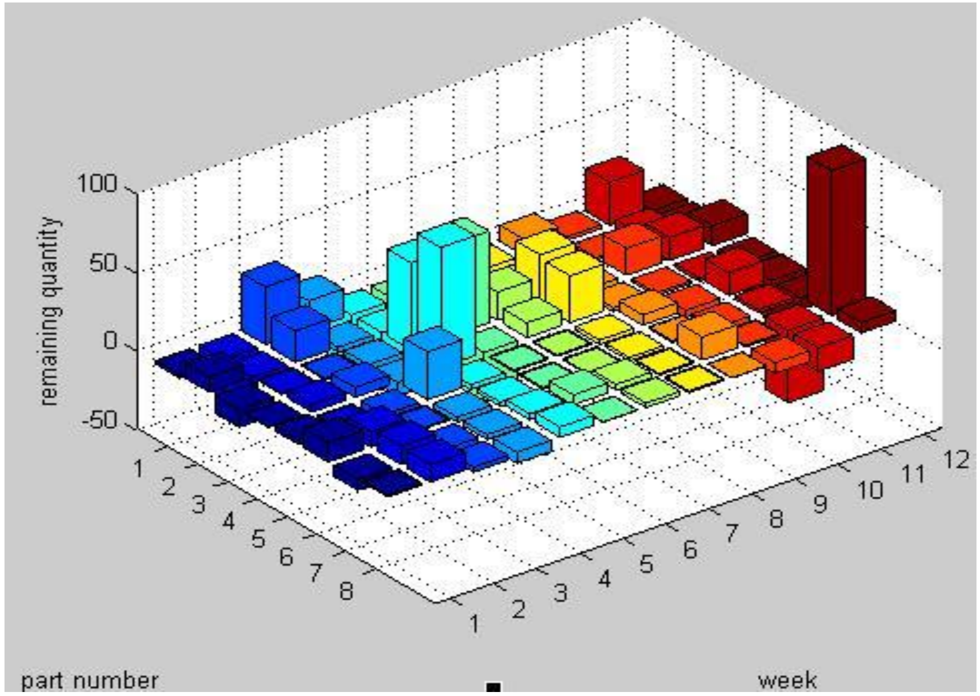

Figure 6-12: Bar graph of remaining quantity for eight part numbers in twelve weeks.

5) Calculate the new inventory quantity. Assume the initial stock level is 20 for each part number. The new inventory quantity for each part number is calculated by adding the remaining quantity to the inventory quantity from previous week. The negative values will be corrected to 0. Figure 6-13 displays the inventory level for each part number.

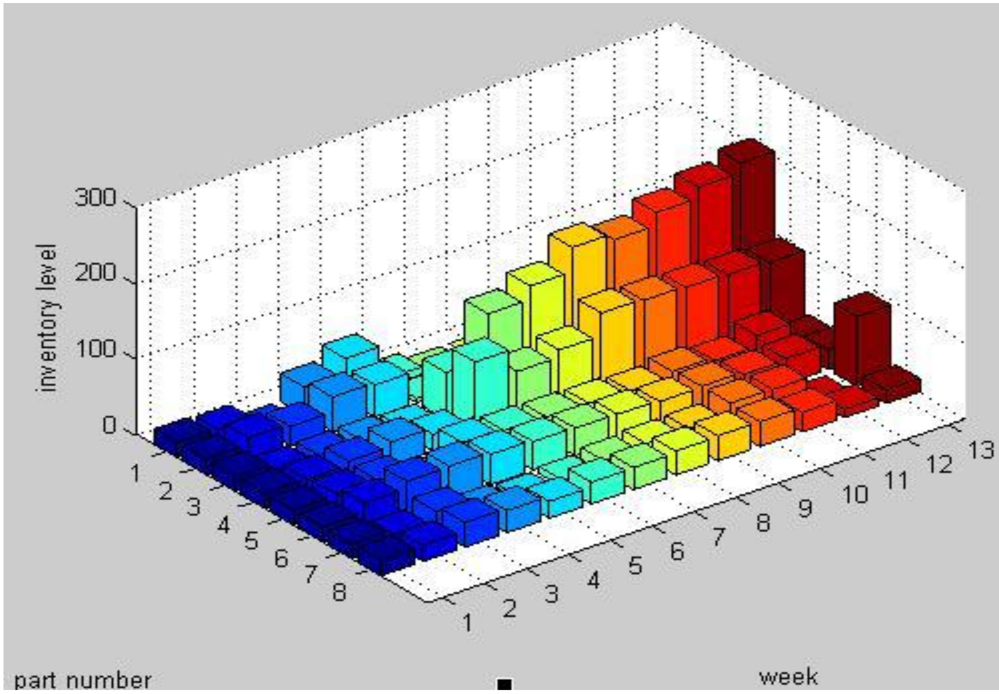

Figure 6-13: Bar graph of inventory quantity for eight part number in twelve weeks.

6) Calculate the extra travel quantity and cost. The extra travel quantity is calculated through summing all the negative values of the warehouse quantity before being corrected to 0. The extra travel cost is obtained by multiplying the extra travel quantity by the unit cost for the extra travel. Table 6-16 shows the matrix of the extra travel quantity which indicates also the part number and related week of extra travel. Figure 6-14 shows the results of the total extra travel cost, by assuming the unit extra travel cost is €500. The total cost is €53672 for this example.

Part number/Week	1	2	3	4	5	6	7	8	9	10	11	12	13
1	0	0	-6	0	0	0	-4	-11	-28	0	0	0	0
2	0	0	0	0	0	0	-12	-10	-21	0	0	0	-2
3	0	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0	0	0	0	0	-12	0
8	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 6-16: Matrix of weekly extra travel quantity of each part number.

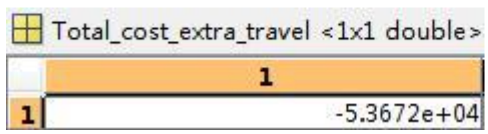

Figure 6-14: Example of total cost of extra travel.

7) Calculate the obsolescence quantity and cost. The obsolescence quantity is calculated as the inventory quantity at the last week of the simulation and assuming that at the end of a year, a new model will be launched and all the inventory quantity would become obsolete. The cost of obsolescence is calculated according to each part number, that is multiplying the cost of that part number with its quantity and summing them together. Figure 6-15 shows the total obsolescence quantity at the last week. Figure 6-16 displays the total obsolescence cost.

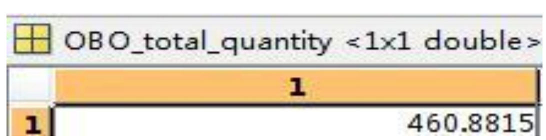

Figure 6-15: Example of total obsolescence quantity.

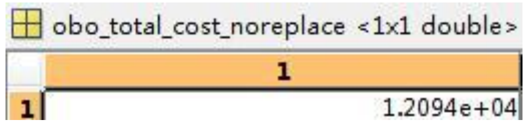

Figure 6-16: Example of total obsolescence cost.

<u>6.1.4 Simulation calculation for the warehouse flow in scenario two</u>

The calculation flow for the substitution case being assessed is similar to the first scenario. The differences are reported as follows:

1) A unique matrix for the safety coefficient is required: for the second scenario, another safety coefficient, which is designed specifically for the richest part number is introduced. The idea is to prevent extra travel which can be quite expensive. The richest part number can be used in place of the other valid part numbers in case of their stock out. To achieve this target, the richest part number requires a higher safety coefficient and the value will not been set to 0 according to its forecasted production volume. Table 6-17 shows the matrix of safety coefficients for the second scenario. Note that the safety coefficient for the richest part number is set to 10%.

Table 6-18 shows the matrix of safety stock needed, and compared to the data in Table 6-15, it can be seen that the safety stock needed for the richest part number for the substitution case is significantly higher.

Part number/Week	1	2	3	4	5	6	7	8	9	10	11	12
1	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
2	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
3	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
4	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
5	0.02	0.02	0.02	0.02	0.00	0.00	0.00	0.00	0.02	0.02	0.02	0.02
6	0.02	0.02	0.02	0.02	0.00	0.00	0.00	0.00	0.02	0.02	0.02	0.02
7	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
8	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10

Table 6-17: Matrix of safety coefficient for each part number in different weeks.

Part number/Week	1	2	3	4	5	6	7	8	9	10	11	12
1	4	6	24	0	0	0	5	5	8	0	0	0
2	0	0	0	0	0	5	5	5	2	2	2	2
3	0	3	2	1	37	0	0	0	0	0	0	0
4	0	0	0	0	18	0	0	0	0	0	0	0
5	0	0	0	18	0	0	0	0	8	0	0	0
6	0	0	0	0	0	0	0	0	2	0	0	0
7	0	0	0	1	0	0	0	0	18	0	0	34
8	5	0	0	0	0	0	0	0	1	0	7	27

Table 6-18: Matrix of safety stock needed for each part number in different weeks.

2) To reduce the obsolescence quantity in the end, substitution rules need to be established. Suppose according to the trade-off analysis, part number A will be substituted by part number B. If the quantity of part number A in the warehouse is larger than the prepared order quantity, no order will be made for the quantity of A in this case. However, if the quantity of part number A in warehouse is not 0 but is smaller than the prepared order quantity, the ordered quantity for part number B that is used for replacing part number A will be the difference between the prepared order quantity and warehouse quantity for part number A.

The reason for doing that is as follows: as the part number that undergoes a substitution usually has a low production volume, even if a smaller order or no order is made, the inventory quantity of that part number together with the stock of the richer part numbers could prevent extra travel. Therefore, the stock level has been reduced as well as the obsolescence cost.

Figure 6-17 shows the ordered quantity for each part number as a bar graph. Figure 6-18 displays the total obsolescence quantity at the last week. Recall in first scenario, the total obsolescence quantity is 461 units, while for this second scenario it is reduced to 352 units. Figure 6-19 shows the total cost of obsolescence. For this case study, the total cost is determined to be €9281.7 while for first scenario, this value is determined to be €12094. Figure 6-20 shows the process flow as mentioned above.

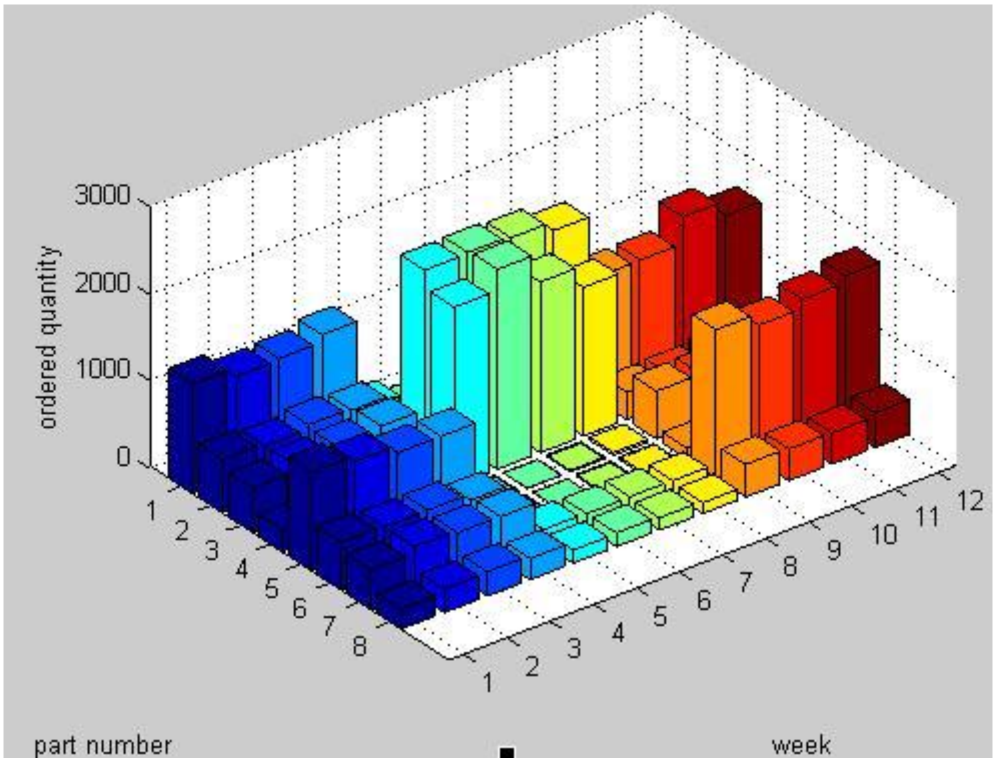

Figure 6-17: Bar graph of ordered quantity for eight part numbers in twelve weeks for second scenario.

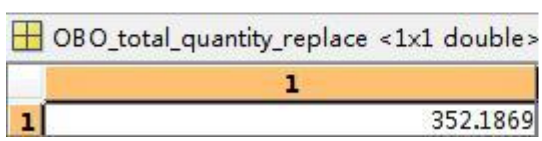

Figure 6-18: Example of total obsolescence quantity for second scenario.

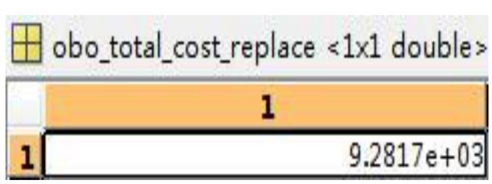

Figure 6-19: Example of total obsolescence cost for second scenario.

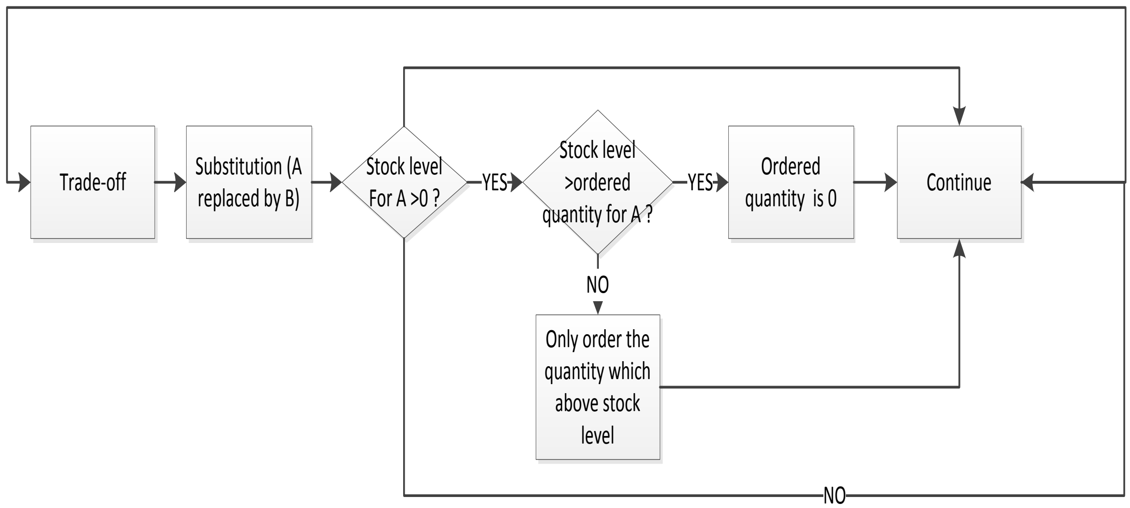

Figure 6-20: Process flow for reducing order quantity of the part number been substituted in order to reduce obsolescence.

3) Another method used for reducing the inventory level focuses on using the inventory quantity of the part number that been substituted when what is ordered is less than what is needed to be assembled.

The trade-off analysis indicates that part number A can be substituted by part number B. The quantity of the required number of part B components is incremented by the required quantity of part A wire harnesses. To simplify the calculation, the forecast, ordered and assembled quantities are still calculated considering the case without any substitution. The effects of a substitution strategy are considered when calculating the remaining quantity and inventory levels for all the part numbers being evaluated.

If the original remaining quantity for part number A is negative, (need more part number A wire harnesses), the new remaining quantity for part number A and B should calculated by the following rules:

a) If the warehouse quantity for part number A is less than absolute value of the remaining quantity of A, the new remaining quantity for A will be equal to the negative value of warehouse quantity of A. All the inventory of part number A will be used; therefore, the new warehouse quantity of part number A will become zero. The new remaining quantity of part number B will be calculated as follows: the original remaining quantity of part number B plus the warehouse quantity of A plus the original remaining quantity of A. The results of latter two items will be a negative value, This quantity will have to be filled with part number B on the basis of the remaining quantity for part number B;

b) If the warehouse quantity of part number A is larger than remaining quantity, the remaining quantity of both part number A and part number B will not change, which means using inventory level of part number A to fully fill the gap resulted by the difference between the ordered and assembled quantity.

On the contrary, if remaining quantity of part number A is positive, which means what assembled is less than what ordered. So the new remaining quantity of part number A will be 0 while the new remaining quantity of part number B will be the sum of origin remaining quantity of part number A and part number B since the part number A is substituted by part number B, the part number being ordered is B, so what left over is part number B.

Figure 6-21 shows the graphic representation of remaining quantity for each part number. Figure 6-22 shows the graphic representation of inventory level of each part number week by week.

Figure 6-23 shows the process flow for calculating remaining quantity in case of substitution as state above.

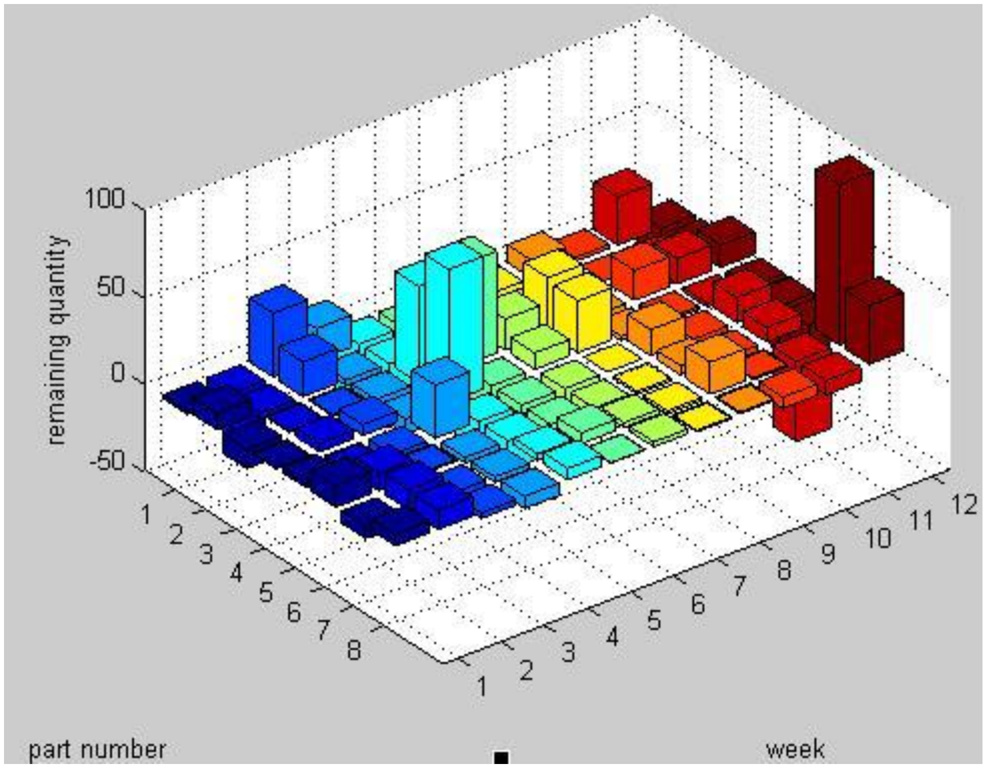

Figure 6-21: Bar graph of remaining quantity for eight part numbers in twelve weeks for second scenario.

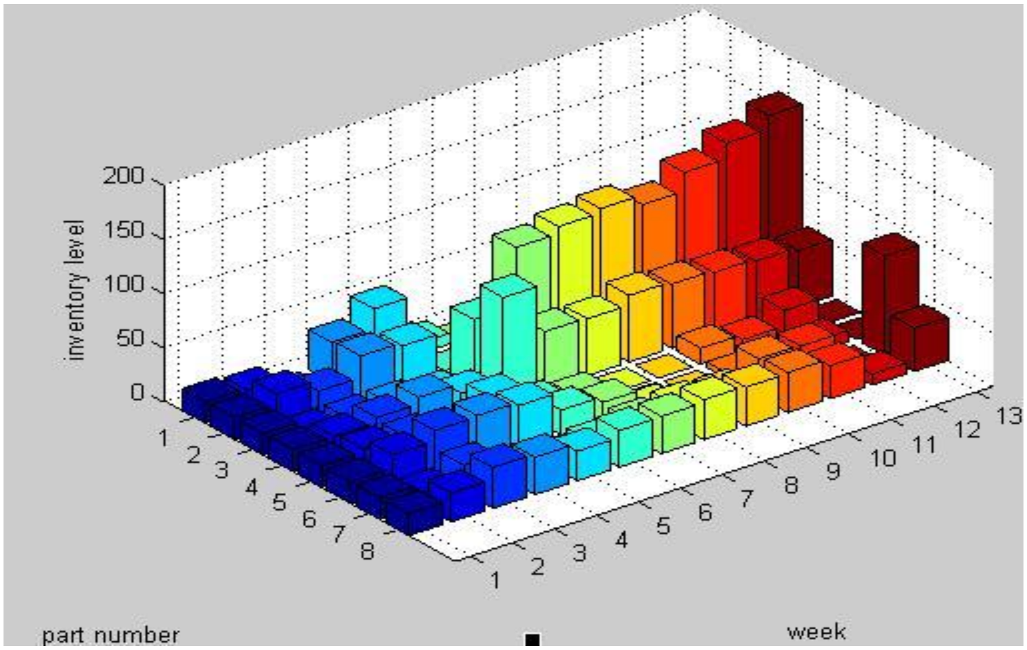

Figure 6-22: Bar graph of inventory level for eight part numbers in twelve weeks for second scenario.

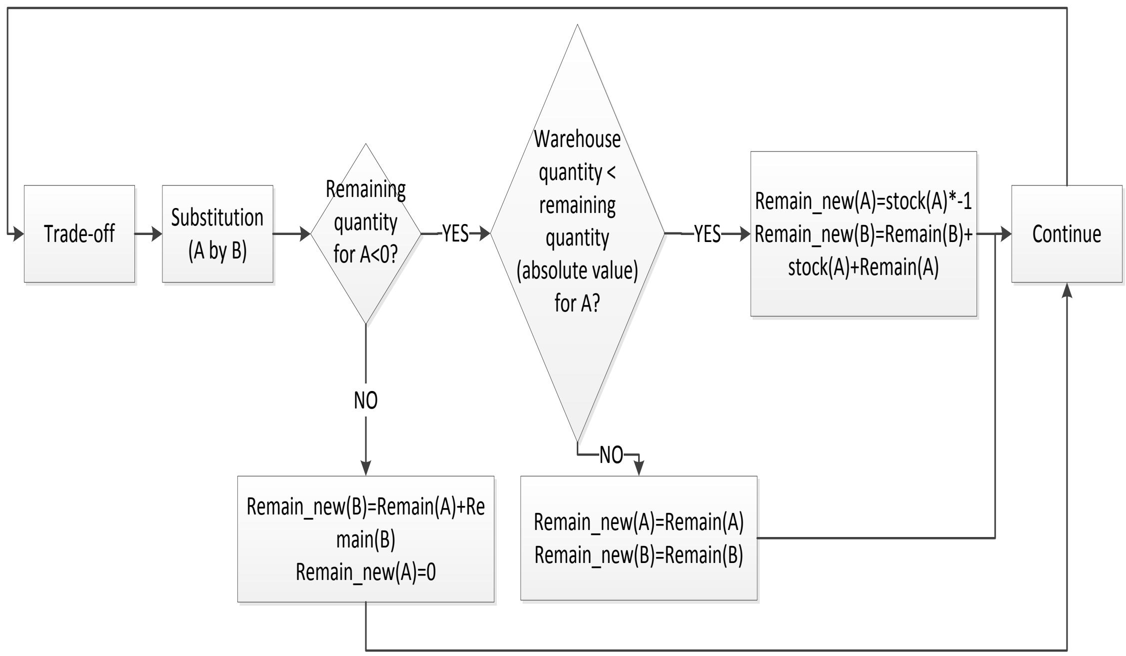

Figure 6-23: Process flow for calculating remaining quantity for part numbers participate substitution for second scenario.

4) Reducing extra travel with richer part numbers. To minimize the quantity of extra travel, once a part number is found to be stocked out, the model will search the possible substitution part numbers according to compatibility matrix. Suppose that part number C is not in stock and part number D can be used for substitution, if the warehouse quantity for part number D is larger than required quantity for part number C, the appropriate quantity of D will be transported to the assembly line instead of part number C. If the quantity of D in the warehouse is not enough to cover all the stock C requirements, to simplify the model, the model will give up part number D and find next possible part number for substitution which have enough quantity in the stock. If even the richest part number cannot cover all the stock out of part number C which is the worst case, in this condition, considers the available stock of richest part number, although not

enough, substitution will be implemented so that the stock level of richest part number will be 0.

Figure 6-24 shows the process flow as written above. Table 6-19 displays the extra travel quantity for each part number, note that in this case there is no extra travel needed.

Obviously, by using richer part number to reduce extra travel must result in product cost increase. This cost should be considered when calculating the final cost. Figure 6-25 shows the related product cost increase due to reducing extra travel quantity.

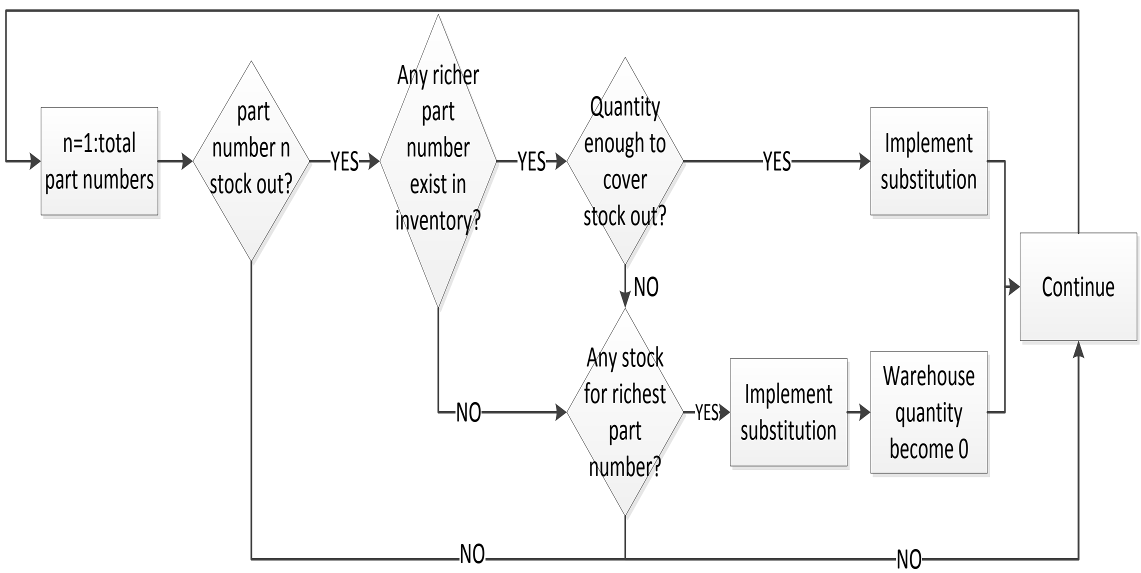

Figure 6-24: Process flow for reducing extra travel quantity using richer part numbers.

Part number/Week	1	2	3	4	5	6	7	8	9	10	11	12	13
1	0	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 6-19: Matrix of extra travel quantity for second scenario.

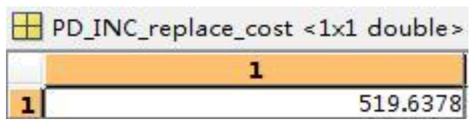

Figure 6-25: Product cost increase due to using richer part number in order to reduce extra travel.

5) Calculate the total saving by using second scenario. The total saving is calculated as the following formula:

$$\begin{aligned} TOTAL_{SAVING\ BY\ REPLACE} &= OBO_{saving} - Delta_{cost\ extra\ travel} + Manufacturing_{saving} \\ &- Product_{costWKD} - Product_{costREX} \end{aligned} \tag{6.1}$$

Where:

"$TOTAL_{SAVING\ BY\ REPLACE}$" is the total saving by managing wiring harness with part number substitution approach.

"OBO_{saving}" is the cost saving from obsolescence reduction by using second scenario.

"$Delta_{cost\ extra\ travel}$" is the cost difference due to extra travel. A negative value means saving by using the second scenario.

"$Manufacturing_{saving}$" is the saving due to manufacturing cost reduction as less part numbers are used in the plant.

"$Product_{costWKD}$" is the product cost increase due to substitution.

"$Product_{costREX}$" is the product cost increase resulted from using richer cable to preventing extra travel.

Figure 6-26 shows the total saving from obsolescence reduction that is €2812.5 in the example.

obo_total_cost_saving <1x1 double>

	1
1	2.8125e+03

Figure 6-26: Total saving from reducing obsolescence compared to first scenario.

Figure 6-27 shows the saving from extra travel reduction, which is €53672 in the example.

delta_cost_extra_travel_replace <1x1 double>

	1
1	-5.3672e+04

Figure 6-27: Total saving from extra travel reduction compared to first scenario.

As the "$Manufacturing_{saving}$" is €1500, "$Product_{costWKD}$" is €998, "$Product_{costREX}$" is €520, the total saving by using second scenario is €56467 a year as shown in Figure 6-28.

TOTAL_saving_by_replace <1x1 double>

	1
1	5.6467e+04

Figure 6-28: Total cost saving obtained by second scenario compared to first one.

6.2 Simulation results and discussions

6.2.1 Simulation inputs

The input parameters of the simulation model are set as follows:

1) Number of options. The number of options considered in the simulation cannot be too large due to several reasons. First during the design phase, usually the total additional free options will be split into several parts, not considered together by the designers. This limits the number of options in each small group. Secondly, too many options will lead to problems when doing the calculations in MATLAB due to the limitation of the software. MATLAB can only access limited amount of memory space in a computer. Therefore, the number of options used in the simulation is 5, which means there are 32 part numbers in the simulation.

2) Total production weeks in a year. The total production week value is set to 46 weeks. This model considers that there are some weeks in which there is no production.

3) Safety coefficient. The safety coefficient will determine the obsolescence quantity and extra travel quantity. There are conflicting issues that need to be discussed. Increases in the safety coefficient will increase the obsolescence quantity but reduce extra travel costs. As it is required that the total number of extra travel situations for new scenarios should be less than 30 times in a year, the safety coefficient is set to 3% (excluding richest part number) while for richest part number this value is 7%.

4) The threshold of the forecast production percentage for setting safety coefficient to 0. This value is set to 1% which means if the forecasted production volume of a part number is less than 1% of total weekly production quantity, the safety coefficient of that part number will be 0 (except richest part number in second scenario).

5) Weekly production quantity. This value is set to 5000 vehicles per week.

6) Base cost of any part number. The base cost of each part number is set to €20.

7) Lead time and stating point of warehouse. The lead time for shipping wiring harnesses from a supplier to the plant is assumed to be 1 week and the warehouse quantity starting point for each part number is 20.

8) Forecast time window. The forecasting time window is assumed to be 4 weeks, which means that the forecast value for each option changes every 4 weeks.

9) Cost of each option. The cost of each option is assumed as following: option 1 is €7.1; option 2 is €4.2; option 3 is €1; option 4 is €3.5; option 5 is €2.01.

10) Manufacturing cost per part number per year. The manufacturing cost for each part number in a year is difficult to set, as in the simulation the total number of individual part numbers is much less than the case study. In reality the standard cost is not suitable and it is difficult to evaluate the new cost when the total number of individual part numbers changes without going to the plant to assess the actual situation. The manufacturing cost is assumed to be €2000 per part number per year which is higher than the standard cost in some situations. At the discussion section, results obtained by varying this manufacturing cost are presented.

11) Number of simulations in each run. As this simulation is using the Monte Carlo Method, repeated random calculations are performed. The number of simulations performed in each run is set to 1000.

6.2.2 Simulation results

The simulation results according to the above inputs are showing in the Table 6-20 and Table 6-21. Table 6-22 shows the agenda used in Table 6-20 and Table 6-21.

PN	PN_RE	PN reduction (%)	Obso quantity	Obso_re quantity	extra travel	extra travel_re
32	22.78	28.82	1640.81	848.58	-202.08	-7.72

Table 6-20: Simulation results (quantity related).

manufacturing saving (€)	pd WKD increase (€)	pd FRC increase (€)	pd inc rich_re (€)	Obso_re sav (€)	Extra_sav_re (€)	Total_re sav (€)
18446.61	7894.35	7379.59	1470.03	22924.48	97178.69	129185.39

Table 6-21: Simulation results (cost related).

Agenda	
PN	Total part numbers used
PN_RE	Part numbers used considering substitution
Obso quantity	Total obsolescence quantity
Obso_re quantity	Total obsolescence quantity with substitution
extra travel	Total extra travel quantity
extra travel_re	Total extra travel quantity with substitution
Manufacturing saving	Total manufacturing cost saving by substitution
pd WKD increase	Product cost increase by substitution
pd FRC increase	Product cost increase by substitution based on forecasted value
pd inc rich_re	Product cost increase by avoiding extra travel with richest cable (€)
Obso_re sav	Total obsolescence saving with substitution (€)
Extra_sav_re	Total extra travel saving with substitution (€)
Total_re sav	Total saving with substitution (€)

Table 6-22: Agenda of simulation results.

As shown in Table 6-20, by implementing the second scenario, the number of individual part numbers used in the plant can be reduced from 32 to approximately 23 which is nearly a 30% reduction.

The savings obtained from the manufacturing side is €18446, which is more than one half of the product cost increase (€7894 for the real product cost increase, €7380 for the forecast condition).

The obsolescence quantity can be reduced from 1641 to 849 units in this case. The savings based on reducing obsolescence costs is approximately € 23,000.

The quantity of extra travel situations is reduced significantly from approximately 200 to 8 cases per year. The reduction of extra travel results in a savings is €97,000; however, €1470 in expenses are incurred by using richer wire harness part numbers.

Figure 6-29 shows the distribution of the number of individual part numbers used for a second scenario. Note that the interval here is between 20 and 27 part numbers, while the average is 22.78 as reported in Table 6-20.

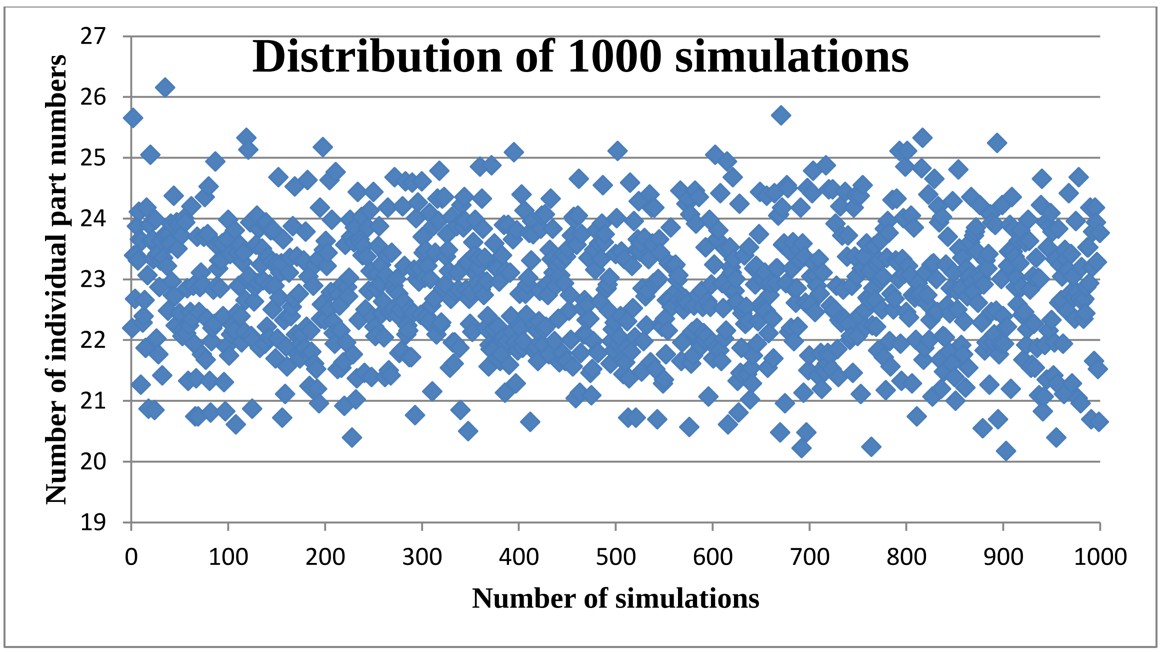

Figure 6-29: Distribution of 1000 simulations of average number of individual part numbers used.

Thus the total saving by implementing a substitution strategy is approximately €129,000 in a year on average, with a standard deviation of €50,000. The absolute total savings range is between €31,000 and €382,000 for 1000 single simulations as shown in Figure 6-30. Note that biggest contribution is from reducing extra travel costs.

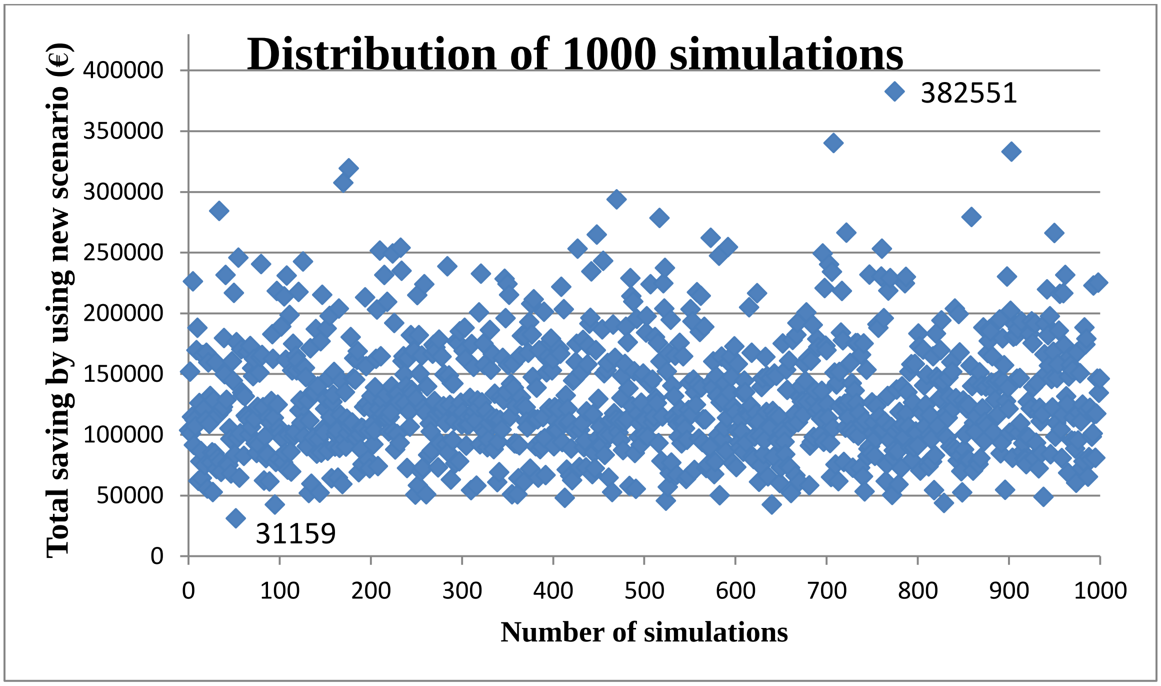

Figure 6-30: Distribution of 1000 simulations of total saving by using new scenario.

6.2.3 Simulation discussion

In this section, a discussion on the influence of specific parameters on the simulation results is given. As some simulation parameters are difficult to evaluate, or determine such as manufacturing cost per part number per year. It is of interest to see how these parameters could influence simulation results.

The discussion focuses on changing the quantities of related model parameters, such as the number of options being assessed. The impact of parameter changes on the total cost is not readily evident.

1) Effects of number of options.

The numbers of optional features impacts the number of total part numbers. It is expected that the reduction of part numbers will also change based on the number of total unique part numbers being assessed, which is confirmed as shown in Table 6-23.

Option	PN	PN_RE	PN reduction (%)	Obso quantity	Obso_re quantity	extra travel	extra travel_re
3	8	7.3	8.7	1028.1	873.6	-109.7	-0.2
4	16	13.1	18.1	1291.5	861.2	-156	-1.9
5	32	22.8	28.8	1640.8	848.6	-202.1	-7.7
6	64	40.4	36.9	2142.2	979.6	-202.1	-14.6

Table 6-23: Effects of number of options on simulation results.

As number of options increases, the reduction of part numbers also increases, from less than 10% to approximately 37%. There are many reasons for this: (i) increasing the number of options increases the substitution potential, and (ii) the obsolescence and extra travel cost scenarios also change. Figure 6-31 shows the part number reduction percentage as a function of the number of options.

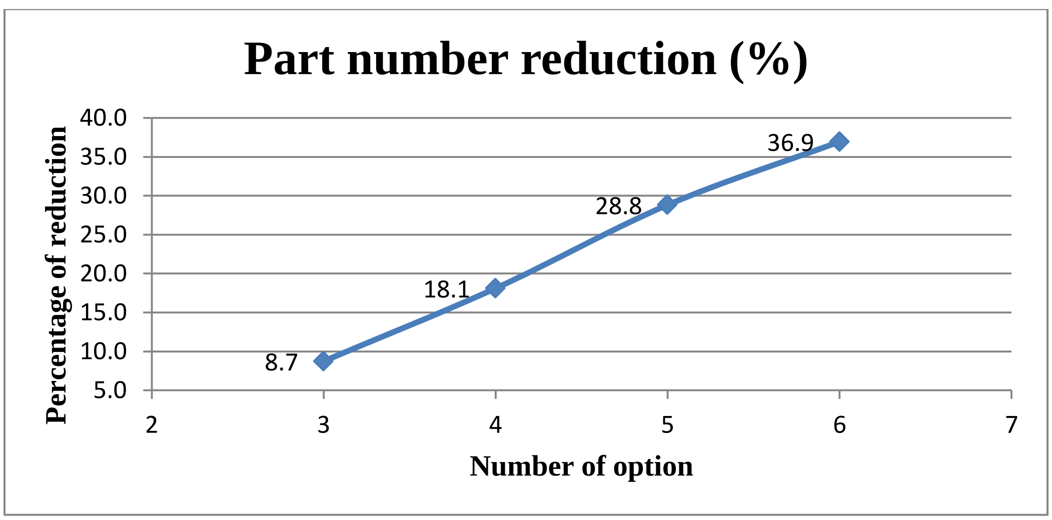

Figure 6-31: Part number reduction percentage as variation of number of option.

2) Effects of cost of options.

It is obvious that the cost of the options will affect the trade-off between the product cost and manufacturing cost. Given a fixed production volume and manufacturing cost, if the cost of the options increases, the total substitution cost will increase as well. This may be greater than the benefits incurred by reducing the total number of unique part numbers.

Table 6-24 shows the results obtained by changing the cost of the options. As costs of the options are reduced, the percentage of part numbers that can be reduced will increase (Figure 6-32). Note that only if the cost of an option reduces to a very low value, for instance less than €1, the influence of a substitution strategy can be clearly seen. The cost of an option has no influence on the obsolescence quantity and quantity of extra travel scenarios. These are impacted by the structural design of the wire harness.

Cost of Option (€)	PN	PN_RE	PN reduction (%)	Obso quantity	Obso_re quantity	extra travel	extra travel_re
[7.1; 4.2; 1; 3.5; 2.01]	32	22.8	28.8	1640.8	848.6	-202.1	-7.7
[3.1; 2.2; 1; 0.71; 1.35]	32	21.6	32.5	1637.6	794.8	-201.8	-8.6
[3.1; 0.61; 0.4; 1.1; 1.35]	32	19.9	37.9	1641.6	878.5	-201.4	-6.4

Table 6-24: Effects of cost of options on simulation results.

3) Effects of manufacturing cost variation.

The variation of the manufacturing cost will certainly affect the part number reduction. As the manufacturing cost is one of the direct inputs for the trade-off cost model, this will be varied, and the results are shown in Table 6-25. Note that as the manufacturing cost increases, the obsolescence quantity (second scenario) will increase and the extra travel quantity is reduced marginally.

Manufacturing cost (€)	PN	PN_RE	PN reduction (%)	Obso quantity	Obso_re quantity	extra travel	extra travel_re
2000	32	22.8	28.8	1640.8	848.6	-202.1	-7.7
3000	32	21.5	32.8	1641.1	841.2	-202.4	-7.9
5000	32	20.1	37.3	1632.9	918.4	-195.7	-6.5
8000	32	18.8	41.3	1635.8	1127.2	-198.9	-5

Table 6-25: Effects of manufacturing cost on simulation results.

Figure 6-32 shows the variation of the part number reduction as a function of the manufacturing cost per part number per year. It can be found that as the manufacturing cost increases from €2000 to €8000, the part number reduction percentage could increase from 29% to 41%.

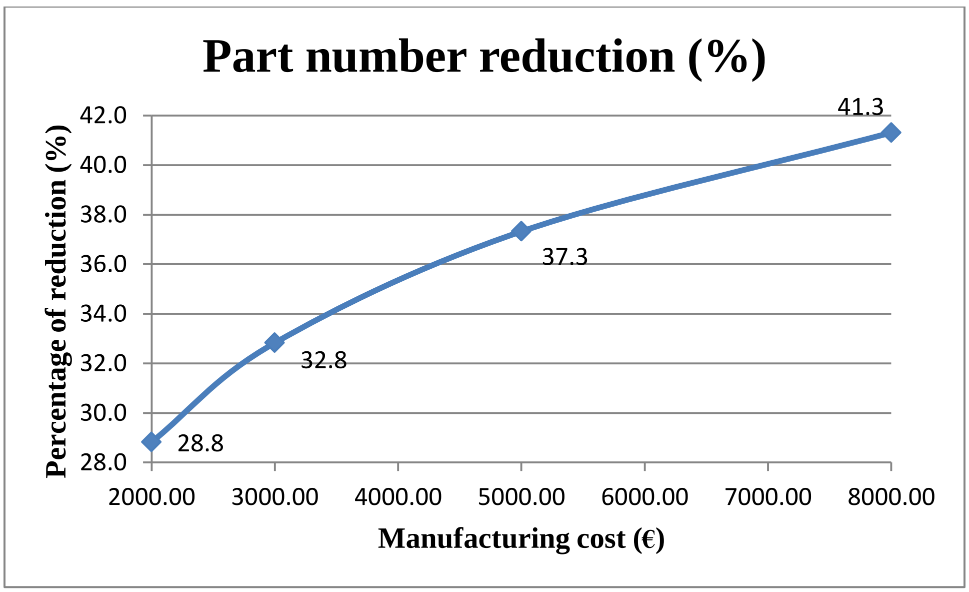

Figure 6-32: Percentage of part number reduction as variation of manufacturing cost.

4) Effects of safety coefficient.

The safety coefficient mainly impacts the obsolescence and extra travel quantities. It can be expected that when the safety coefficient increases, the obsolescence quantity will increase, but the need for extra travel costs would reduce. Table 6-26 shows the related results by changing the safety coefficient. As the safety coefficient increases from 2% to 4%, no impact can be seen on the part number reduction. But the obsolescence quantity increases as expected for both scenarios. The results show the opposite trend for the extra travel quantity, which meets expectations.

Safety coefficient	PN	PN_RE	PN reduction (%)	Obso quantity	Obso_re quantity	extra travel	extra travel_re
2%	32	22.8	28.6	1476.9	662.9	-294.8	-30.4
3%	32	22.8	28.8	1640.8	848.6	-202.1	-7.7
4%	32	22.8	28.7	1828.6	1014.6	-141.1	-2

Table 6-26: Effect of safety coefficient on simulation results.

5) Effects of the safety coefficient for the richest part number.

As this safety coefficient is especially designed for the second simulation scenario, it is expected to see the effects of changing this parameter only on the second scenario. Table 6-27 shows the related results as safety coefficient increases from 5% to 10%, the extra travel quantity can be reduced from 12 to 5 units, while the obsolescence quantity increases slightly from 835 to 870 units.

Safety coefficient of richest part number	PN	PN_RE	PN reduction (%)	Obso quantity	Obso_re quantity	extra travel	extra travel_re
5%	32	22.8	28.7	1636.2	834.9	-199.6	-11.6
7%	32	22.8	28.8	1640.8	848.6	-202.1	-7.7
10%	32	22.8	28.7	1642.6	869.5	-198.9	-4.6

Table 6-27: Effects of safety coefficient of richest part number on simulation results.

6) Effects of the forecast error.

As the trade-off decisions are made based on forecast data, the forecast error will change the benefits incurred by reducing the complexity.

Table 6-28 shows the related results obtained by changing the maximum allowed forecasting error for the options. For instance, a 5% forecasting error means the maximum allowed forecasting error of an option is 5% of the original forecasting probability. The results showed that the variation of the forecasting error will not affect the part number reduction. The forecast error will influence the real product cost as the accuracy is reduced, the product cost is increased.

Error of forecast	**PN**	**PN_RE**	**PN reduction (%)**	**manufacturing saving (€)**	**pd WKD increase (€)**	**pd FRC increase (€)**	**Difference due to forecast error (€)**
5%	32	22.8	28.6	18333.2	7493.5	7308.8	184.8
10%	32	22.8	28.8	18446.6	7894.4	7379.6	514.8
20%	32	22.9	28.5	18267.8	8768.5	7318.1	1450.4

Table 6-28: Effects of forecast error on the simulation results.

Figure 6-33 shows the difference between the actual product cost increases as a function of the forecast error. The figure indicates that as the forecasting error for an option changes from 5% to 10%, the difference increases from €185 to €1450. This is a reduction of benefits that has been obtained from the complexity reduction.

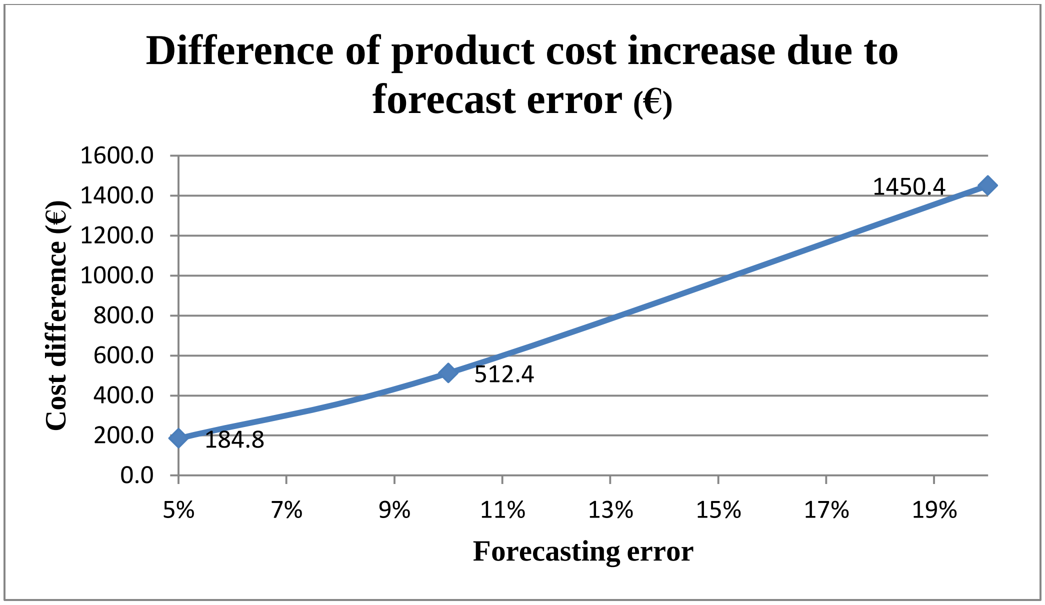

Figure 6-33: Difference between actual product cost increase and forecasted product cost increase as variation of forecasting error.

7) Effects of the customer order change

The customer order change is the maximum percentage allowed of customer changes for an option, as the customer order changes are assumed to occur after ordering the required part numbers from the supplier. It is expected to see the related changes on the obsolescence quantity and the extra travel quantity.

Table 6-29 shows the related results obtained by varying the maximum allowed percentage of customer order changes. The results indicate that increasing the customer order change value, the obsolescence quantity also increases for both scenarios because what ordered is not used in the production. For both scenarios, the rate of increase for the obsolescence quantity is similar, but the absolute values are different because of the model structure and assumptions. The results also indicate that as the customer order changes increases, the extra travel quantity also increases significantly because what needed in production is not ordered in the proper time frame. The influence on the product cost increase due to substitution is not as obvious. It increases only €140 (from €7850 to €7990) because the percentage of variation is small.

Order change	PN	PN_RE	Obso quantity	Obso_re quantity	extra travel	extra travel_re	pd WKD increase (€)
1.0%	32	22.8	1178.9	656.1	-21.4	-0.1	7849.6
2.0%	32	22.8	1640.8	848.6	-202.1	-7.7	7894.4
2.5%	32	22.8	1897.3	937.1	-362.9	-33.9	7854.5
5.0%	32	22.8	3198.4	1401.9	-1453.8	-506.5	7990.7

Table 6-29: Effects of customer order change on simulation results.

Figure 6-34 shows the obsolescence quantity as a function of the customer order changes for both scenarios. As the customer order change increase form 1% to 5%, the obsolescence quantity increase from 1179 to 3200 for first scenario while in case of second scenario, the obsolescence quantity increase from 656 to 1400. The values obtained from the second scenario are approximately half of that of the first scenario.

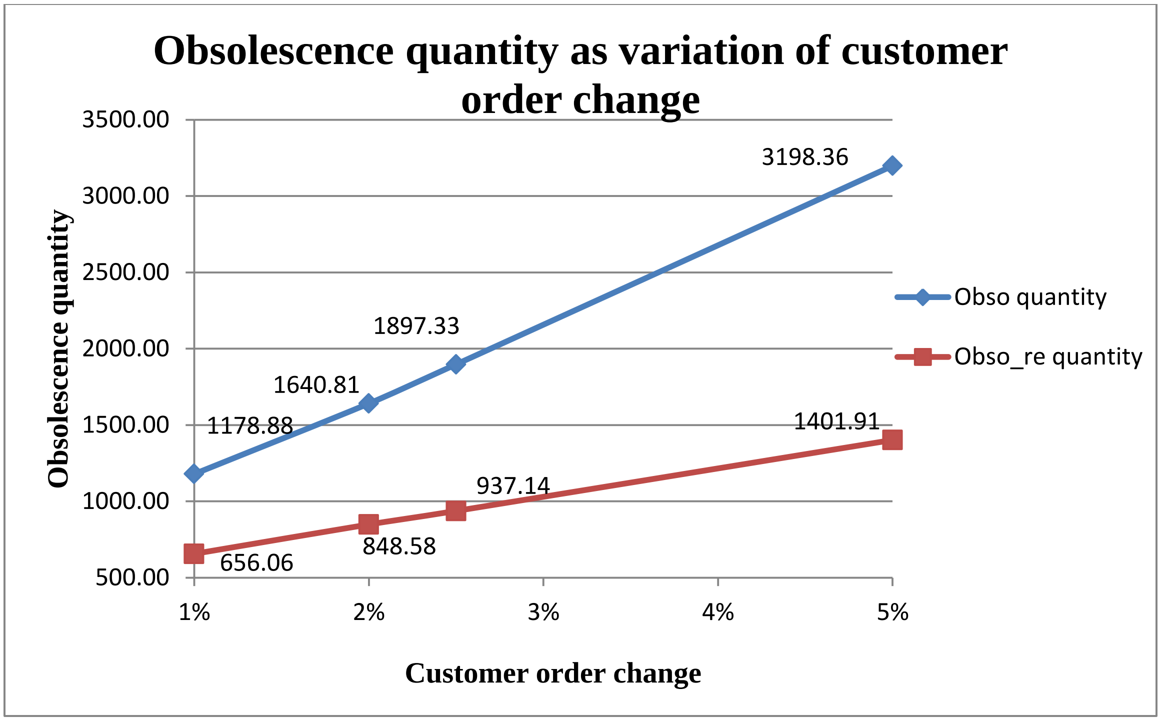

Figure 6-34: Obsolescence quantity for both scenarios as variation of customer order change.

Figure 6-35 shows the extra travel quantity as a function of the customer order changes for both scenarios. As customer order changes from 1% to 5%, the extra travel quantity raises from 21 to 1453 for the first scenario. For the second scenario, the extra travel quantity increases from almost 0 to 506. For both scenarios, the extra travel quantity increases significantly as the customer order changes increase from 2.5% to 5%.

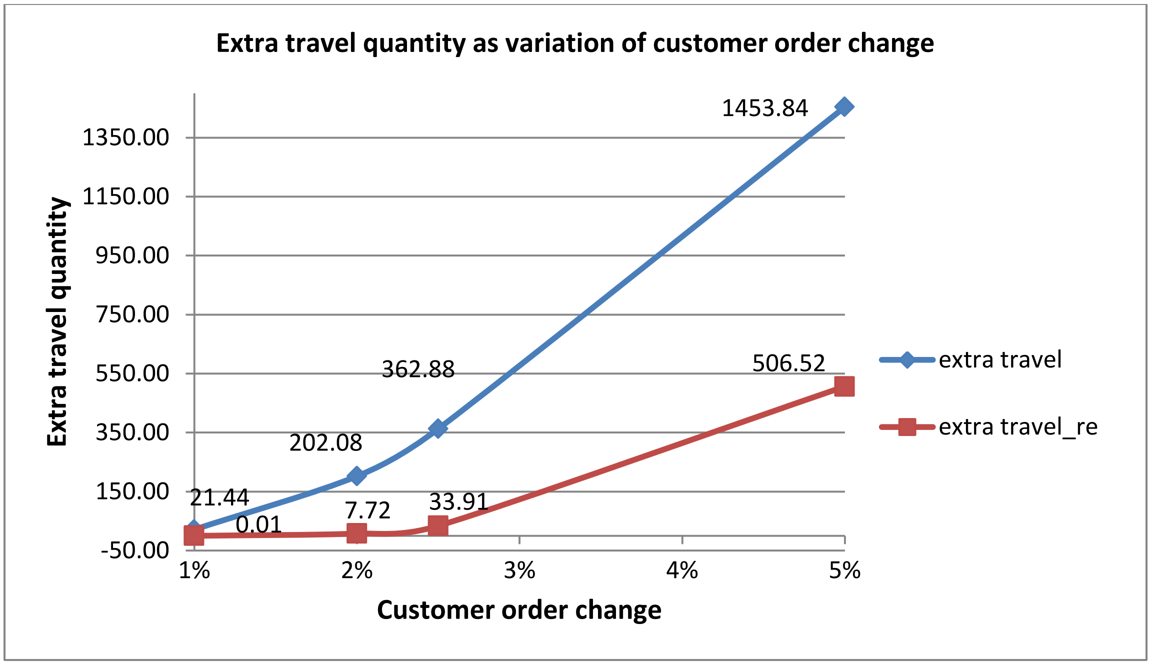

Figure 6-35: Extra travel quantity for both scenarios as variation of customer order change.

6.3 Simulation summary

A MATLAB simulation using the Monte Carlo Method for performing trade-off analyses between the wiring harness product cost and manufacturing cost is presented in this chapter.

Two scenarios are simulated in the model: one focuses on minimizing product cost regardless of the manufacturing cost, which results in generating the maximum complexity level. The second scenario focuses on maintaining the maximum wiring harness complexity at the supplier side, and determining the best subset of part numbers according to the trade-off cost model, which is established on a week by week basis. This reduces complexity at plant level but also balances product costs.

Additional simulation results showed that the cost savings are impacted significantly by varying the input parameters.

CHAPTER

7. CONCLUSIONS AND FUTURE WORK

7.1 Conclusions

This thesis focuses on complexity management for automotive wiring harnesses. As the design of wiring harnesses is usually performed without considering the complexity issues that arise during the vehicle manufacturing process, a large number of excess part numbers are designed, but an optimal number needs to be quantified using a systematic analytical approach.

A trade-off cost model for the wiring harness product cost and the manufacturing cost is established by analysing the key literature, and by investigating all the relevant tasks associated with wire harnesses in the assembly plant. In this derived model, the operations which generate the related manufacturing costs are determined and quantified using a Full Time Equivalent modelling approach. This is used to develop a comprehensive total manufacturing cost model which includes administration, inventory, material handling, extra travel and obsolescence cost elements. The total manufacturing cost generated in a year is divided by the number of individual part numbers for the analysis performed in this work.

A case study using an existing vehicle model called “Vehicle W” is presented to highlight the merits of this assessment strategy using actual production data. An approximate savings of €0.9 per vehicle can be obtained using the trade-off cost model to minimize the total costs for 2 wiring families. Higher savings could be achieved if more wire harness families are evaluated.

A MATLAB simulation using the Monte Carlo Method is developed to simulate a new scenario which considers prediction and probability aspects. The Monte Carlo Method is used for generating random numbers to simulate fluctuating customer demand, so that a forecasting process can be included in the model. In addition to this, elements of uncertainty such as a forecasting error and potential customer order changes are considered in the model. When considering a set of 5 optional features, the results obtained from the simulation indicated that a part number reduction of approximately 30% can be achieved with a total saving about €129,000. Also discussions about the influence of the input parameters on simulation results are provided.

When combining the results from the case study and the MATLAB simulation, it can be concluded that the implementation of complexity management strategies for wiring harnesses is essential. Real and significant cost savings can be achieved when assessing multiple perspectives within the system along with the application of a robust trade-off cost model.

7.2 Future work

It is expected supplementary research would be beneficial among the additional tasks that should be undertaken are:

1) Further analysis is needed on manufacturing cost deployment. The manufacturing cost per part number per year should be a function of the number of individual part numbers managed in an assembly plant. As the manufacturing cost has a fixed and a variable element, which consist of several operations, it cannot be computed from simple mathematical formulas. To perform this analysis for each cost component, which varies with the number of individual part numbers changes, it is important to

establish the relationship between the amount of cost that will change and the variation of the part numbers. For instance, if the part numbers managed in the plant is reduced by 50%, there is a question as to what will be the new cost for the sequencing operation calculated from the new FTE coefficient. The new FTE value may be reduced by 30% or 40% in this case, mathematical expressions are needed to describe this.

2) An expansion of the MATLAB simulation model. The present model only focuses on the option features without considering mandatory features. The future model should also include the addition of the mandatory feature “variants”. This will make the model more practical. For the manufacturing cost, a function related to the number of the distinct part numbers that developed from 1) should be used instead of a fixed cost, which was utilized in this work.

APPENDICES

A. WCM AND CONTINUOUS IMPROVEMENT RELATED TO WIRING HARNESS ISSUES AT AN ASSEMBLY PLANT

The author had the opportunity to be engaged with the WCM process targeting wiring harnesses at an assembly plant. The technical pillar in which the author was involved is quality control.

A.1 Introduction to quality control technical pillar

Quality control is an important technical pillar of the WCM structure as the quality of a vehicle directly affects the customer satisfaction.

The purposes of applying quality control are the following:

1) Guarantee product quality for customers, while minimizing costs due to reworking and rejects.

2) Define production process conditions able to prevent the occurrence of non-conformities and maintain the conditions defined to guarantee conformity in time. For example, quality issues may arise such as some parts of harness may become too tight which might over stressed if the operating sequence for installing clips to the car body are different due to different operators working on different shifts. So in this case, the correct installation sequence must be defined and applied in all the shifts.

3) Improve operators' problem solving knowledge. The goal is to help operators to understand the root cause of a given problem and to know the correct actions to prevent the problem from reoccurring.

The main activities include:

1) Deployment of defects, reworking and rejects to analyze the origin of non-conformities.

2) Definition of operating conditions able to guarantee the desired quality and process capability.

3) Set-up, training and management of improvement teams.

4) Definition of standard operating procedures.

The main approach used is the seven steps of quality control:

1) Select the theme

2) Understand the situation and objectives

3) Plan activities

4) Analyze causes

5) Define and apply corrective actions

6) Check results

7) Standardize and apply control

A.2 Quality problems on wiring harness

As the plant needs to manage at least several hundred wiring harness part numbers for assembly, quality problems usually happen. Typical wiring harness quality problems are summarised as follows:

1) Harness interference with other parts which influence or cause difficulties for following assembly operations. For instance, harness interference with the subwoofer corner, which leads to the subwoofer not being installed at the correct position. As well, the harness may get damaged because of the improper subwoofer installation.

2) The length of a harness is not appropriate (too short or too long) that leads to difficulties for the connector installation or results in not enough space for other operations.

3) Difficult to install clips into corresponding holes on the car body. This is due to mismatching between the clips and holes. The position of the hole or clip position needs to be modified to solve problems.

4) Not appropriate insertion force. High insertion forces needed during installation may cause pins of the connector to be over stressed or even break. Low insertion force can cause connector to lose contact with electric device during normal operating conditions.

5) BSR caused by unused connectors. BSR noises are generated by unused connectors due to movement. In some cases, the generated noises will affect customer satisfaction; therefore, necessary operations must be performed to prevent this.

A.3 Seven steps of quality control for solving wiring harness problems

To better use the seven steps approach, a PDCA (Plan-Do-Act-Check) table is used as a tool for displaying the progress of problem solving.

Table A-1 illustrates main items listed in a PDCA table.

The 1st column "item #" lists the number of the issue. Column 2 is the status of issue, and three different colours can be chosen from: red means the issue is at the stage of planning, no recommended solution is proposed, and is indicated with an "R"; yellow means a solution has been proposed but the effect needs to be checked and estimated, and is indicated with an "Y"; Green means the issue has already been solved and the change is fully implemented, and is indicated with a "G".

The 3rd column "area" in this case is wiring. Next column "harness" specifies the wiring harness family of part number in which the issue is involved.

The 5th column called “issue and root cause” which describes the problem and the root cause. The 6th column is “corrective action and next steps” which shows the proposed solution of the issue including the short term and long term actions. The content of this column needs to be updated frequently according to the results of the corrective actions. The following two columns list the model which is related to the issue, and the source of the issue.

Columns 9 and 10 specify the responsible engineer from the plant and responsible engineer from the technical team. The following two columns issue the starting date and target date. Column 13 lists all the documents that are necessary for the modifications of the wiring so that related people could easily check the process. The last columns illustrate the PDCA status and next review dates.

A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
Item #	Status	Area	Harness	Issue and Root Cause	Corrective Action (Short/Long Term) and Next Steps	Model	Source	Plant ENG	Design team ENG	Start Date	Target Date	Related documents	PDCA Status	P	D	C	A	Next Review Date

Table A-1: A typical PDCA table.

Here is an example of the seven steps approach to solving quality issues on wiring harnesses. Figure A-1 shows general process flow of 7 steps of quality control.

Figure A-1: Seven steps of quality control.

The first step is to select the theme, for instance, a customer service report that there is unexpected noise generated due to the wiring harness in the instrument panel for a model that is produced in the plant.

Step two is to understand the situation and objectives. In this step, customer service will try to understand the severity of the issue and also the percentage of occurrences so that the priority of the problem can be defined and the objectives can be set. In this case, the objective is to eliminate the noise in the instrument panel.

The third step is to plan activities. During this step, the issue will be added into PDCA table so that an issue number will be created. The area and harness will be clearly defined. Also the source and model related to the issue can be written into the table. Then responsible persons for solving this issue need to be defined. The root cause of the issue is not clear, as it may due to inappropriate design or inadequate operations performed by operators during vehicle assembly. So two responsible persons need to be assigned, one is from plant for quality control, the other one is from the wiring design technical team for that model, who usually would be the same person who designed the harness for instrument panel. Also the starting date and target date should be planned at this stage.

Step 4 is to analyze causes. In this step, the two responsible engineers will work together to find the root cause of the issue. The plant engineer will first go to the assembly line to check if related operators follow the correct procedure for installing that wiring harness. If yes, he will consider if the issue is due to inadequate assembly operations defined by manufacturing department. As no problem was found in the above two procedures, the root cause of noise should be due to design. So the engineer from design team will look at his design in details and it was found that the noise is generated from an unused connector that having contact and collisions with the instrument panel if vibration of vehicle is large enough. As in this stage, the cell of "issue and root cause" can be filled in the PDCA table saying that "BSR on unused connector in the instrument panel" together with the code of that connector.

Step 5 is to define and apply corrective actions. As the case of BSR, a typical solution is to add an item to the unused connector to prevent or reduce noise to a low level or to use tape to fix the position of that connector if it is possible. For the short term action, they proposed to use a foam patch over that connector so that the noise is dampened. In the long term, the design engineer prepared to add a feature to store the unused connector. As the solution came out, the cell for "corrective action and next steps" can be updated. Since both long term and short term solutions require design modification on the harness, the design engineer needs to send the related information to the wiring harness supplier and ask the supplier to build a certain amount of new samples according to the quantity he needed during next step.

Step 6 is to check results of the proposed solution. For the wiring harness, the results checking is usually performed through a process called PER. PER stands for Parts Evaluation Run, which is an important process aiming at testing if the proposed solution is effective or not. The PER will be done at the production line and it must not influence the normal production, for instance, performing a PER cannot delay other operations. Obviously, the related wiring engineer and the responsible from plant must be present at the assembly line when PER is running to give some instructions and evaluate the result of PER. The related information about PER including when the PER parts arrived at plant, what is the time for PER and results of PER should be updated in the PDCA table under the cell "corrective action and next steps"

In the case of this example, the major focus on the PER is to check if the newly added foam patch will cause any difficulties for wiring harness assembly such as interference with other parts as operation space for operator is reduced in this case. Obviously, it is not possible to check if the noise will still exist or not immediately after harness is being installed. The final check should be performed during the road test when the final assembly is finished.

The next step to be performed is dependent on the results of the PER. If the result is not satisfactory, a new corrective action needs to be performed.

Step 7 is to standardize and apply the controls. It means to implement the solution on the entire production.

With the 7 steps approach of quality control and the usage of the PDCA table, both the plant and the wiring technical team will concentrated on effectively solving quality issues that appeared when using certain wiring harnesses-option set combinations, and the results showed that cost reduction or quality improvements are achieved.

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