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Development of environmentally sustainable supply chain networks

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Development of Environmentally Sustainable Supply Chain Networks

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A thesis in fulfilment of the requirements for the degree of
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The development of a generic Decision Support System (DSS) for Supply Chain Network Design (SCND) is one of the most challenging research areas in Supply Chain Management. It must evolve with an emphasis on improving the supply chain performances; to reduce the cost, lead time and environmental impact. The three performances are generally influenced by several planning decisions (i.e. sources of supply and facility locations, order quantity allocations, transportation modes and lot-sizes) and various time-dependent parameters (e.g. currency exchange rates). As a result, there is a need to develop a generic decision support system to assist in designing the supply chain network by considering the issues aforementioned.

This research aims to develop a generic DSS for an environmentally sustainable SCND. It covers from cradle-to-gate stages that aim to achieve the lowest cost, shortest lead time and least environmental impact in a dynamic environment. The development of a generic DSS applies the integration of Fuzzy Goal Programming (FGP) with a weighted max-min operator and system dynamics optimisation with Powell algorithm. The FGP with a weighted max-min operator is used to trade-off the multiple conflicting objectives and overcome vagueness in target values of the individual objectives. The multivariable and dynamic behaviour is configured and solved by using the system dynamics optimisation with Powell algorithm. The generic DSS eventually suggests the best-fitted sources of supply and facility locations, the optimal order quantity allocations, and the appropriate transportation modes and lot-sizes in order to achieve the aim of this research.

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ABSTRACT

The development of a generic Decision Support System (DSS) for Supply Chain Network Design (SCND) is one of the most challenging research areas in Supply Chain Management. It must evolve with an emphasis on improving the supply chain performances; to reduce the cost, lead time and environmental impact. The three performances are generally influenced by several planning decisions (i.e. sources of supply and facility locations, order quantity allocations, transportation modes and lot-sizes) and various time-dependent parameters (e.g. currency exchange rates). As a result, there is a need to develop a generic decision support system to assist in designing the supply chain network by considering the issues aforementioned.

This research aims to develop a generic DSS for an environmentally sustainable SCND. It covers from cradle-to-gate stages that aim to achieve the lowest cost, shortest lead time and least environmental impact in a dynamic environment. The development of a generic DSS applies the integration of Fuzzy Goal Programming (FGP) with a weighted max-min operator and system dynamics optimisation with Powell algorithm. The FGP with a weighted max-min operator is used to trade-off the multiple conflicting objectives and overcome vagueness in target values of the individual objectives. The multivariable and dynamic behaviour is configured and solved by using the system dynamics optimisation with Powell algorithm. The generic DSS eventually suggests the best-fitted sources of supply and facility locations, the optimal order quantity allocations, and the appropriate transportation modes and lot-sizes in order to achieve the aim of this research.

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ii. Boonsothonsatit, K. , Kara, S., Kayis, B., Ibbotson, S., 2013. Weighted Additive Fuzzy Goal Programming-based Decision Support System for Green Supply Network Design. The IEEE International Conference on Industrial Engineering and Engineering Management (IEEM), Bangkok, Thailand 10-13 December 2013.

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iv. Boonsothonsatit, K., Kara, S., Kayis, B., Ibbotson, S., 2013. Dynamic and Green Supply Chain Network Design. Supply Chain Management: International Journal (under preparation)

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1

INTRODUCTION

The business environment has become fiercely competitive due to issues such as shorter product life cycles and higher customer expectations. The fierce competition has forced companies to invest in technologies that support communication and transportation. As a result, these technological investments have led to the enhancement of supply chain competitivenessthat further motivates the continuous evolution of the supply chain.

In the 1980s, supply chain management emerged to effectively integrate material and information flows along the supply chain (Oliver and Webber, 1982), aiming to minimise supply chain costs and maximise responsiveness to customers (Russell and Taylor, 2011). Over the past few decades, the aspects of economic globalisation has been incorporated into managing the supply chain (Meixell and Gargeya, 2005) to assist in securing international sources of supply and setting up international facilities. The so-called global supply chain management aims to gain competitive advantages. They are tariff and trade concessions, reduction in costs due to low-cost materials, labours, logistics and capital subsidies, increases in revenue due to quick response to customer needs, and improvement in reliability due to close proximity of suppliers (Ferdows, 1997). However, the global supply chain of sourcing, manufacturing and delivering presents new challenges in managing the geographical distances and infrastructures of transportation (Meixell and Gargeya, 2005). These difficulties have adverse effects on costs of transportation and inventory holding, lead time, and environmental impact. In addition, managing the global supply chain poses serious risks due touncertaintities in currency exchange rates, economics and politics and changes in environmental regulations that are outside the control of the manufacturer (Dornier et al., 1998). These challenges continually evolve over time which influences the design of supply chain network.

Due to increasing awareness on the issue of environmental impact in society, the environmental aspects have been integrated into supply chain management since the 1990s. The so-called green supply chain management is driven by pressures from stakeholders, increases in environmental deterioration and regulatory requirements (Srivastava, 2007, Holt and Ghobadian, 2009, Sarkis et al., 2011). These drivers aim to reduce environmental impact such as greenhouse gas emission and it has been found that up to 50% of the environmental impact along the entire product life cycle can be reduced by changes in supply chain configurations (Kara et al., 2010). The changes may be controlled by selecting different sources of supply and facility locations, order quantity allocations, transportation modes and lot-sizes. These planning decisions primarily support the decision making process in the design of green supply chain network (Kara et al., 2010).

Therefore, the design of supply chain networks must evolve with an emphasis on improving the supply chain performances; to reduce the cost, lead time and environmental impact. The three performances are generally influenced by several planning decisions (i.e. sources of supply and facility locations, order quantity allocations, transportation modes and lot-sizes) and various time-dependent parameters (e.g. currency exchange rates). As a result, there is a need to develop a generic decision support system to assist in designing the supply chain network by considering the issues aforementioned (Harrison, 2001, Goetschalckx et al., 2002, Meixell and Gargeya, 2005, Melo et al., 2009).

1.1 Research aim and scope

This research aims to develop a generic Decision Support System (DSS) for an environmentally sustainable supply chain network design. It covers from cradle-to-gate stages that aim to achieve the lowest cost, shortest lead time and least environmental impact in a dynamic environment. The development of a generic DSS applies the integration of Fuzzy Goal Programming (FGP) with a weighted max-min operator and system dynamics optimisation with Powell algorithm. The FGP with a weighted max-min operator is used to trade-off the multiple conflicting objectives and overcome vagueness in target values of the individual objectives. The multivariable and dynamic behaviour is configured and solved by using the system dynamics optimisation with Powell algorithm. The generic DSS eventually suggests the best-fitted sources of supply and facility locations, the optimal order quantity allocations, and the appropriate transportation modes and lot-sizes in order to achieve the aim of this research.

1.2 Organisation of the thesis

To achieve the research aim, this thesis is organised into five chapters. They consist of introduction, literature review, research methodology, illustrated examples, and conclusions which are described briefly as follows.

Chapter 1 Introduction

Chapter 1 introduces research motivation for the development of a decision support system for supply chain network design. The reseach motivation contributes to stating the research problem, specifying the research aim and scope, and organising the thesis into five chapters which are individually presented.

Chapter 2 Literature review

Chapter 2 provides background information on the development of supply chain management, and literature review related to decision support systems for supply chain network design. Their previous studies are reviewed and discussed in terms of basic features, decision variables, performances and time-dependent parameters. Review of existing literature leads to the conclusion that development of decision support systems in supply chain management is in need of further research with the possibility of using simulation-optimisation approach. The research needs are eventually highlighted and used in chapter 3.

Chapter 3 Research methodology

Chapter 3 presents the six steps in developing the research methodology framework. It supports the development of a generic decision support system for an environmentally sustainable supply chain network design. The six steps include system understanding, conceptualisation, formulation, configuration, verification, and validation. This chapter presents the first four steps, whereas the last two steps are demonstrated further in chapter 4.

Chapter 4 Case studies

Chapter 4 demonstrates the successful verification and validation through various industrial cases. An industrial case is demonstrated step-by-step to verify the generic decision support system. The verified decision support system is subsequently implemented in four industrial cases as the system validation. They include: (1) cryogenic storage tank manufacturing company, (2) automotive part manufacturing company, (3) roof sheet manufacturing company, and (4) power boat manufacturing company. Their baseline and optimal results are eventually compared and discussed.

Chapter 5 Conclusion

Chapter 5 provides the conclusion of this research. It summarises the research needs corresponding to the research aim, methodology, and outcomes. They subsequently dictate several contributions to this research field, which is the development of decision support systems in supply chain management, with suggestions for further work.

CHAPTER 2
LITERATURE REVIEW

The introduction in chapter 1 stated the research aim to develop a generic Decision Support System (DSS) for Supply Chain Network Design (SCND) based on optimisation of cost, lead time, and environmental impact. To achieve the stated research aim, this chapter conducts literature review to explore previous studies related to this research as presented in Figure 2-1. It consists of the following seven sections as follow.

Supply Chain Management (SCM) is overviewed as background information in section 2.1 and it is identified that one of the most challenging research areas in SCM is SCND. The previous DSSs related to SCND involve basic features, decision variables, performances and time-dependent parameters. The basic features, which are reviewed and synthesised in section 2.2, indicate complexity in the development of a generic DSS for SCND. They generally consist of multiple stages, multiple layers within each stage, multiple commodities, and multiple periods of time (complex). The best-suited layers and their commodity allocations with appropriate transportation modes are determined by planning decisions (multivariable), and reviewed and discussed in sections 2.3. As the planning decisions support the achievement of desired supply chain performances (multi-objective), they are reviewed and discussed in sections 2.4. In addition, it is dependent on parameters which are sensitive to time change (dynamic). The time-dependent parameter are hence reviewed and discussed in sections 2.5. To optimise the multivariable, multi-objective, complex and dynamic nature of SCND, an integrated approach of simulation and optimisation (simulation optimisation) is reviewed and discussed in section 2.6. Consequently, these research findings lead to the research needs corresponding to the research aim as stated in section 1.1 and are highlighted in section 2.7. They are used for the development of research methodology framework presented in chapter 3.

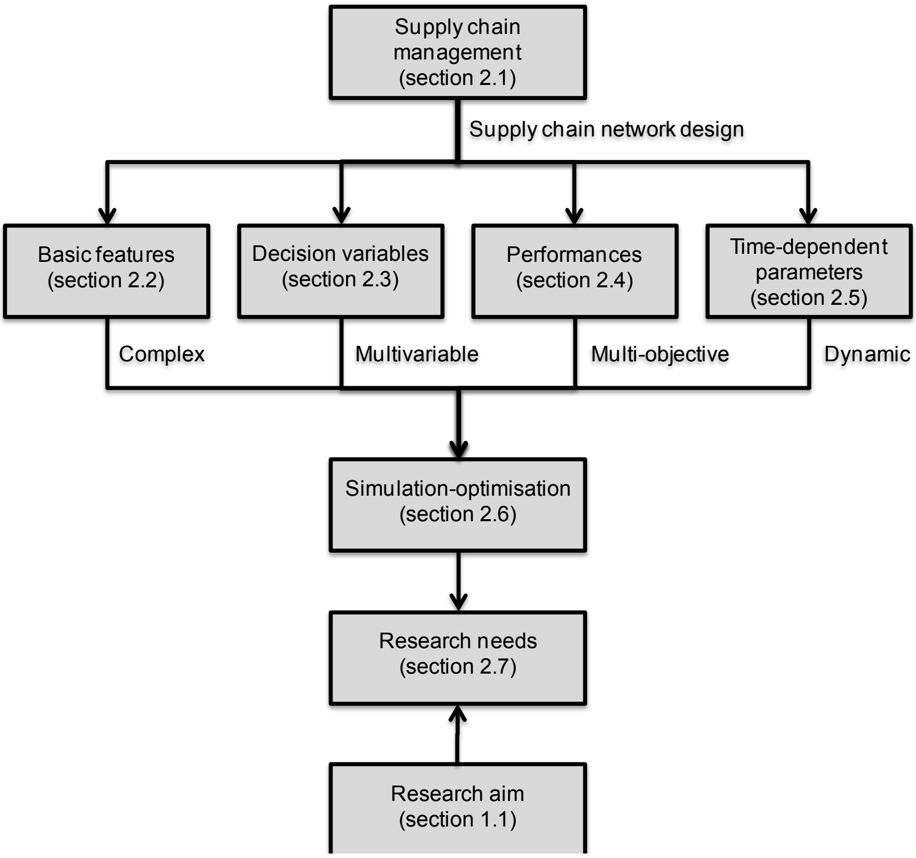

Figure 2-1 Literature review framework

2.1 Overview of supply chain management and supply chain network design

Figure 2-2 shows the framework of Supply Chain Management (SCM) which is the effective integration of inbound and outbound logistics of capital, commodities and information (Russell and Taylor, 2011). The inbound logistics involve material procurement and product manufactureiing, whereas the outbound logistics relate to product warehousing and distribution to retailers and consumers.

The integrated activities are synchronised as a series of inter-related business processes through collaboration among all stakeholders (Lummus and Vokurka, 1999). The synchronisation aims to eliminate wastes, reduce non-value added activities while improving value added activities (Corbett and DeCroix, 2001). Through the integrated activities, reduction in cost and lead time across the entire supply chain (e.g. costs of materials, transportation, manufacturing and inventory) is achieved while enhancing customer service (Simchi-Levi et al., 2008) and quality of product (Christopher and Towill, 2000).

***Figure 2-2** Typical supply chain networks*
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Although much research has been conducted to improve SCM, there are a number of challenges that need to be overcome which can be summarised as follows:

- There is a need to align the decision making process with organisational goals,
- Organisation goals may be in conflict with each other with multiple goals that need to be considered for a global optimum and,
- The uncertainties and risks along the supply chain need to be managed.

The need to overcome the SCM difficulties leads to effective management of strategic, tactical and operational planning on an integrated basis. The strategic, tactical and operational planning is established as a hierarchical order based on the time dimension (Laínez et al., 2009). At the top level, the strategic or long-term plans influence the achievement of organisational goals over sourcing and investment decisions which cannot be easily altered when implemented. The strategic decisions support well-designed supply chain networks. Their commodity flows are planned for middle term as part of strategic and tactical plans, whereas the short-term or operational plan is established for daily or weekly activities. The most successful organisations significantly emphasise the importance of strategic and tactical planning because 80% of supply chain cost is locked in with sources of supply, facility locations, and commodity flows (Watson et al., 2012). Due to these issues, the Supply Chian Network Design (SCND) has presented new challenges for both academics and practitioners (Harrison, 2001, Goetschalckx et al., 2002, Meixell and Gargeya, 2005, Melo et al., 2009).

Thus, the challenges in SCND have led to the development of several Decision Support Systems (DSSs) in the last two decades with corresponding scopes (Laínez et al., 2009). They are hence reviewed and synthesised in the next section through basic features (referred to Figure 2-1).

2.2 Basic features of supply chain network design

Supply chain networks as referred to Figure 2-2 are typically featured with multiple stages, multiple layers within each stage, multiple commodities and multiple periods of time. In addition, the typical features of supply chain networks are dependent on periods of time (or dynamic). The basic features are hence characterised into four groups. They include (1) number of supply chain stages, (2) single or multiple layers within each stage, (3) single or multiple commodities, and (4) single or multiple periods of time.

Based on the four basic features, the previous Decision Support Systems (DSSs) for Supply Chain Network Design (SCND) are synthesised in Table 2-1. It revealed that the initial DSSs for SCND were simply developed by covering few supply chain stages and multi-layers for a single commodity under static behaviour (Adhitya et al., 2011). The simple DSSs for SCND were developed further to cover multiple stages and multiple layers for several commodities (Vidal and Goetschalckx, 2001, Perron et al., 2010, Chaabane et al., 2011, Harris et al., 2011, Wang et al., 2011, Abdallah et al., 2012, Jaegler and Burlat, 2012); however, they behave statically. The static DSSs for SCND were developed further to cover a dynamic behaviour (You and Grossmann, 2008, Elmaraghy and Mahmoudi, 2009, Bojarski et al., 2009, Laínez et al., 2009, Chaabane et al., 2010b, Jones et al., 2010, Adhitya et al., 2011).

Table 2-1 Basic features of supply chain network design

Researches	Stages	Layers	Commodities	Periods
Vidal and Goetschalckx (2001)	4	Multiple suppliers, Multiple manufacturing plants, Multiple distribution centres, Multiple market zones	Multiple	Single
You and Grossmann (2008)	4	Multiple suppliers, Multiple manufacturing plants, Multiple distribution centres, Multiple customers	Multiple	Multiple
Bojarski et al. (2009)	3	Multiple suppliers, Multiple facility locations, Multiple markets	Multiple	Multiple
Elmaraghy and Mahmoudi (2009)	3	Multiple suppliers, Multiple manufacturing plants, Multiple distribution centres,	Multiple	Multiple
Laínez et al. (2009)	4	Multiple suppliers, Multiple manufacturing plants, Multiple distribution centres, Multiple market zones	Multiple	Multiple
Reich-Weiser and Dornfeld (2008)	3	Multiple suppliers, Single manufacturing plant, Multiple customers	Multiple	Single
Chaabane et al. (2010b)	4	Multiple suppliers, Multiple manufacturing plants, Multiple distribution centres, Multiple customers	Multiple	Multiple
Jones et al. (2010)	4	Multiple suppliers, Multiple manufacturing plants, Multiple distribution centres, Multiple customers	Multiple	Multiple
Perron et al. (2010)	4	Multiple suppliers, Multiple manufacturing plants, Multiple distribution centres, Multiple market zones	Multiple	Single
Adhitya et al. (2011)	4	Multiple suppliers, Single manufacturing plant, Single distribution centre, Multiple retailers or customers	Single	Multiple
Chaabane et al. (2011)	4	Multiple suppliers, Multiple subcontractors, Multiple manufacturing plants, Multiple customer zones	Multiple	Single
Harris et al. (2011)	3	Multiple suppliers, Multiple warehouses, Multiple customers	Multiple	Single
Wang et al. (2011)	3	Multiple suppliers, Multiple facility locations, Multiple customers	Multiple	Single
Abdallah et al. (2012)	4	Multiple suppliers, Multiple manufacturing plants, Multiple distribution centres, Multiple retailers	Multiple	Single
Jaegler and Burlat (2012)	3	Multiple suppliers, Multiple manufacturing plants, Multiple customers	Multiple	Single

It is found that a DSS for SCND is generally featured with at least four stages including suppliers, manufacturing plants, distribution centres or warehouses, and customers. The individual stages have multiple layers for making, storing and delivering multiple commodities with various transportation modes under a dynamic behaviour. The finding of these basic features indicates complexity in the development of a generic DSS for SCND. It leads to inclusion of several planning decisions which are reviewed and discussed in the next section.

2.3 Decision variables of supply chain network design

As presented in the previous section, the development of a generic Decision Support System (DSS) for Supply Chain Network Design (SCND) requires considering several planning decisions (referred to Figure 2-1). They correspond to the basic features as follows.

- Sources of supply determine which suppliers, vendors, and Third Party Logistics (3PL) providers are outsourced for long-term contracts.
- Facility locations determine where manufacturing plants, distribution centres or warehouses are located for long-term investment.
- Order quantity allocations determine how many order quantities of commodities are allocated to the selected sources of supply and located facilities. However, their production capacities may constrain the determination of order quantity allocations.
- The availability of different transportation modes (e.g. air, truck, rail, and sea) determines which mode is utilised to deliver lot-sizes of commodities from upstream to downstream supply chain members. The lot-sizes for transportation are determined for a roundtrip which may be constrained by transportation capacities and minimum order quantities.

These four planning decisions are characterised into three types of network design as shown in Table 2-2. Firstly, Supply Network Design (SND) includes the choosing the sources of supply as part of the long-term planning decisions and it can be included with the tactical planning decisions (i.e. order quantity allocations and transportation modes and/or lot-sizes). Secondly, Facillty Network Design (FND) includes the long-term planning decision of facility locations which can be included as part of the tactical planning decisions. Thirdly, SCND is an integration of SND and FND which includes the sources of supply, facility locations and order quantity allocations. These planning decisions can be included along with transportation modes and/or lot-sizes in SCND. Accordingly, the previous Decision Support Systems (DSSs) related to the three types of network design are reviewed in sections 2.3.1 to 2.3.3. They are discussed based on the four planning decisions.

Table 2-2 Planning decisions of network design

Type of network design	Planning decisions			
	Sources of supply	Facility locations	Order quantity allocations	Transportation modes and/or lot-sizes
Supply (section 2.3.1)	x			
	x		x	
	x		x	x
Facility (section 2.3.2)		x		
		x	x	
		x	x	x
Supply chain (section 2.3.3)	x	x	x	
	x	x	x	x

2.3.1 Supply network design

The first type of network design is "Supply Network Design (SND)" which has been a challenging research area for academics and practitioners in supply chain management (Choy et al., 2002, Zamboni et al., 2009). The Decision Support Systems (DSSs) have been developed continuously to support the decision-making process in selecting the (1) sources of supply, (2) sources of supply and allocations, and (3) sources of supply and allocations with transportation modes and/or lot-sizes.

The three DSSs for SND were previously based on different supply chain performance measures (i.e. traditional, environmental, and sustainable performances) as shown in Table 2-3. Firstly, the sources of supply were selected to achieve the desired traditional, environmental, and sustainable performances. Secondly, the sources of supply and allocations supported the achievement of the desired traditional and environmental performances. Thirdly, the sources of supply and allocations with transportation modes and/or lot-sizes were decided based on traditional performance measures. These three DSSs for SND are reviewed in subsections 1 to 3 and discussed based on supply chain performance measures.

Table 2-3 Supply chain performance measures of supply network design

Decision support systems for supply network design	Supply chain performance measures		
	Traditional	**Environmental**	**Sustainable**
Sources of supply (subsection 1)	1.1	1.2	1.3
Sources of supply and allocations (subsection 2)	2.1	2.2	
Sources of supply and allocations with transportation modes and/or lot-sizes (subsection 3)	3		

1) Sources of supply

The sources of supply or supplier selection are part of the long-term plan decision-making included in the DSSs for SND as referred to Table 2-2. They support the selection of the best-fitted suppliers, vendors, and Third Party Logistics (3PL) providers in supply chain networks. Their DSSs have been developed qualitatively to achieve the traditional, environmental, and sustainable performance targets.

1.1) Traditional performances

The DSSs for SND based on the sources of supply have been developed to achieve the desired traditional performances (referred to Table 2-3) since the 1960s. They were previously optimised using qualitative methods which capture and analyse detailed description. Dickson (1966) has surveyed and prioritised twenty-three traditional factors for vendor selection and they are shown in Table 2-4. Although these traditional factors have been adopted widely, their relative priorities have been continuously evolv over time (Weber and Current, 1993). Roa and Kiser (1980) and Bache et al. (1987) further developed multiple criteria identification for supplier selection. Choy et al. (2002) developed an intelligent customer-supplier relationship management system to select potential suppliers and trading partners and eventually form a supply network. Chou and Chang (2008) solved supplier or vendor selection problems by considering the operation management strategy. Kirytopoulos et al. (2008) evaluated and selected the best suppliers in the pharmaceutical industry. Bhattacharya et al. (2010) ranked and selected candidate suppliers within a value chain framework governed by engineering and customer requirements. Azambuja and O'Brien (2012) developed a decision support system to rapidly evaluate and compare engineered equipment supply alternatives in the early project phases.

Table 2-4 *Vendor selection factors*
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1.2) Environmental performances

More recently, the DSSs for traditional SND based on the sources of supply have been developed further by including the environmental performance measures as shown in Table 2-3 due to the growing concern from stakeholders as a result of increases in environmental deterioration, and regulatory requirements. The need to include environmental performance measures has led to the development of DSSs for green SND based on the sources of supply. They were previously optimised using qualitative methods as follows.

Noci (1997) initiated the measurement of environmental performance in supplier selection. Handfield et al. (2002) adopted the Delphi approach to identify environmental impact attributes for supplier selection and determined their relevance, ease of measurement, and importance on organisational strategies. Chen (2005) emphasised the role of International Standardisation Organisation (ISO) 14000 on green purchasing being incorporated into the traditional supplier selection process. Lee et al. (2009b) proposed a green supplier evaluation and a selection model for high-tech industry. Kumar and Bisson (2008) and Tseng and Chiu (2010) developed a unified system based on environmental and non-environmental impact attributes to evaluate and rank alternative suppliers. Ertay et al. (2011) built a multi-criteria decision support system for green supplier selection and clustering. Lee et al. (2011) aimed to select green suppliers and improve their performance in the Taiwanese hand-tool industry. Büyüközkan and Ifi (2012) proposed a supplier evaluation framework including Green Supply Chain Management (GSCM) capability dimensions. Zhou et al. (2012) proposed a supplier selection method for the chemical industry based on the philosophy of GSCM.

1.3) Sustainable performances

The DSSs for green SND based on the sources of supply have been developed further by including the social performance measures as shown in Table 2-3. They aimed to achieve the Triple Bottom Line (TBL) of sustainability which is described as the intersection of economic, environmental, and social elements (Adams et al., 2004, Elkington, 2004). The need to include the TBL of sustainability has led to the development of DSSs for sustainable SND based on the sources of supply and they were previously optimised using qualitative methods.

The TBL of sustainability was emphasised on supplier selection modelling by Bai and Sarkis (2010). Dou and Sarkis (2010) constructed an outsourcing or off-shoring decision model with consideration of facility location, supplier selection, and sustainable attributes. Ho et al. (2011) developed a group-based decision support system for sustainable supplier selection in which all relevant company stakeholders are involved.

It is evident that the previous DSSs for SND based on sources of supply were initially developed to achieve the desired traditional performances. Recently, the attention was paid to environmental performance measures due to the growth of environmental consciousness. To achieve the TBL of sustainability, the previous DSSs for SND based on sources of supply considered the social considerations in addition to the traditional and environmental performance measures. However, the previous DSSs for SND have overlooked the planning decision of order quantity allocations. They are reviewed further in the next subsection.

2) Sources of supply and allocations

The DSSs for SND are based on the two planning decisions that include the sources of supply and order quantity allocations as referred to in Table 2-2. They support the selection of the best-fitted sources of supply and the determination of the optimal order quantity allocations. Their DSSs have been developed to achieve the desired traditional and environmental performances.

2.1) Traditional performances

The DSSs for SND based on the sources of supply and allocations have been developed to achieve target traditional performances as referred to in Table 2-3. They were previously optimised using quantitative and mixed methods. The quantitative methods are applied to capture and analyse numerical data but the mixed methods are applied when qualitative data is included. The quantitative methods adopted by previous studies will be further discussed: Weber et al. (2000) presented an approach to select the best-fitted vendors and allocate the optimal vendor-order quantities aiming to minimise purchasing cost and late and rejected items. Zarandi and Saghiri (2003) and Zarandi et al. (2003) developed a supplier selection process involving the cost and service level. Amid et al. (2006) and Amid et al. (2009) developed a model to allocate the optimal order quantities to the selected supplier achieving the desired cost, quality, delivery, lead time, service level, etc. Narasimhan et al. (2006) proposed a multi-objective model to optimally select suppliers and supplier bids that considers Product Life Cycle (PLC). Their model then, was further developed by incorporating of supply risk (Kull and Talluri, 2008). Wadhwa and Ravindran (2007) modelled vendor selection problems in a multi-sourcing network with consideration of lead time, rejects, and quantity discount-based purchasing cost. Deane et al. (2009) proposed a framework for supplier selection aiming to mitigate global supply chain disruptions and risks.

Osman and Demirli (2010) addressed outsourcing strategies to achieve on-time delivery performance, supplier preference, and purchasing cost minimisation. Ravindran et al. (2010) modelled disruption and quality risks-adjusted supplier selection problems to reduce supplier base and allocate order quantities among them. Wu et al. (2010) proposed a multi-objective model for supplier selection to minimise purchasing cost, rejected items, items delivered late, and risks of economic, environment and supplier service rating. Rezaei and Davoodi (2011) constructed a multi-objective optimisation model for supplier selection with lot-sizing problems based on cost, quality, and service level. Vanteddu et al. (2011) developed a strategic model with regard to supplier selection problems affecting cost and responsiveness as the most significant matrix of order winners. Woo and Saghiri (2011) tackled order assignment to suppliers and 3PL problems under vague decision making to minimise total cost. Zhang and Zhang (2011) addressed supplier selection and purchasing problems under stochastic demand and order size restriction to minimise total cost.

The DSSs for traditional SND based on the sources of supply and allocations have been developed further by including qualitative attributes and have previously been optimised using the mixed methods. Perçin (2006) presented an integrated qualitative and quantitative model for supplier selection and allocations. The qualitative attributes related to traditional performances were measured as a quantitative objective of supplier score or purchasing value. It was combined with other quantitative and traditional performances (i.e. purchasing cost, defect rate, rate of late order delivery, and after-sales service level). Demirtas and Üstün (2008), Ustun and Demirtas (2008), and Demirtas and Üstün (2009) considered tangible and intangible attributes in selecting the best suppliers and determining the optimal order quantities among them aiming to optimise purchasing value, budget and defect rate. Mendoza et al. (2008) solved complicated and risky supplier selection problems to reduce supplier base and optimise order quantity allocations. Their optimisation was based on purchasing value and cost, delivery, quality, flexibility, service and lead time.

Kokangul and Susuz (2009) determined the best suppliers and the optimal order quantities under a constraint of quantity discounts aiming to optimise purchasing value and cost simultaneously. Razmi and Rafiei (2009) addressed supplier selection and allocation problems based on purchasing cost and supplier scores. Kirytopoulos et al. (2010) provided a meta-model for multiple sourcing and order quantity allocations to optimise purchasing value and cost, supplier market share, and delivery time. Mafakheri et al. (2011) proposed a multi-criteria dynamic programming approach for supplier ranking and order quantity allocations aiming to optimise purchasing value and supply chain cost under time-dependent demand and costs.

Araz et al. (2007) developed an integrated qualitative and quantitative model for outsourcer selection and allocations. The qualitative attributes related to traditional performances were measured as relative weights. They were combined with a quantitative function of traditional objectives (i.e. purchasing cost, accepted unit in incoming quality control and unit arriving on-time). Tan et al. (2007) presented a supplier selection and order quantity allocations-based framework based on performance matrix of a supply chain operational reference model. Ting and Cho (2008) took an approach to support identification of candidate suppliers and allocation of the optimal order quantities focusing on purchasing cost, quality and delivery reliability. Wu and Olson (2008) modelled a risk-embedded supplier selection process with a trade-off between expected cost, quality acceptance level and on-time delivery. Lee et al. (2009a) applied an integrated model to select Thin Film Transistor-Liquid Crystal Display (TFT-LCD) suppliers and allocate purchasing orders among them.

Lin (2009) suggested a comprehensive decision method to identify top suppliers and achieve their optimal order quantity allocations. His suggestion is to optimise purchasing value and cost, items delivered late and defective items. Rabbani et al. (2009) presented a new decision making framework for supplier selection and order supply in a make-to-order system focusing on cost, quality and time. Razmi and Rafiei (2009) addressed a problem of supplier selection with order quantity allocations. Their problem was solved aiming to minimise the costs of ordering, purchasing, holding, supplier switching. Ku et al. (2010) determined how to select the best suppliers and order quantities from the selected suppliers based on cost, quality, service, and risk concerns. Liao and Kao (2010) solved a problem of supplier selection and order quantity allocations aiming to optimise quality, price, service satisfaction, delivery time and warranty degree. Amid et al. (2011) found out the appropriate order to each supplier and allowed decision makers to manage cost, quality and service.

2.2) Environmental performances

More recently, the DSSs for traditional SND based on the sources of supply and allocations have been further developed by including the environmental performance measures as referred to in Table 2-3 due to the growing concern from stakeholders as a result of increases in environmental deterioration, and regulatory requirements. The need to include environmental performance measures has led to the development of DSSs for green SND based on the sources of supply and allocations. They were previously optimised by the mixed methods as follows.

Humphreys et al. (2003) measured environmental performances as environmental costs in a supplier selection process. Özgen et al. (2008), Yu and Tsai (2008), and Erol and Ferrell Jr (2009) qualitatively evaluated the potential suppliers based on traditional and environmental performance measures. The potential suppliers were assigned with the optimal order quantities based on quantitative and traditional performance measures. Herrmann and Hauschild (2009) quantitatively evaluated carbon dioxide (CO_2) efficiency ratios of Chinese to European production systems for production outsourcing. Yeh and Chuang (2011) measured qualitative and environmental performances as green appraisal score. It was integrated into a traditional framework of supplier selection. Shaw et al. (2012) presented an integrated approach for supply selection in supply chains. The qualitative attributes related to traditional and environmental performances were measured as relative weights. They were combined with a quantitative function of traditional and environmental objectives including cost, quality, lead time, Green House Gas (GHG) emission and demand.

Evidentially the previous DSSs for SND based on sources of supply and allocations paid much attention to the achievement of desired traditional performances, whereas recent attention was paid in achieving the desired environmental performances. The previous DSSs for SND, however, overlooked the planning decisions of transportation modes and/or lot-sizes. They are reviewed further in the next subsection.

3) Sources of supply and allocations with transportation modes and/or lot-sizes

The DSSs for SND are based on the three planning decisions including the sources of supply, order quantity allocations, and transportation modes and/or lot-sizes can be referred to in Table 2-2. They support the selection of the best-fitted sources of supply, the determination of the optimal order quantity allocations, the choosing of appropriate transportation modes and/or the determination of the optimal transportation lot-sizes. Their DSSs have been developed to achieve the desired traditional performances as referred to in Table 2-3 which were previously optimised using quantitative methods as follows.

Liao and Rittscher (2007a) developed a multi-objective optimisation model to select suppliers, determine procurement lot-size, and select carriers under dynamic demand conditions. The dynamic demand was considered as stochastic in the model of Liao and Rittscher (2007b). Their studies aimed to optimise cost, quality rejection rate, late delivery rate, and flexibility rate. Xu and Nozick (2009) traded-off between cost and risks (geographic dispersion and loss of production capability) to support the selection of suppliers with suitable contract options, and allocations of order quantities with appropriate transportation modes. Bhatnagar et al. (2011) addressed a problem of planning and scheduling decisions in global supply networks with dual supply modes (air and ship) aiming to minimise the total cost.

It is found that the previous DSSs for SND primarily included the decisions of sources of supply and order quantity allocations. On the other hand, the decisions of transportation modes and/or lot-sizes were scarcely included. The previous DSSs for SND based on sources of supply and allocations with transportation modes and/or lot-sizes paid attention only to the achievement of the desired traditional performances, whereas the environmental performances were overlooked. The need to achieve the traditional and environmental performances leads to the development of a unique DSS for SND based on sources of supply and allocations with transportation modes and/or lot-sizes.

2.3.2 Facility network design

The second type of network design is “Facility Network Design (FND)” which has also been a challenging research area for academics and practitioners in supply chain management (Melo et al., 2009, Dong et al., 2010). Similar to the suppler network design in section 2.3.1, Decision Support Systems (DSSs) for FND have been developed continuously to support the decision-making of (1) facility locations, (2) facility locations and allocations and (3) facility locations and allocations with transportation modes and/or lot-sizes.

The three DSSs for FND were previously based on different supply chain performance measures (i.e. traditional, environmental, and sustainable performances) as shown in Table 2-5. Firstly, the facility locations were selected to achieve the desired traditional performances. Secondly, the facility locations and allocations supported the achievement of the desired traditional and environmental performances. Thirdly, the sources of supply and allocations with transportation modes and/or lot-sizes were decided based on traditional and environmental impact performance measures. These three DSSs for SND are reviewed in subsections 1 to 3, and discussed based on supply chain performances.

Table 2-5 Supply chain performance measures of facility network design

Decision support systems for facility network design	Supply chain performance measures		
	Traditional	Environmental	Sustainable
Facility locations (subsection 1)	1		
Facility locations and allocations (subsection 2)	2.1	2.2	
Facility locations and allocations with transportation modes and/or lot-sizes (subsection 3)	3	3	

1) Facility locations

The facility locations are part of the long-term planning decision included in the DSSs for FND as referred to in Table 2-2. They support the selection of the best-fitted locations of manufacturing plants, distribution centres, and warehouses in supply chain networks. Their DSSs have been developed to achieve the desired traditional performances as referred to in Table 2-5. They were previously optimised using qualitative methods which capture and analyse detailed description as follows.

Atthirawong and MacCarthy (2002) proposed a structured model for international location selection using evidence from an empirical study. MacCarthy and Atthirawong (2003) investigated major factors strongly influencing international location decisions as shown in Table 2-6. These major factors included management practice, policy-making of government and other agencies, and previous studies in global operations. Viswanadham and Kameshwaran (2007) developed a generic framework to identify and group multi-criteria for location selection in a global supply chain. Tuzkaya et al. (2008) addressed problems of undesirable facility location selection by trade-offs between benefits, opportunities, costs, and risks. Chou et al. (2008) solved facility location selection problems using objective and subjective attributes under group decision making conditions. Shen and Yu (2009) presented an empirical approach for facility location selection with risks of dynamic product and process change under group decision-making processes.

Table 2-6 *Factors influencing international facility location decisions*
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It is evident that the previous DSSs for FND based on facility locations paid attention only to the achievement of the desired traditional performances, whereas the environmental performances were overlooked. The need to achieve the desired traditional and environmental performances leads to the development of a unique DSS for FND based on facility locations. In addition, the previous DSSs for FND overlooked the planning decision of order quantity allocations. They are reviewed further in the next subsection.

2) Facility locations and allocations

The DSSs for FND are based on the two planning decisions including facility locations and order quantity allocations as referred to in Table 2-2. They support the selection of the best-fitted facility locations and the determination of the optimal order quantity allocations. Their DSSs have been developed to achieve the desired traditional and environmental performances.

2.1) Traditional performances

The DSSs for FND based on the facility locations and allocations have been developed to achieve the desired traditional performances as referred to in Table 2-5. They were previously optimised using quantitative methods. Canel and Khumawala (2001) provided a framework to deal with international facility location problems based on profit maximisation with regard to currency exchange rates. Goh et al. (2007) presented a stochastic model for treating international facility location and distribution logistics planning problems with profit maximisation and risk (supply, demand, exchange, and disruption) minimisation. Amiri et al. (2009) found the least number of distribution centres (DCs) and located them based on optimisation of DCs location, quality and cost. Das and Sengupta (2009) presented an integrated strategic (locations) and operational (allocations) planning model subject to government regulations in an environment of uncertain demand and transportation time. Their model aimed to maximise profit. Ho et al. (2009) applied a deliverer and customer-oriented multi-criteria optimisation model for facility location and allocation problems. Hua et al. (2009) presented a mathematical model to optimise facility locations, capacity acquisition, and production and distribution decisions based on profit maximisation with regard to currency exchange rates over a planning horizon. Sabio et al. (2010) presented a decision support tool to design production and distribution networks in the hydrogen industry for vehicle use under uncertainties in operating costs.

2.2) Environmental performances

More recently, the DSSs for traditional FND based on the facility locations and allocations have been developed further by including the environmental performance measures as referred to in Table 2-5 due to the growing concern from stakeholders as a result of increases in environmental deterioration, and regulatory requirements. The need to include environmental performance measures has led to the development of DSSs for green FND based the facility locations and allocations. They were previously optimised by the quantitative methods as follows.

Hugo and Pistikopoulos (2005) developed a generic optimisation-based model for hydrogen infrastructure design aiming to simultaneously maximise net present value and minimise GHG emission. Hugo et al. (2005) proposed a mathematical programming-based methodology for plant location and capacity expansion problems with the principles of Life Cycle Assessment (LCA). It aimed to maximise net present value and minimise environmental impact. Harris et al. (2009) presented an exploratory study incorporating environmental impact into the operating costs of distribution networks. Guillén-Gosálbez et al. (2010) determined production and distribution network design in the hydrogen industry for vehicle use to minimise cost and environmental impact. Guillén-Gosálbez and Grossmann (2009) and Guillén-Gosálbez and Grossmann (2010) optimised facility network design for the chemical industry to maximise net present value and minimise environmental impact. Elhedhli and Merrick (2012) considered CO_2 emission cost alongside location and production costs for facility network design. Pishvaee and Razmi (2012) proposed a multi-objective optimisation model for facility network design to minimise cost and environmental impact.

Evidentially, the previous DSSs for FND based on facility locations and allocations were initially developed to achieve the desired traditional performances. Their recent attention was paid to environmental performance measures due to the growth of environmental consciousness. The previous DSSs for FND, however, overlooked the planning decisions of transportation modes and/or lot-sizes. They are reviewed further in the next subsection.

3) Facility locations and allocations with transportation modes and/or lot-sizes

The DSSs for FND are based on the three planning decisions including facility locations, order quantity allocations, transportation modes and/or lot-sizes as referred to in Table 2-2. They support the selection of the best-fitted facility locations, the determination of the optimal order quantity allocations, the choosing of appropriate transportation modes and/or the determination of the optimal transportation lot-sizes. Their DSSs have been developed to achieve the desired traditional and environmental performances. These performances were previously optimised using quantitative methods as follows.

Zamboni et al. (2009) developed an optimisation framework to design bio-fuel facility networks concerning GHG emission credits along with operating costs and potential differences in vehicle conversion efficiency and technology. Nagurney and Nagurney (2010) developed a framework for facility network design which determined alternative manufacturing plants, storage facilities, and transportation modes. It aimed to minimise the costs of design or construction, operation, and emission. Pishvaee et al. (2012) proposed a bi-objective (cost and environmental impact) optimisation model for facility network design with consideration of transportation modes and production technologies.

It is found that the previous DSSs for FND primarily included the decisions of facility locations and order quantity allocations, whereas the decisions of transportation modes and/or lot-sizes were scarcely included. They are incapable of designing supply chain networks as a whole which lead to the need for reviewing the previous DSSs for Supply Chain Network Design (SCND) as follows.

2.3.3 Supply chain network design

Supply Chain Network Design (SCND) is an integration of SND and FND in supply chain management. Its Decision Support Systems (DSSs) have been developed continuously to support the decisions of (1) sources of supply, facility locations and allocations, and (2) sources of supply, facility locations and allocations with transportation modes and/or lot-sizes.

The two DSSs for SCND were previously based on different supply chain performance measures (i.e. traditional, environmental, and sustainable performances) as shown in Table 2-7. Firstly, the sources of supply, facility locations and allocations were optimised to achieve the desired traditional, environmental, and sustainable performances. Secondly, the sources of supply, facility locations and allocations with transportation modes and/or lot-sizes supported the achievement of the desired traditional and environmental performances. These two DSSs for SND are reviewed in subsections 1 and 2. They are discussed based on supply chain performances.

Table 2-7 Supply chain performance measures of supply network design

Decision support systems for supply network design	Supply chain performance measures		
	Traditional	**Environmental**	**Sustainable**
Sources of supply, facility locations and allocations (subsection 1)	1.1	1.2	
Sources of supply, facility locations with transportation modes and/or lot-sizes (subsection 2)	2		

1) Sources of supply, facility locations and allocations

The DSSs for SCND are based on the three planning decisions including sources of supply, facility locations and order quantity allocations as referred to in Table 2-2. They support the selection of the best-fitted sources of supply and facility locations, and the determination of the optimal order quantity allocations. Their DSSs have been developed to achieve the desired traditional and environmental performances.

1.1) Traditional performances

The DSSs for SCND based on sources of supply, facility locations and allocations have been developed to achieve the desired traditional performances as referred to in Table 2-7. They were previously optimised using quantitative methods. Elmaraghy and Mahmoudi (2009) developed a decision support model to determine the most economic global supply chain configuration. It considered currency exchange rates at various sites, and the optimal modular product structure. You and Grossmann (2008) addressed optimisation of supply chain design and planning based on responsiveness (lead time) and economic (net present value) objectives in an uncertain demand environment. Laínez et al. (2009) determined the optimal supply chain network structure to achieve the best net present value. Jones et al. (2010) determined the impacts of poor quality by using Six Sigma to evaluate its financial risk which was traded-off with profit and customer satisfaction for supplier selection in supply chain networks.

1.2) Environmental performances

More recently, the DSSs for traditional SCND based on the sources of supply, facility locations and allocations have been further developed by including the environmental performance measuresdue to the growing concern from stakeholders as a result of increases in environmental deterioration, and regulatory requirements. The need to include environmental performance measures has led to the development of DSSs for green SCND based on the sources of supply, facility locations and allocations. They were previously optimised using quantitative methods as follows.

Bojarski et al. (2009) incorporated environmental impact and regulations in a holistic supply chain design and planning whose objectives are to optimise environmental impact and net present value. Reich-Weiser and Dornfeld (2008) proposed a DSS for global SCND aiming to minimise GHG emission. Adhitya et al. (2011) proposed a framework for diaper supply chain decisions such as network configuration, ordering policy, and inventory. They supported minimisation of carbon emission cost along with operating cost known as the carbon-sensitive supply chain design. Harris et al. (2011) took logistics cost and CO_2 emission from transportation having different freight vehicle utilisation ratios into the supply chain structure. Wang et al. (2011) traded-off between costs of operating and environmental investment at a required environmental protection level, and CO_2 emission.

It is evident that the previous DSSs for SCND based on sources of supply, facility locations and allocations were initially developed to achieve traditional performance targets. Their recent attentions were paid to environmental performances due to the growth of environmental consciousness. The previous DSSs for SCND, however, overlooked the decisions of transportation modes and/or lot-sizes. They are reviewed further in the next subsection.

2) Sources of supply, facility locations, and allocations with transportation modes and/or lot-sizes

The DSSs for SCND are based on the four planning decisions including the sources of supply, facility locations, order quantity allocations, transportation modes and/or lot-sizes as referred to in Table 2-2. They support the selection of the best-fitted sources of supply and facility locations, the determination of the optimal order quantity allocations, the choosing of appropriate transportation modes and/or the determination of the optimal transportation lot-sizes. Their DSSs have been developed to achieve the desired traditional performances. They were previously optimised using quantitative methods as follows.

Vidal and Goetschalckx (2001) presented a global supply chain model aiming to maximise after-tax profit by considering the currency exchange rates, border crossing costs and transportation modes. More recently, environmental performance measures have been included in the DSSs for traditional SCND as follows. Chaabane et al. (2010a) and Chaabane et al. (2011) introduced a framework for supply chain design trading-off between GHG emission and costs together with Emission Trading Scheme (ETS). Jaegler and Burlat (2012) provided a realistic decision support system to design the minimised CO_2 supply chains under tuneable variables of manufacturing capability, locations, transportation modes, and product types.

It is found that the previous studies paid much attention to the development of DSSs for SND and FND, whereas little attention was paid to the development of DSSs for SCND as a whole. The previous DSSs for SCND primarily included the decisions of sources of supply, facility locations and order quantity allocations. Otherwise, the decisions of transportation modes and lot-sizes were scarcely included. The four planning decisions which were included in the previous DSSs for SCND supported the achievement of the desired traditional and environmental performances. They are synthesised in the next section (referred to Figure 2-1).

2.4 Performances of supply chain network design

As presented in the previous section, the development of a generic Decision Support System (DSS) for Supply Chain Network Design (SCND) supports the achievement of the desired supply chain performance(s). They can be single or multiple, and traditional and/or environmental which depends on supply chain strategies (Wang et al., 2004). The economic strategy of reducing the cost and lead time are considered as traditional performance measures and the improvement of environmental performances are part of the environmental strategy.

Based on the traditional and environmental performance measures, the previous Decision Support Systems (DSSs) for Supply Chain Network Design (SCND) are synthesised in Table 2-8. It reveals that the DSSs for SCND were initially developed based on economic performance measures (e.g. cost and profit). They were often optimised as a single-objective optimisation (Vidal and Goetschalckx, 2001, Bhatnagar and Teo, 2009, Elmaraghy and Mahmoudi, 2009, Laínez et al., 2009, Perron et al., 2010). The DSSs for economic SCND may, however, worsen other traditional performances (e.g. lead time). The trade-offs between economic and lead time performances were aimed as a bi-objective optimisation (You and Grossmann, 2008).

Table 2-8 Performance measures of supply chain network design

Researches	Number of performances	Traditional performance measures	Environmental performance measures
Vidal and Goetschalckx (2001)	Single	After-tax profit	
Elmaraghy and Mahmoudi (2009)	Single	Total cost	
You and Grossmann (2008)	Multiple	Net present value Lead time	
Bojarski et al. (2009)	Single	Net present value	CO_2 emission trading
Laínez et al. (2009)	Single	Net present value	
Reich-Weiser and Dornfeld (2008)	Single		GHG emission
Chaabane et al. (2010a)	Multiple	Logistics cost	GHG emission trading GHG emission
Jones et al. (2010)	Multiple	Profit Quality	
Perron et al. (2010)	Single	After-tax profit	
Adhitya et al. (2011)	Multiple	Profit	Environmental impact
Chaabane et al. (2011)	Multiple	Total cost	GHG emission trading GHG emission
Harris et al. (2011)	Multiple	Logistics cost	CO_2 emission
Wang et al. (2011)	Multiple	Total cost	Environmental investment CO_2 emission
Abdallah et al. (2012)	Single	Total cost	CO_2 emission cost
Jaegler and Burlat (2012)	Single		CO_2 emission

More recently, the DSSs for traditional SCND have been developed by inclusion of environmental performances. They were often expressed as carbon dioxide (CO_2) emission and Green House Gas (GHG) emission, and minimised as a single-objective optimisation (Reich-Weiser and Dornfeld, 2008, Jaegler and Burlat, 2012). The DSSs for green SCND may, however, have adverse effects on economic performances. As a result, a method of trading-off between environmental and economic performances were aimed for a viable solution (Bojarski et al., 2009, Chaabane et al., 2010a, Adhitya et al., 2011, Chaabane et al., 2011, Harris et al., 2011, Wang et al., 2011, Abdallah et al., 2012). In addition, the DSSs for green and economic SCND may lengthen lead time; however, it was overlooked by the previous studies.

It is evident that a DSS for SCND needs to support the achievement of the desired traditional and environmental performances. The traditional performances such as cost and lead time are in conflict with each other. They also have adverse effects on environmental impact. The tradeoffs between the three performances are needed when a generic DSS for SCND is developed. The three performances are measured as follows.

2.4.1 Environmental impact

The first performance measure of SCND is environmental impact which is incurred by consuming materials and energy, and generating waste and emissions along the product life cycle. It typically undergoes cradle-to-grave stages of raw material extraction, manufacturing, transportation, usage, and disposal (end-of-life). Their environmental impact is assessed using Life Cycle Assessment (LCA) methodology. It follows four phases including goal and scope definition, inventory analysis, impact assessment, and interpretation (Wenzel et al., 1997) as shown in Figure 2-3. Firstly, goal and scope of a product is essentially defined by the unit function of that product. Secondly, the data on inputs (material and energy consumption) are transformed into quantitative environmental burdens or impacts as a function of Life Cycle Inventory (LCI). Thirdly, the LCI results are converted into indicators of environmental impact which can be in units of points or monetary units as a result of a Life Cycle Impact Assessment (LCIA). Fourthly, the life cycle interpretation aims to identify significant end-point issues based on the results of the first three phases to determine the conclusions, limitations, and recommendations.

The four-phase or full LCA methodology was applied for numerous products. They include recycling portable nickel-cadmium batteries (Rydh and Karlström, 2000), egg packaging made of polystyrene (Zabaniotou and Kassidi, 2003), and a photocopy machine of Fuji Xerox (Kerr and Ryan, 2001). However, these full LCA-based applications consumed substantial resources (i.e. expenses and time) for calculating the environmental impact. The consumption of substantial resources is caused by the requirement of detailed data. To significantly reduce the resource consumption, Simplified Life Cycle Assessment (SLCA) methodologies have been developed by Jensen et al. (1997), Todd and Curran (1999), and Manmek et al. (2008).

Figure 2-3 *LCA methodology*
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Manmek et al. (2008) developed the SLCA database through a full LCA analysis of the Eco-Indicator 99 H/A method from the SimaPro 7.0 software. The development of SLCA database aimed to identify major emission substances and impact categories.

They were analysed to produce drivers of single scores for all life cycle stages including material extraction, manufacturing process, usage, transportation and disposal. The usage and transportation stages were specified as groups of energy and vehicle types, whereas the others were based on material types. The produced drivers of single scores ($D_{stage,\,i}$) were used to calculate the indicators (I_{stage}) for each stage of the product life cycle. Their calculations are expressed by equations 1 to 5.

$$I_M = \sum_i \left(W_i \times D_{M,i} \right) \tag{1}$$

$$I_P = \sum_i \left(W_i \times D_{P,i} \right) \tag{2}$$

$$I_U = \sum_i \left(U_i \times D_{U,i} \right) \tag{3}$$

$$I_T = \sum_i \left(km_i \text{ or } tkm_i \times D_{T,i} \right) \tag{4}$$

$$I_D = \sum_i \left(W_i \times D_{D,i} \right) \tag{5}$$

where

stage	Index of the product life cycle stages which are Material (M), Process (P), Usage (U), Transportation (T), and Disposal (D)
I_{stage}	Environmental impact of the product life cycle stage
$D_{stage,\,i}$	Environmental impact driver of the product life cycle stage in the *i*-th group
W_i	Material volume of the *i*-th material group in the unit of kilogram
U_i	Lifetime energy consumption of the *i*-th energy source in the unit of kilogram or mega joule
km_i or tkm_i	Transportation distance of the *i*-th transportation mode in kilometre or ton (carriage weight)-kilometre

In the previous DSSs for SCND, the SLCA methodology was applied to calculate carbon dioxide (CO_2) emission (Harris et al., 2011, Wang et al., 2011, Abdallah et al., 2012, Jaegler and Burlat, 2012), Green House Gas (GHG) emission (Reich-Weiser and

Dornfeld, 2008, Chaabane et al., 2010a, Chaabane et al., 2011), and environmental impact based on Eco-indicator 99 (Pishvaee and Razmi, 2012). These SLCA applications provided results close to those of a full LCA (Manmek et al., 2008). Accordingly, the SLCA-based environmental impact is an appropriate methodology to calculate the environmental performance of SCND at the preliminary design stage.

2.4.2 Lead time

The second performance measure of SCND is lead time defined as *Text has been removed due to Copyright restrictions* (You and Grossmann, 2008). That means lead time can be used to measure supply chain responsiveness. Based on a two-stage supply chain, lead time is counted from when a customer places an order of product or service to a supplier until that customer receives that order (Wangphanich, 2008). This time duration covers preparation within a supply chain stage and transportation between that supply chain stage and its downstream stage as shown in Figure 2-4.

Figure 2-4 *Lead time of two supply chain stages*
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However, supply chain networks are generally featured with more than two stages and multi-layers within each stage (referred to Figure 2-2). At a supply chain stage, lead time is calculated by the longest time among the multi-layers of that stage. This calculation is based on Critical Path Method (CPM) (Walker et al., 2008). Otherwise, the lead time between the supply chain stages are summed (Simchi-Levi et al., 2008). Accordingly, the CPM-based lead time is an appropriate methodology to measure the responsive performance of SCND.

2.4.3 Cost

The third performance measure of SCND is the cost incurred by inbound and outbound logistics activities. These activities include material procurement and product manufacturing (inbound logistics activities), and finished product storage and delivery (outbound logistics activities). The activity of material procurement influences Supply Network Design (SND) as it incurs costs of supply sources" contract (C_1) (Eq. 7) (Razmi and Rafiei, 2009), materials (C_2) (Eq. 8) (You and Grossmann, 2008, Laínez et al., 2009, Razmi and Rafiei, 2009, Jones et al., 2010, Chaabane et al., 2011), material transportation (C_3) (Eq. 9) (Bhatnagar et al., 2011), and material importation (C_4)

(Eq. 10) (Vidal and Goetschalckx, 2001). The cost structure of SND (C_{SND}) (Eq. 6) is expressed as follows.

$$C_{SND} = C_1 + C_2 + C_3 + C_4 \tag{6}$$

$$C_1 = S_i I_i + (1 - S_i)T_i \tag{7}$$

$$C_2 = P_i Q_i \tag{8}$$

$$C_3 = TV_i D_i Q_i + TF_i \left(Q_i \big/ LS_i \right) \tag{9}$$

$$C_4 = ID_i C_2 \tag{10}$$

where

I_i	Costs of initiation to order materials from the *i*-th source of supply e.g. costs of legal contracts, tenders, etc
T_i	Costs of termination to order materials from the *i*-th source of supply
P_i	Material unit price quoted by the *i*-th source of supply
TV_i	Transportation variable cost charged on materials of the *i*-th source of supply
TF_i	Transportation fixed cost charged on materials of the *i*-th source of supply
D_i	Transportation distance of the *i*-th source of supply
ID_i	Custom and duty charged on material importation of the *i*-th source of supply
Q_i	Material order allocation of the *i*-th source of supply
LS_i	Transportation lot-sizes of the *i*-th source of supply
S_i	Binary variables = $\begin{cases} 1, & \text{if the } i\text{-th source of supply is selected} \\ 0, & \text{otherwise} \end{cases}$

The rest of the activities that influence the cost of Facility Network Design (FND) are start-up and shutdown for existing facilities (C_5) (Eq. 12) (Das and Sengupta, 2009, Jones et al., 2010), labour employment (C_6) (Eq. 13) (Elmaraghy and Mahmoudi, 2009, Das and Sengupta, 2009), energy consumption (C_7) (Eq. 14) (Zhou et al., 2000), inventory holding (C_8) (Eq. 15) (Perron et al., 2010, Bhatnagar et al., 2011), product transportation (C_9) (Eq. 16) (Bhatnagar et al., 2011), and product importation (C_{10}) (Eq. 17) (Vidal and Goetschalckx, 2001). The cost structure of FND (C_{FND}) (Eq. 11) is expressed as follows.

$$C_{FND} = C_5 + C_6 + C_7 + C_8 + C_9 + C_{10} \tag{11}$$

$$C_5 = F_j I_j + (1 - F_j) T_j \tag{12}$$

$$C_6 = L_j W_j \tag{13}$$

$$C_7 = E_j \left(Q_j / LS_j \right) \tag{14}$$

$$C_8 = SS_j \times P_j \times H_j \tag{15}$$

$$C_9 = TV_j D_j Q_j + TF_j \left(Q_j / LS_j \right) \tag{16}$$

$$C_{10} = ID_j (P_j Q_j) \tag{17}$$

where

I_j	Costs of starting-up the *j*-th existing facility location to produce products e.g. labour cost, waste incurs, etc at one time
T_j	Costs of keeping the *j*-th existing facility location that are not operating but being kept for the future operation e.g. fixed costs for having the existing manufacturing plants, depreciation, expenses for permanent labour, etc.
L_j	Wage rate for product operation at the *j*-th facility location
W_j	Working time for product operation at the *j*-th facility location
E_j	Energy price for product operation at the *j*-th facility location
SS_j	Safety stock at the *j*-th facility location which is calculated as follows. $Z \times SD \times \sqrt{LT^e{}_j}$ (Simchi-Levi et al, 2008) where: Z is service factor refering to the service level (probability of not stocking out during lead time) SD is standard deviation of (aggregate) demand $LT^e{}_j$ is echelon lead time at the *j*-th facility location

P_j	Product unit price quoted by the *j*-th facility location
H_j	Inventory holding cost for product storage and maintenance at the *j*-th facility location as a percentage of product unit price
TV_j	Transportation unit cost charged on products of the *j*-th facility location
TF_j	Transportation fixed cost charged on products of the *j*-th facility location
D_j	Transportation distance of the *j*-th facility location
ID_j	Custom and duty charged on product importation of the *j*-th facility location
Q_j	Product order allocation to the *j*-th facility location
LS_j	Transportation lot-sizes of the *j*-th facility location
F_j	Binary variables = $\begin{cases} 1, & \text{if the } j\text{-th facility location is selected} \\ 0, & \text{otherwise} \end{cases}$

All of the cost elements of SND and FND are converted into a single currency and are integrated as an appropriate methodology to measure the economic performance of SCND (Vidal and Goetschalckx, 2001, Goh et al., 2007, Elmaraghy and Mahmoudi, 2009, Das and Sengupta, 2009, Perron et al., 2010).

In summary the performances of cost, lead time and environmental impact are measured by the cost elements of SND and FND, CPM-based lead time and SLCA-based environmental impact respectively. These measurements are developed dynamically by including the time-dependent parameters. They are hence reviewed and discussed in the next section (referred to Figure 2-1).

2.5 Time-dependent parameters

As presented in the previous section, the development of a generic Decision Support System (DSS) for Supply Chain Network Design (SCND) requires considering the time-dependent parameters. They significantly influence the achievement of desired cost, lead time and environmental impact, along with the long-term plan decisions. The time-dependent parameters can be internal and external. The internal parameters are based on organisational policies (i.e. product volume and energy consumption) while the external parameters are influenced by government policies and economy (i.e. energy and fuel prices, wage rate, and currency exchange rate).

2.5.1 Product volume

The first time-dependent parameter of SCND is product volume (sales). It changes over time due to the growth of the product life cycle (PLC) in the market as shown in Figure 2-5. The PLC positioning is influenced by organisational policies (You and Grossmann, 2008, Adhitya et al., 2011). If a product is positioned in the stages of market introduction and maturity, its volume is slowly increased. In contrast, the volume of a product significantly increases and declines when that product is positioned in the stages of growth and decline, respectively.

Figure 2-5 *Product life cycle in the market*
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The growth of product volume consumes more resources (i.e. materials, energy, fuel, and labour-forces) and leads to increases cost and environmental impact. In addition, the growth of product volume may cause larger product lot-sizes and less frequent roundtrips. The larger product lot-sizes lengthen the lead time which increases safety stocks and inventory holding cost, whereas the less frequent roundtrips reduce transportation fixed cost. Accordingly, the change of product volume significantly influences the achievement of the desired cost, lead time, and environmental impact.

2.5.2 Energy consumption and price

The second time-dependent parameter of SCND is energy consumption of activites along the supply chain. The energy consumption is interrelated to energy price and economic growth, and vice versa (Lee and Lee, 2010). The growth of product volume increases energy consumption and then increases energy price. The increased energy price incurs higher costs of energy and transportation. The higher costs in turn leads to the need to improve the energy consumption (Popp, 2001) and one of the ways this can be achieved is through technological development (Veerapaneni et al., 2007). The improvement in energy consumption contributes to lower-cost energy and better environmental impact performance.

The energy consumption, energy price and the rates of change are different for each location. They may cause changes in sources of supply and facility locations to where more efficient forms of energy at lower price is available. The supply chain reconfiguration has effects on geographical distance and other time-dependent parameters (i.e. product volume, wage rate, and currency exchange rate). Accordingly, the changes in energy consumption and price significantly influence the achievement of desired cost, lead time, and environmental impact.

2.5.3 Wage rate

The third time-dependent parameter of SCND is wage rate. It is defined as *Text has been removed due to Copyright restrictions* (International Labour Organization, 2011). The wage rate grows when larger labour-forces are required. The wage rate and its growth rate are different for each location (MacCarthy and Atthirawong, 2003). They may cause changes in sources of supply and facility locations to where lower wage rates are offered. The supply chain reconfiguration has effects on geographical distance and other time-dependent parameters (i.e. product volume, energy consumption and price, and currency exchange rate). Accordingly, the change in wage rate significantly influences the achievement of cost, lead time, and environmental impact.

2.5.4 Currency exchange rate

The fourth time-dependent parameter of SCND is currency exchange rate. It is defined as *Text has been removed due to Copyright restrictions* (OANDA, 2011). The cost of supply chain is strongly sensitive to currency exchange rate when an organisation is involved in global logistics (Canel and Khumawala, 2001, Elmaraghy and Mahmoudi, 2009, Hua et al., 2009). Each location has an individual currency exchange rate and its depreciation rate. They may cause changes in the sources of supply and facility locations where a stronger currency exchange rate and a slower rate of currency depreciation are offered. The supply chain reconfiguration has effects on geographical distance and other time-dependent parameters (i.e. product volumes, energy consumption and price, and wage rate). Accordingly, the change of currency exchange rate significantly influences the achievement of the desired cost, lead time, and environmental impact.

In summary the changes in product volume, energy consumption and price, labour cost and currency exchange rate significantly influence the achievement of the desired cost, lead-time, and environmental impact. It involves the long-term planning decisions which are souces of supply and facility locations.

According to sections 2.2 to 2.5, the DSS for SCND is characterised as a multivariable, multi-objective, complex and dynamic problem. It needs optimisation approaches to find the optimal solution, and simulation techniques to overcome complex and dynamic behaviour. The simulation-optimisation approach is hence reviewed and discussed in the next section (referred to Figure 2-1).

2.6 Simulation optimisation

The Decision Support System (DSS) for Supply Chain Network Design (SCND) is characterised as a multivariable, multi-objective, complex and dynamic problem. It needs optimisation approaches to find the optimal solution, and simulation techniques to overcome complex and dynamic behaviour. The integrated approach of simulation and optimisation (simulation optimisation) is hence capable of finding the optimal solution among all possible decision variables (fine-grained decisions) in a single run (automated algorithm).

The simulation optimisation approach as shown in Figure 2-6 is an integration of simulation model and optimisation strategy (Dangerfield and Roberts, 1996, Fu, 2001, Ólafsson and Kim, 2001). An optimisation strategy uses an output of a simulation model for providing feedback on progress and searching an optimal solution. It is subsequently input into the simulation model in order to provide a new output. This algorithm is iterated until the global optimum is found (Carson and Maria, 1997). The iterative algorithm of simulation optimisation contributes to minimisation of resource consumption in the automated optimisation and maximisation of information obtained in the simulation experiments (Carson and Maria, 1997, Hachicha et al., 2010).

Figure 2-6 *Iterative algorithm of simulation optimisation*
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In the last decade, the iterative algorithm of simulation optimisation has been developed in commercial simulation software. It integrates with an optimisation strategy as an add-on. A genetic algorithm is integrated into ProModel and AutoMod, whereas

SIMUL8, Arena and Crystal Ball are added-on by neural networks (Fu, 2002). The Powell algorithm is an add-on of Vensim software (Marquez, 2010). Obviously, numerous strategies of optimisation and several simulation techniques are provided. They have specific advantages and disadvantages and thus, the selections of optimisation strategies and simulation technique based on problem characteristics are needed. Accordingly, optimisation strategies and simulation techniques related to the multivariable, multi-objective, complex and dynamic problem are reviewed and discussed in sections 2.6.1 to 2.6.3.

2.6.1 Multivariable optimisation

As presented in the section 2.3, the development of a generic DSS for SCND requires considering several planning decisions (multivariable). They include sources of supply, facility locations, order quantity allocations, transportation modes and lot-sizes. The need to optimise the multivariable problem leads to the need to review the approaches related to the multivariable optimisation. They can be classified into direct search, gradient-based, and evolutionary approaches (Deb, 2004).

The direct search approach uses functional values at different points, whereas the gradient-based approach requires derivative information to constitute a search. The derivative algorithm is capable of representing more real-world perspectives, so the gradient-based approach may be more efficient but a more intelligent software package is required. In contrast to the traditional (direct search and gradient-based) approaches, the evolutionary approach intelligently searches solutions based on the mechanism of biological evolution and the Darwin theory of survival-of-the-fittest (Holland, 1975, Goldberg, 1989). They require no functional and gradient information and protect against quick convergence to the local optimum (Hsiao et al., 2001); however, dynamic data and messy algorithm cannot be operated and encoded. Accordingly, the direct search approach is considered as useful (Deb, 2004) which includes several algorithms as follows.

1) Evolutionary optimisation algorithm

Developed by G.E.P. Box (1957), the evolutionary optimisation algorithm forms an N-dimensional hypercube which requires (2N + 1) points. Their function values are compared and identified as the best point. In the next iteration, another hypercube whose size is smaller than the previous one is formed around the best point. This algorithm is iterated until the hypercube becomes very small, so it consumes substantial time and cost of computation.

2) Simplex search algorithm

The simplex search algorithm requires N + 1 points aiming to find the best point and then replace the worst point. That direction is iteratively expanded until the better point is no longer found. This iterative algorithm rescales the simplex which tends to wander about the global optimum when the simplex is larger.

3) Hook-Jeeves algorithm

The Hook-Jeeves algorithm iteratively forms at least N search directions (exploratory moves) and performs heuristic pattern moves. An exploratory move systematically searches the best point around the current point. Such two points are used to create a heuristic pattern move. This iterative algorithm, however, tends to degenerate the global optimum when exploratory moves are numerous.

4) Powell algorithm

The Powell algorithm iteratively forms a set of N search directions and performs a series of unidirectional searches along each search direction. A search direction starts from the previous best point which is replaced by the better point in the adjacent space. This iterative algorithm in the adjacent space may, however, cause dead ends and provide the local optimum. To avoid the dead ends, multiple optimisation trials are performed with different starting points and compared in order to find the global optimum (Russell and Norvig, 2003). It is guaranteed to find the global optimum with one or more passes of N unidirectional searches for an N-dimensional problem (Deb, 2004).

In summary, the Powell algorithm with multiple starting points is the most suitable for the development of a generic DSS for SCND based on the multivariable optimisation. It guarantees the convergence to the global optimum. Other algorithms consume substantial time and cost of computation (Evolutionary optimisation algorithm), tendency to wander about the global optimum (Simplex search algorithm), and tendency to degenerate the global optimum (Hook-Jeeves algorithm) when the problem size is large.

2.6.2 Multi-objective optimisation

As presented in the section 2.4, the development of a generic DSS for SCND supports the achievement of the desired supply chain performances (multi-objective) including cost, lead time, and environmental impact. They are in conflict with each other when simultenously optimised as follows. Firstly, global sourcing may gain tariff and trade concessions and lower-cost materials, however, geographical distances cause longer lead time, and higher environmental impact (Meixell and Gargeya, 2005). This implies that the cost objective has a conflict with the lead time and environmental impact objectives. Secondly, transportation modes with faster speeds (i.e. air mode) provide a shorter lead time, but freight rates are higher and more fuel is consumed than with slower transport (i.e. sea mode) (Boonsothonsatit et al., 2012). This implies that the lead time objective is in conflict with the cost and environmental impact objectives. Thirdly, more frequent roundtrips, which are determined by smaller lot-sizes, contribute to shortening of lead time and reduction of inventory holding cost. However, smaller lot-sizes increase transportation cost. This implies that the inventory holding cost has a conflict with the transportation cost. Consequently, the need to trade-off the three conflicting objectives leads to the review of approaches related to the multi-objective optimisation as follows.

1) Qualitative approaches

The trade-offs between multiple conflicting objectives (criteria) involving qualitative decisions can be achieved through pair-wise comparisons relying on the subjective judgement of decision makers. The achievement of Pareto optimality can be produced by several approaches as follows. Analytic Hierarchy Process (AHP) is an approach to measure multiple conflicting criteria in a hierarchy in a one direction. The AHP approach consists of four elements which are a goal, a number of criteria related to the goal, a number of sub-criteria related to the criteria, and a number of alternatives (Saaty, 1977) as shown in Figure 2-7a. On the other hand, the interdependence and feedbacks among the elements are measured applying an approach of Analytic Network Process (ANP) (Saaty, 1996) as shown in Figure 2-7b. The ANP approach is capable of handling intricate systems and performing pair-wise comparisons more accurately (Taslikali et al., 2006); however, the pair-wise comparisons are vague which relies on the subjective judgement of decision makers.

To address the vagueness of pair-wise comparisons, Fuzzy Set Theory (FST) (Zadeh, 1965) is integrated into the ANP approach. The so-called Fuzzy Analytic Network Process (FANP) approach, however, confronts difficulties in determining the interdependency and feedback among the elements and performing a higher number of the pair-wise comparisons. These difficulties may cause a misleading final solution (Yu and Tzeng, 2006). Accordingly, the qualitative approaches are not suitable for optimising the multi-objective DSS for SCND. Its quantitative approaches are reviewed in the next subsection.

Figure 2-7 *Structural difference between AHP and ANP has been removed due to Copyright restrictions*

2) Quantitative approaches

The trade-offs between multiple conflicting objectives involving quantitative decisions can be achieved through Pareto optimality. It aims to improve at least one objective without causing deterioration of other objectives. The achievement of Pareto optimality can be produced by no-preference, priori, posteriori, and interactive approaches (Rangaiah, 2008). The priori approach is capable of providing one Pareto-optimal solution. It is consistent with the given preferences, and consuming lower computational effort and time. Other approaches equally emphasise multi-objectives (no preference methods), do not guarantee the convergence to the global optimum (posteriori methods), and become impractical due to continual preference requirement from decision makers (interactive methods). Accordingly, the priori approach is considered as efficient (Miettinen, 2004).

The priori approach includes several techniques which are weighted-sum, lexicographic ordering, and goal programming (Rangaiah, 2008, Andersson, 2011). The goal programming is capable of providing the optimal solution close to target values of objectives (goals). Other techniques confront vagueness of relation between objective weighting and obtained solution (weighted-sum), and may not consider all objectives (lexicographic ordering). Accordingly, the goal programming is considered as efficient which includes several variants (Masud and Ravindran, 2008) as follows.

2.1) Weighted goal programming

The weighted (non-pre-emptive) goal programming utilises the weighted-sum technique in the goal programming. It requires relative objective weighting from decision makers. The given weights are conducted to formulate a weighted summation of undesired deviations from goals. The weights can be changed when a solution is not impacted. The changes of weights continue until a better solution is yielded. The weighted goal programming may, therefore, provide very poor value in one or more goals.

2.2) Lexicographic goal programming

The Lexicographic (pre-emptive) goal programming utilises the lexicographic ordering technique in the goal programming. It requires goal prioritising from decision makers. The undesired deviations from the foremost goal are minimised to generate a set of solutions. They are then searched to find a subset optimising the undesired deviation from the lower-priority objective. The solution is final when a single point remains, so not all goals may be considered. The lexicographic goal programming is, therefore, not appropriate for every multi-objective problem (Tamiz et al., 1995).

2.3) Chebyshev goal programming

Introduced by Flavell (1976), the Chebyshev (min-max) goal programming aims to minimise the maximum weighted deviation from any goal. It contributes to good balance between the achievements of the set of solutions of weighted and lexicographic variants. The Chebyshev goal programming may, therefore, generate near-optimal solutions (Tamiz et al., 1995).

2.4) Fuzzy goal programming

The Fuzzy Goal Programming (FGP) utilises Fuzzy Set Theory (FST) (Zadeh, 1965) in the weighted goal programming (Tiwari et al., 1987) aiming to address the vagueness in target values of the objectives (goals). It conducts an operator (e.g. max-min, weighted additive and weighted max-min) to detect non-Pareto optimal solutions and then restore Pareto optimal solutions. Zimmermann (1978) introduced a max-min operator to acquire the Pareto optimal solutions. The max-min operator places the same importance on each goal. Tiwari et al. (1987) developed a weighted additive operator to give a different emphasis to each goal, however, the Pareto-optimal solution is inconsistent with the relative objective weights (Chen and Tsai, 2001, Amid et al., 2006). To achieve consistency, Lin (2004) proposed a weighted max-min operator.

In summary, the FGP with a weighted max-min operator is the most suitable method for the development of a generic DSS for SCND based on the multivariable optimisation. It is capable of providing one Pareto-optimal solution which is consistent with the relative objective weights and close to non-vague target values of the objectives. In addition, lower computational effort and time are needed. Other variants of goal programming may not consider all goals (Lexicographic goal programming), and do not guarantee the convergence to the global optimum (Chebyshev goal programming).

2.6.3 System dynamics

As presented in the sections 2.2 and 2.5, the development of a generic DSS for SCND is considered as complex and dynamic. It includes multiple stages, multiple layers within each stage, multiple commodities, multiple periods of time, and time-dependent parameters. The need to overcome the complex and dynamic behaviour leads to the review of approaches related to System Dynamics (SD).

Conventionally, SD is an approach of systematic simulation aiming to analysis a holistic system over the passage of time (Kleijenen, 2005) through a set of simulation experiments (what-if). The conventional SD is widely applied for strategic analyses and initial approximation (Kellner et al., 1999) such as bullwhip effects (Disney and Towill, 2003), strategic management of spare parts in closed-loop supply chains (Spengler and Schröter, 2003), distribution chain modelling (Ashayeri et al., 1998), supply chain modelling (Higuchi and Troutt, 2004), prediction of energy consumption and carbon dioxide (CO_2) emission (Feng et al., 2012, Wu and Xu, 2013), transportation structure planning (Xu et al., 2012), and other applications (Tako and Robinson (2012).

The conventional SD can integrate an optimisation strategy as SD optimisation. It aims to find the optimal solution among all possible decision variables in a single run. The SD optimisation was previously applied for policy design of a project model (Keloharju and Wolstenholme (1986) and policy design of an irrigation system (Elmahdi et al., 2005).

Accordingly, the SD optimisation is the most suitable for the development of a generic DSS for SCND which includes the long-term plan decisions involving continuous changes of state (dynamic). To develop the DSS for SCND based on the SD optimisation, the following basic structure and process of system dynamics modelling are understood as follows.

1) Basic structure

Basically, system dynamics modelling is structured by following the framework of Forrester (1961). It captures the level, flow rate, delay, and information feedback as shown in Figure 2-8. The level and flow rate are used to process resources between states in a system. The resources can be tangible (e.g. materials, personnel, capital equipment, orders, money, etc.) and intangible (e.g. goodwill, brand recognition, etc.). They are accumulated and functioned as the level (state, stock, or accumulation). The level is controlled by the flow rate to increase or decrease the level and it is determined by the rate equation. The determination of rate equation also involves the delay and information feedback. The information feedback is transmitted by the level to the flow rate for future decisions. The so-called feedback loop is iterated aiming to regenerate new decisions. The resources and information cannot be, however, processed and transmitted instantaneously (Pidd, 2003), so the delay is needed in the feedback loop.

Figure 2-8 *Basic structure of system dynamics modelling*
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2) Basic process

The development of system dynamics model undergoes qualitative and quantitative processes (Wangphanich, 2008) as shown in Figure 2-9. The qualitative process covers system understanding and conceptualisation, whereas the quantitative process undergoes system formulation, verification, and validation as follows.

Figure 2-9 *Basic process of system dynamic modelling*
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2.1) System understanding

Understanding of a system is first needed to define its goals and scope. The system scope encompasses specific entities, input parameters, decision variables, constraints, and outputs (system elements) with each of them interacting together to achieve the system goals.

2.2) System conceptualisation

The system elements, which were defined in the step of system understanding, are linked as interrelations of causes and their effects. The so-called causal loop diagrams describe the system graphically and mathematically, as well as providing feedback information.

2.3) System formulation

The causal loop diagrams, which were formed in the step of system conceptualisation, are formulated into mathematical equations. They are configured into a system dynamics software such as Vensim (Ventana, 2012) through the basic structure of system dynamics modelling (i.e. levels, flow rates, delay, and information feedback).

2.4) System verification

The system, which was formulated and configured in the step of system formulation, needs to be verified. The system verification is to ensure that the system elements (i.e. input parameters, decision variables, and constraints) are converted into the system outputs with sufficient accuracy. Proof of correctness is considered the most effective technique for system verification (Whitner and Balci, 1989) and it aims to thoroughly check the mathematical equations. In the case where the configured system is unverified, the system conceptualisation and formulation need to be revised and corrected.

2.5) System validation

The verified system is validated as the last step of system dynamics modelling. The system validation is performed through industrial case studies with formal tests (Barlas. 1996) as follows. Firstly, structure confirmation test aims to qualitatively compare the mathematical equations to the causal loop diagrams. Secondly, parameter confirmation test is performed to numerically and conceptually evaluate the constant parameters against knowledge of the real system. Thirdly, extreme-condition test is peformed to assess the system outputs against knowledge of the real system when extreme values are assigned to the input variables. Fourthly, dimensional consistency test is performed to ensure that the right-hand side and left-hand side of each equation are consistent. Fifthly, behaviour sensitivity test is performed to investigate the effects on the corresponding results when their parameters are fed to the system with different values (Myers, 1979, Howden, 1980, Hekimoglu and Barlas, 2010). In addition to the formal tests, the optimal outputs and decisions (results) are compared against the knowledge of the real system. The completion of formal tests with comparable results leads to a successful validation.

2.7 Research needs

According to the literature review, the development of a generic Decision Support System (DSS) for Supply Chain Network Design (SCND) is one of the most challenging research areas in Supply Chain Management (SCM) that needs further development. It involves basic features, decision variables, performances and time-dependent parameters. Their findings lead to the research needs as follows.

The DSS for SCND is generally featured with at least four stages including suppliers, manufacturing plants, distribution centres or warehouses, and customers. The individual stages have multiple layers for making, storing and delivering multiple commodities with various transportation modes under a dynamic behaviour. The finding of these basic features indicates the complexity in the development of a generic DSS for SCND which includes several planning decisions. The planning decisions related to SCND include the sources of supply, facility locations and order quantity allocations. However, the planning decisions in selecting the transportation modes and lot-sizes have scarcely been included. These planning decisions support the achievement of desired traditional (i.e. cost and lead time) and environmental performances. In addition, the factors are in conflict with each other and the trade-off decision-making between the cost, lead-time and environmental impact have been overlooked.

The cost performance is measured by the cost elements of Supply Network Design (SND) and Facility Network Design (FND), while the lead time performance is determined by Critical Path Method (CPM)-based lead-time. The measurement of environmental impact is based on Simplified Life Cycle Assessment (SLCA). These performance measurements are developed dynamically by including time-dependent parameters. They are product volume, energy consumption and price, labour cost, and currency exchange rate and any changes in these parameters significantly influence the achievement of desired cost, lead-time, and environmental impact. It involves the long-term plandecisions which are the sources of supply and facility locations.

Accordingly the DSS for SCND is characterised as a multivariable, multi-objective, complex and dynamic problem. It needs optimisation approaches to find the optimal solution, and simulation techniques to overcome complex and dynamic behaviour. The Powell algorithm with multiple starting points is used for the multivariable optimisation. The Fuzzy Goal Programming (FGP) with a weighted max-min is conducted to optimise the multi-objectives. The complex and dynamic behaviours are overcome by applying the System Dynamics (SD).

CHAPTER 3

RESEARCH METHODOLOGY

The literature review in chapter 2 highlighted the research needs in Supply Chain Management. They were the development of a generic Decision Support System (DSS) for Supply Chain Network Design (SCND)which supports achieving the desired cost, lead-time and environmental impact, and suggestting the best-fitted sources of supply and facility locations, the optimal order quantity allocations, and the appropriate transportation modes and lot-sizes. The need for further research as outlined above has led to the development of research methodology framework as presented in Figure 3-1. It undergoes the following six steps as follows.

Firstly, the methodology framework identifies the research problem in the proposed system which is dictated by the system elements (i.e. entities, input parameters, constraints, decision variables, and outputs). They are conceptualised into causal loop diagrams in the second step. Thirdly, the causal loop diagrams are formulated into mathematical equations and then configured into a system dynamics model in Vensim version 5.4d software in the fourth step. The configured system is verified in the fifth step before being validated with industrial cases in the sixth and final step.

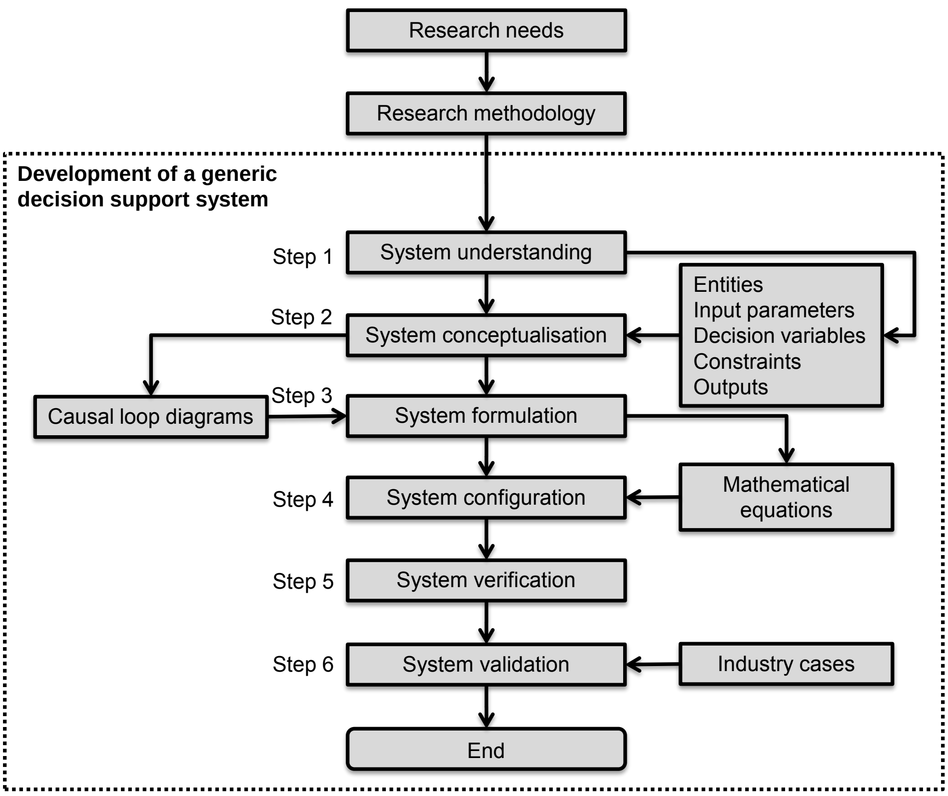


Figure 3-1 Research methodology framework

3.1 System understanding

To understand the proposed system, its architecture is presented in Figure 3-2 and it is an integrated design of supply and facility networks. The integrated design cover eight entities which are (1) suppliers, (2) manufacturing plants (MPs), (3) distribution centres or warehouses (DCs), (4) customers, (5) products, (6) components, (7) materials, and (8) transportation modes. The entities of suppliers, MPs, DCs, and customers are stationary while the rest of the entities move from one stationary entity to another one (the so-called material flows). The eight entities are configured into nine generic modules which include (1) product demand, (2) product manufacturing and warehousing, (3) product distribution, (4) component demand, (5) component manufacturing and warehousing, (6) component distribution, (7) material demand, (8) material procurement, and (9) material distribution modules.

The product demand module gets information on product volume (from customers) in order to decide locations and allocations of product MPs and product DCs, transportation modes and lot-sizes, along with rates of change of product volume, energy consumption, currency depreciation, energy and fuel prices and labour cost. These decisions give feedbacks on the modules of product manufacturing, warehousing, and product distribution. The feedback on the product manufacturing and warehousing modules are costs of energy, labour, inventory holding, and importation, preparation time, and environmental impact of energy consumption. The feedbacks on the product distribution module are transportation cost, time, and environmental impact. These two feedbacks lead to the need to review the decisions in achieving minimisation of cost, lead time, and environmental impact in the product demand module. The located product MPs and product DCs release component and material volumes to the modules of component demand and material demand. They have a similar mechanism to the product demand module. The component demand module supports the decisions of locations and allocations of component MPs and component DCs, transportation modes and lot-sizes. The material demand module supports the decisions of sources of supply, material order allocations, transportation modes and lot-sizes. These decisions give feedbacks related to supply chain cost, lead time, and environmental impact. The three objectives are achieved by decision-making process based on feedbacks.

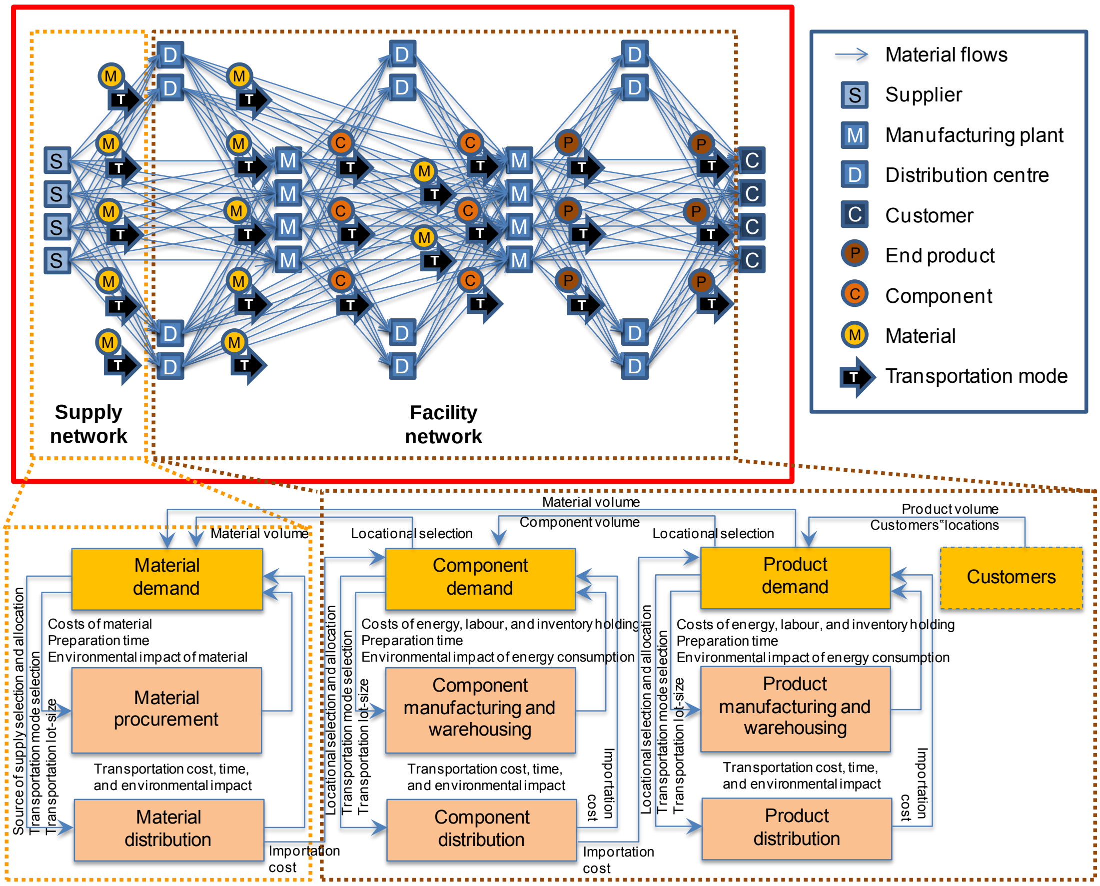


Figure 3-2 Architecture of the proposed system

The modules of material demand, material procurement and warehousing, and material distribution enable the proposed system to support Supply Network Design (SND), while the rest of the modules support Facility Network Design (FND). The nine generic modules interact to achieve minimisation of cost, lead time, and environmental impact (multi-objectives). Each of the modules is developed in the next step (the second step of the development of generic DSS), namely system conceptualisation.

3.2 System conceptualisation

The nine generic modules are developed into causal loop diagrams from conceptualisation of their individual sets of input parameters (I), constraints (C), decision variables (D), and outputs (O). The contents of I, C, D, and O elements are linked extensively to develop twenty-four causal loop diagrams as shown in Figures 3-3 to 3-26. The orange, red, blue, and pink fonts are depicted as I, C, D, O and O respectively. The blocks represent stocks whose levels are mechanised by flows and controlled by connectors. For example, the product volume (stock) increases when a change of product volume is growing (connector). This mechanism changes the level of product volume (flow) as shown in Figure 3-3. The arrows between elements are signified by the plus sign (+) when the causes reinforce their effects while the minus sign (-) indicates that the causes contradict their effects.

3.2.1 Product demand module

The product demand module aims to decide locations and allocations of product manufacturing plants (product MPs) and product distribution centres (product DCs), along with their transportation modes and lot-sizes. Product MPs manufacture products to satisfy either customers (Figure 3-3) or product DCs (Figure 3-5), while product DCs warehouse manufactured products to satisfy customers (Figure 3-4).

If product MP$\rightarrow$customer is selected, product MPs manufacture products to satisfy customers as shown in Figure 3-3. The location of product MPs are selected (locational selection of product MP) with product volume allocated with an integer value according to the amount ordered by customers (product order allocation: customer$\rightarrow$product MP). The integer product volume is annually increased by its growth rate (+), so product orders are increased (+). Subsequently, transportation modes are selected (mode selection: product MP$\rightarrow$customer) based on feasbilitiy of (either global or local) locations, infrastructures, and product sizes. The selected transportation modes are utilised to distribute the increased product orders from the selected product MPs to customers (product order distribution: product MP$\rightarrow$customer) (+). The product order distributions indicate whether product MPs are closed (shutdown of product MP) or opened (start-up of product MP). The shutdown (valued by 0) and start-up (valued by 1) of product MPs are represented by (0/1) binary variables (binary variable for locational selection of product MP). If the product order distributions are increased, the start-up of product MPs is expanded (+). Otherwise, the shutdown of product MPs is contracted (-). The frequent change of product MP locations increases the costs of shutdown (to keep the existing ones for the future operation e.g. fixed cost, permanent labour cost, depreciation, etc.) (+), and start-up (e.g. labour cost, waste incurs, etc.) (+). These costs (locational selection cost of product MP) are also proportionally influenced by currency depreciation of product MPs (+). After that, integer transportation lot-sizes (integer lot-size: product MP$\rightarrow$customer) are determined to indicate the integer number of roundtrips needed (integer number of roundtrip: product MP$\rightarrow$customer). They are less frequent when the integer lot-sizes are larger (-) and the product order distributions are smaller (+). However, the integer lot-sizes are not more than the product order distributions. To assure full service level (service level: product MP→customer), the value of multiplication of integer roundtrips (+) and integer lot-sizes (+) (total product order distribution: product MP→customer) is no less than integer product volume (-). This mechanism is similar to the two other sub-modules as shown in Figures 3-4 and 3-5.

The product demand module: product MP→customer eventually returns five outputs. They are (1) product order distribution: product MP→customer, (2) integer lot-size: product MP→customer, (3) integer number of roundtrips: product MP→customer, (4) service level: product MP→customer, and (5) locational selection cost of product MP. The first three outputs are used for other related modules, while the rest of the outputs can be optimised as follows. The service level is full (100%) when the located product MPs are capable of fully satisfying the product orders to customers. The locational selection cost of product MPs can be minimised when product MP locations are similar to those in the previous period. If product MP locations are unchanged, they do not incur the shutdown and start-up costs involved.

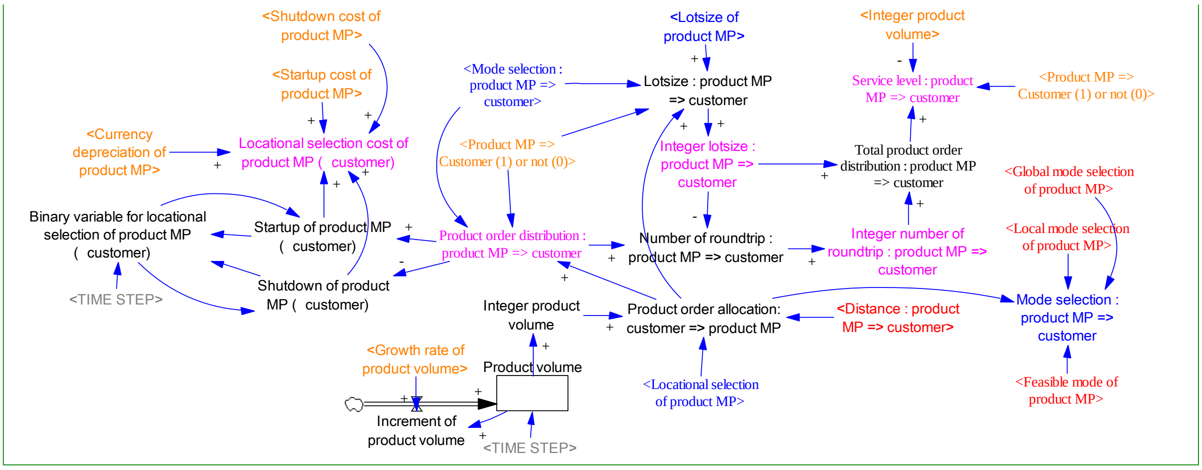


Figure 3-3 Product demand module: product MP→customer

In Figure 3-4, the product demand module: product DC→customer returns four outputs. They include (1) product order distribution: product DC→customer, (2) integer lot-size: product DC→customer, (3) integer number of roundtrips: product DC→ customer, (4) service level: product DC→customer, and (5) locational selection cost of product DC. They are further used for other related modules. The first three outputs are used for other related modules, while the rest of the outputs can be optimised as follows. The service level is full (100%) when the located product DCs are capable of fully satisfying the product orders to customers. The locational selection cost of product DCs can be minimised when product DC locations are similar to those in the previous period. If product DC locations are unchanged, they do not incur the shutdown and start-up costs involved.

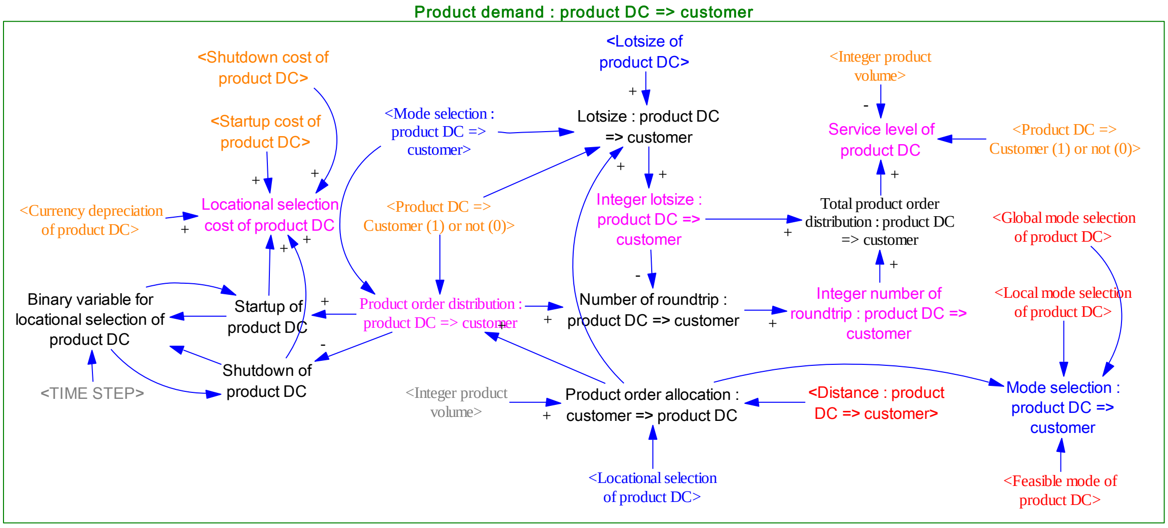


Figure 3-4 Product demand module: product DC→customer

In Figure 3-5, the product demand module: product MP→product DC returns four outputs. They include (1) product order distribution: product MP→product DC, (2) integer lot-size: product MP→product DC, (3) integer number of roundtrips: product MP→product DC, (4) service level: product MP→product DC, and (5) locational selection cost of product MP. They are further used for other related modules. The first three outputs are used for other related modules, while the rest of the outputs can be optimised as follows. The service level is full (100%) when the located product MPs are capable of fully satisfying the product orders to the located product DC. The locational selection cost of product MPs can be minimised when product MP locations are similar to those in the previous period. If product MP locations are unchanged, they do not incur the shutdown and start-up costs involved.

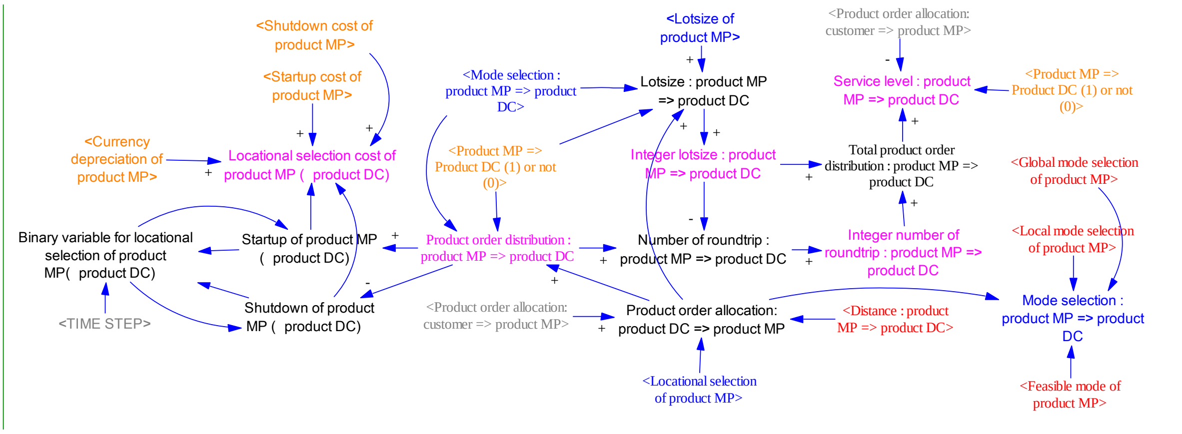


Figure 3-5 Product demand module: product MP→product DC

3.2.2 Product manufacturing and warehousing module

The product manufacturing and warehousing module aims to give feedback on the costs of energy, labour, and inventory holding, preparation time, and environmental impact of energy consumption. These feedbacks contribute to the decision-making process in the three sub-modules of product demand as shown in Figures 3-6 to 3-8.

If product MP→customer in the product demand module is selected, product MPs require numerous resources (i.e. energy, labour, space, and time) for manufacturing products to satisfy customers as shown in Figure 3-6. These resources are more heavily consumed when product orders (product order distribution: product MP→ customer) are increased (+). The increased product orders cause (1) more energy consumption, (2) longer total preparation time, and (3) higher safety stocks. Firstly, the more energy consumption worsens cost (energy price: product MP→customer) (+) and environmental impact (energy EI: product MP→customer) (+). The increase in energy price is annually aggravated by its growth rate (+) and higher currency depreciation of product MPs (+). The energy EI is also degraded when energy emitting more pollution is used (+). The pollution emission is indicated by the environmental impact driver of energy consumption (energy EI driver) based on SLCA database of Manmek et al. (2008). To reduce the cost of energy and environmental impact, energy consumption is improved by actions such as technological development. Secondly, the longer total preparation time increases labour cost (labour cost: product MP→customer) (+). The increase in labour cost is aggravated by its growth rate (+) and higher currency depreciation of product MPs (+). In addition, total preparation time can be longer when lot-sizes (integer lot-size: product MP→customer) are smaller. The smaller lot-sizes lengthen setup unit time (-) which takes longer preparation unit time (+), and longer total preparation time (+). On the other hand, larger lot-sizes cause longer production time (+) and longer preparation time (preparation time: product MP$\rightarrow$customer) (+). Thirdly, the higher safety stocks increase inventory holding cost (product holding cost: product MP$\rightarrow$customer) (+). The increase in product holding cost is aggravated by higher service factor (+), standard deviation of product volume (+), percentage of inventory holding cost (+), product unit price (+), and currency depreciation of product MPs (+), and longer lead time (+). Given that the lead time is the sumof preparation time and transportation time, the lead time of product MPs is dominated by the longest lead time. This mechanism is similar to the two other sub-modules as shown in Figures 3-7 and 3-8.

The product manufacturing module: product MP$\rightarrow$customer eventually returns five outputs. They are (1) energy price: product MP$\rightarrow$customer, (2) energy EI: product MP $\rightarrow$customer, (3) labour cost: product MP$\rightarrow$customer, (4) product holding cost: product MP$\rightarrow$customer, and (5) preparation time: product MP$\rightarrow$customer. The five outputs can be optimised through two decisions including (1) product order distribution: product MP $\rightarrow$customer, and (2) integer lot-sizes: product MP$\rightarrow$customer as follows. The product orders are manufactured in product MP locations that have higher energy efficiency, lower energy unit price and its growth rate, lower wage rate and its growth rate, lower percentage of inventory holding cost, and lower currency depreciation, consuming greener energy, and taking shorter lead time. The shorter lead time is achieved by smaller lot-sizes (shorter preparation time) and also reduce product holding cost (lower product safety stocks); however, labour cost is raised (frequent setups). To trade-off these conflicts, lot-sizes are optimally determined. It should be noted that not all of these preferences may be available within one location, so they are traded-off to select the best-fitted locations of product MPs.

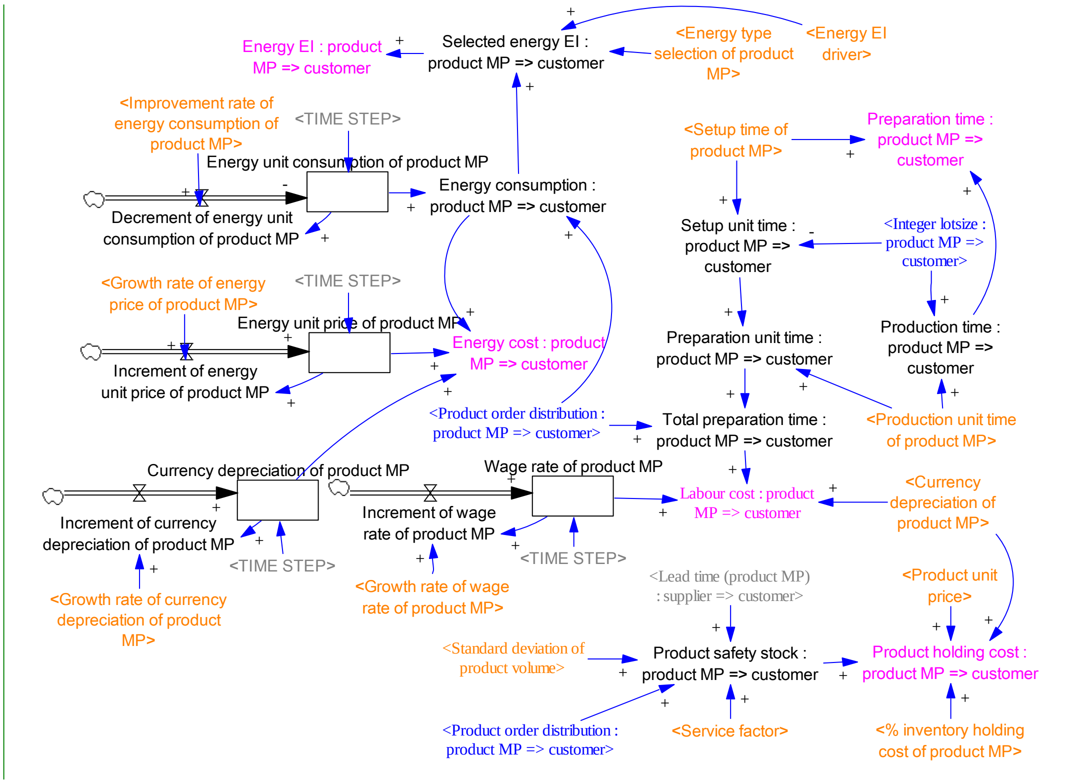


Figure 3-6 Product manufacturing module: product MP→customer

In Figure 3-7, the product warehousing module: product DC→customer returns five outputs. They are (1) energy price: product DC→customer, (2) energy EI: product MP →customer, (3) labour cost: product DC→customer, (4) product holding cost: product DC→customer, and (5) preparation time: product DC→customer. The five outputs can be optimised through two decisions including (1) product order distribution: product DC →customer, and (2) integer lot-sizes: product DC→customer as follows. The product orders are warehoused in product DC locations that have higher energy efficiency, lower energy unit price and its growth rate, lower wage rate and its growth rate, lower percentage of inventory holding cost, and lower currency depreciation, consuming greener energy, and taking shorter lead time. The shorter lead-time is achieved by smaller lot-sizes (shorter preparation time) and also reduce product holding cost (lower product safety stocks); however, labour cost is raised (frequent setups). To trade-off these conflicts, lot-sizes are optimally determined. It should also be noted that not all of these preferences may be available within one location, so they are traded-off to select the best-fitted locations of product DCs.

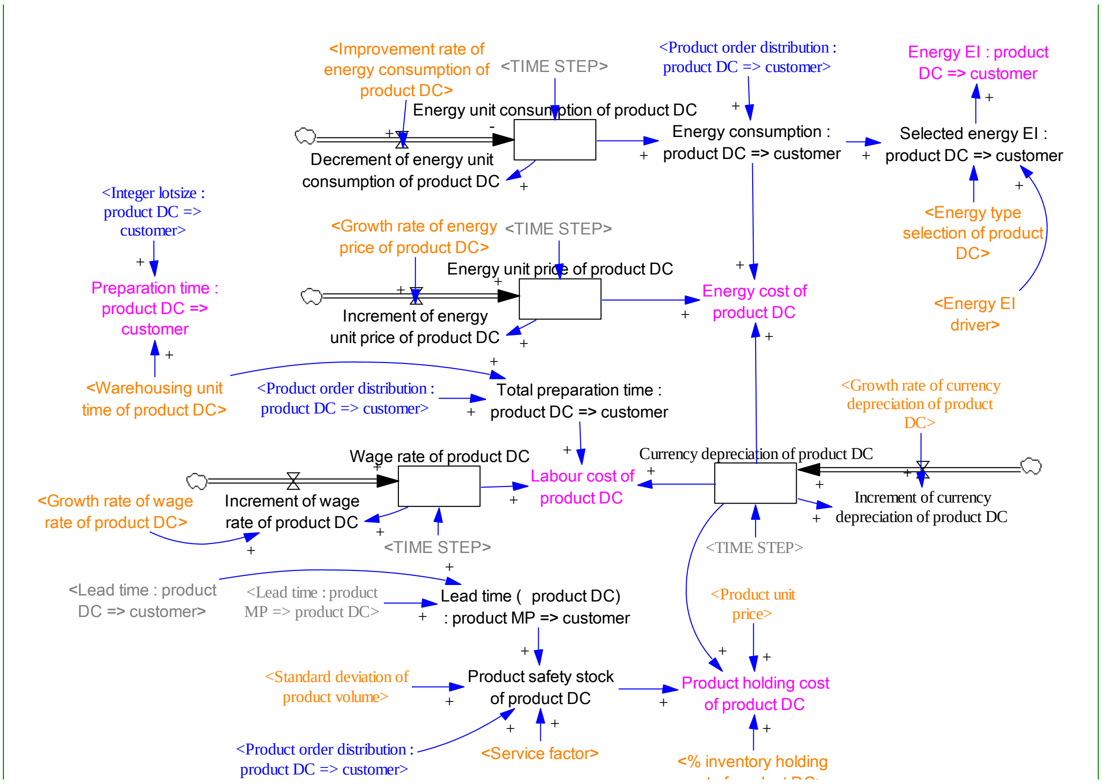


Figure 3-7 Product warehousing module: product DC→customer

In Figure 3-8, the product manufacturing module: product MP→product DC eventually returns five outputs. They are (1) energy price: product MP→product DC, (2) energy EI: product MP→product DC, (3) labour cost: product MP→product DC, (4) product holding cost: product MP→product DC, and (5) preparation time: product MP→ product DC. The five outputs can be optimised through two decisions including (1) product order distribution: product MP→product DC, and (2) integer lot-sizes: product MP→product DC as follows. The product orders are manufactured in product MP locations that have higher energy efficiency, lower energy unit price and its growth rate, lower wage rate and its growth rate, lower percentage of inventory holding cost, and lower currency depreciation, consuming greener energy, and taking shorter lead time. The shorter lead time is achieved by smaller lot-sizes (shorter preparation time) and the smaller lot-sizes also reduce product holding cost (lower product safety stocks); however, labour cost is raised (frequent setups). To trade-off these conflicts, lot-sizes are optimally determined. It should also be noted that not all of these preferences may be available within one location, so they are traded-off to select the best-fitted locations of product MPs.

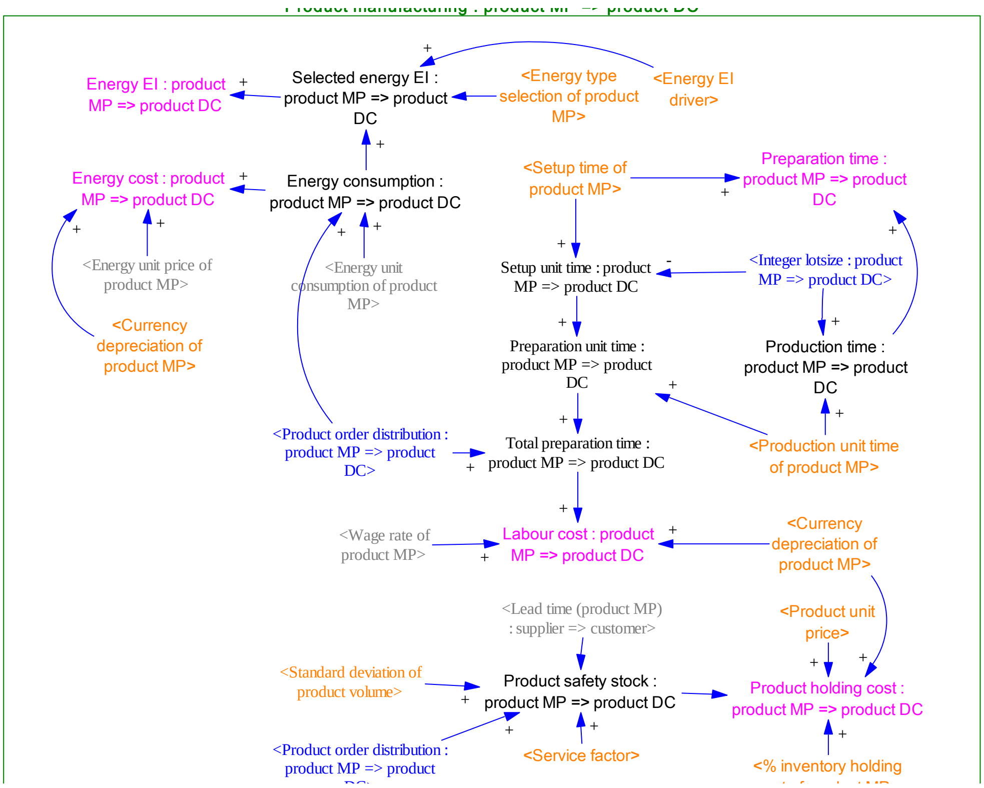


Figure 3-8 Product manufacturing module: product MP→product DC

3.2.3 Product distribution module

The product distribution module aims to give feedback on the transportation cost, time, environmental impact, and importation cost. These feedbacks contribute to decision-making process in the three sub-modules of product demand as shown in Figures 3-9 to 3-11.

If product MP→customer in the product demand module is selected, the product MPs distribute product orders to customers (product order distribution: product MP→customer) by utilising individual transportation modes as shown in Figure 3-9. The individual transportation modes have specific freight rates, emissions, and speeds. They significantly influence the (1) transportation cost (transportation cost: product MP →customer), (2) time (transportation time: product MP→customer), and (3) environmental impact (mode EI: product MP→customer). Firstly, transportation cost is related to variable cost and fixed unit cost of transportation, product orders, and currency depreciation of product MPs. The higher transportation cost hence arises from higher variable cost (+) and fixed unit cost (+), larger product orders (+), and higher currency depreciation of product MPs (+). The higher transportation variable cost is caused by growth rate of fuel price (+), higher ratio of fuel unit cost to transportation unit cost (+), longer distance (+), and heavier-weight products (+) given that product weight is the multiplication of product orders and Bill of Materials (BOM). The higher fixed unit cost of transportation is caused by smaller lot-sizes (integer lot-size: product MP$\rightarrow$customer) in the case where the fixed cost is constant (not dependent on time). Secondly, transportation time is dependent on distance, speed, and number of roundtrips (integer number of roundtrips: product MP$\rightarrow$customer). It is hence increased when distance is longer (+), speed is slower (-), and roundtrips are more frequent (+). Thirdly, mode EI is influenced by distance, product weight, transportation capacity, and mode type. Hence, it becomes worse when the distance is longer (+), product weight is heavier (+), transportation capacity is higher (+), and transportation mode that consumes more fuel and emits more pollution is utilised (+). The pollution emission is assessed by environmental impact driver of transportation (mode EI driver) based on SLCA database of Manmek et al. (2008). The use of higher transportation capacity is to support larger product orders (+) and production capacity (+), and smaller lot-sizes (-) that requires a greater number of transport vehicles. This mechanism is similar to the other two sub-modules as shown in Figures 3-10 and 3-11.

The product distribution module: product MP$\rightarrow$customer eventually returns three outputs. They are (1) transportation cost: product MP$\rightarrow$customer, (2) transportation time: product MP$\rightarrow$customer, and (3) mode EI: product MP$\rightarrow$customer. The three outputs can be optimised through three decisions of (1) product order distribution: product MP$\rightarrow$customer, (2) integer lot-sizes: product MP$\rightarrow$customer, and (3) integer number of roundtrips: product MP$\rightarrow$customer as follows. The preferred locations of product MPs that are closer to customers have a lower growth rate of fuel price, lower ratio of fuel unit cost to transportation unit cost, and lower currency depreciation. All of these preferences may not be practically available within one location and thus they are traded-off to select the best-fitted locations of product MPs. The located product MPs distribute product orders by utilising cheaper, faster, and greener modes of transport with larger lot-sizes. Unfortunately, cheaper and greener transportation modes are slower, whereas faster transportation modes have a higher freight rate and environmental impact. To trade-off these conflicts, the transportation modes are optimally selected.

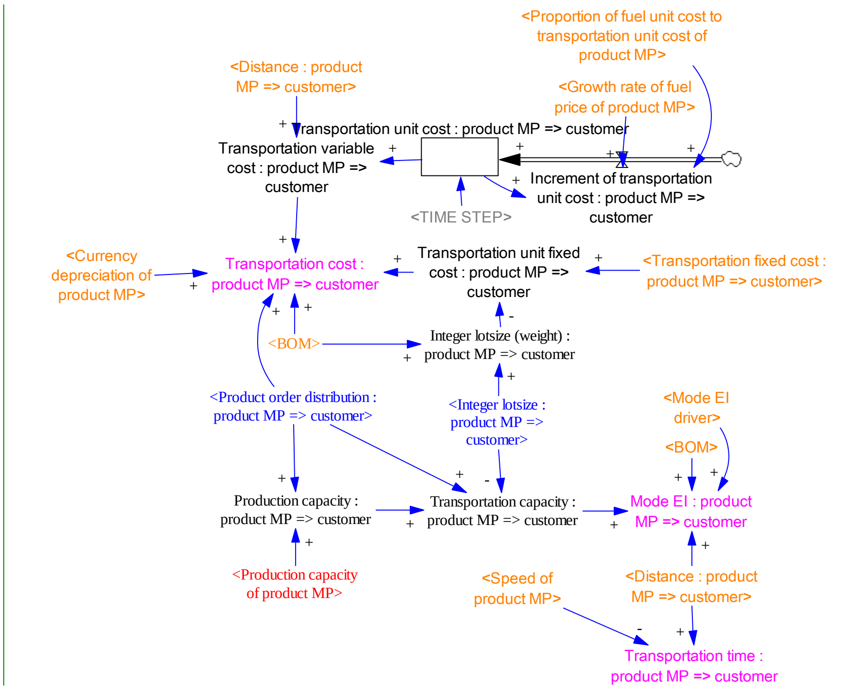


Figure 3-9 Product distribution module: product MP→customer

In Figure 3-10, the product distribution module: product DC→customer returns three outputs. They are (1) transportation cost: product DC→customer, (2) transportation time: product DC→customer, and (3) mode EI: product DC→customer. The three outputs can be optimised through three decisions including (1) product order distribution: product DC→customer, (2) integer lot-sizes: product DC→customer, and (3) integer number of roundtrips: product DC→customer as follows. The preferred locations of product DCs that are closer to customers have a lower growth rate of fuel price, lower ratio of fuel unit cost to transportation unit cost, and lower currency depreciation. All of these preferences may not be practically available within one location and thus they are traded-off to select the best-fitted locations of product DCs. The located product DCs distribute product orders by utilising cheaper, faster, and greener transport modes with larger lot-sizes. Unfortunately, cheaper and greener transportation mode is slower, whereas faster transportation mode has a higher freight rate and environmental impact. To trade-off these conflicts, the transportation modes are optimally selected.

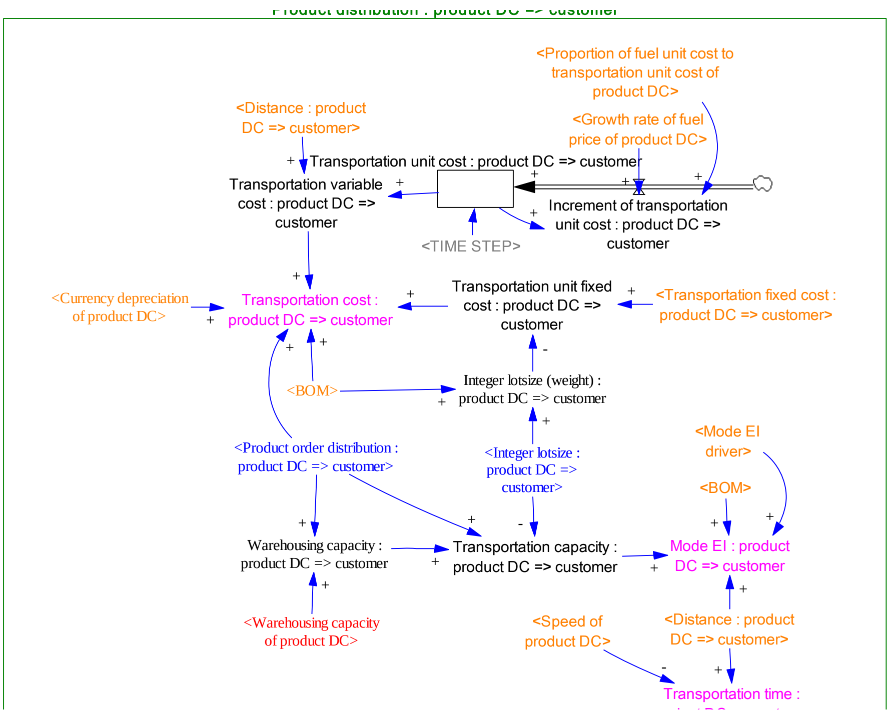


Figure 3-10 Product distribution module: product DC→customer

In Figure 3-11, the product distribution module: product MP→product DC returns four outputs. They are (1) transportation cost: product MP→product DC, (2) transportation time: product MP→product DC, (3) mode EI: product MP→product DC, and (4) importation cost: product MP→product DC. The three outputs can be optimised through three decisions of (1) product order distribution: product MP→product DC, (2) integer lot-sizes: product MP→product DC, and (3) integer number of roundtrips: product MP→product DC as follows. The preferred locations of product MPs that are closer to product DCs have a lower growth rate of fuel price, lower ratio of fuel unit cost to transportation unit cost, and lower currency depreciation. All of these preferences may not be practically available within one location and thus they are traded-off to select the best-suited locations of product MPs. The preferred locations of product DCs are exempt product import duty. The located product MPs distribute product orders to the located product DCs by utilising cheaper, faster, and greener transportation modes with larger lot-sizes. Unfortunately, cheaper and greener transportation mode is slower; alternatively, faster transportation mode has a higher freight rate and environmental impact. To trade-off these conflicts, the transportation modes are optimally selected.

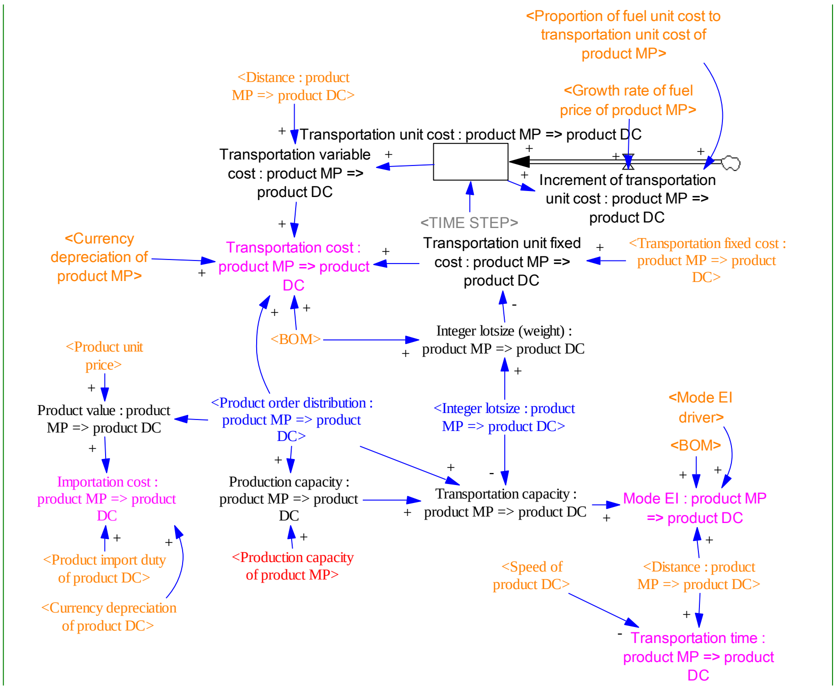


Figure 3-11 Product distribution module: product MP→product DC

3.2.4 Component demand module

The component demand module aims to decide locations and allocations of component manufacturing plants (component MPs) and component distribution centres (component DCs), along with their transportation modes and lot-sizes. Component MPs manufacture components to support either product MPs (Figure 3-12) or component DCs (Figure 3-14), while component DCs warehouse manufactured components to support product MPs (Figure 3-13).

If component MP→product MP is selected, component MPs manufacture components to support product MPs as shown in Figure 3-12. Component MPs are located (locational selection of component MP) and allocated with component volume ordered by product MPs (component order allocation: product MP→component MP). The component volume is proportionally converted from product order allocations to product MPs and Bill of components (BOC). It is annually increased by its growth rate (+), so component orders are increased (+). Subsequently, the feasible transportation modes are selected (mode selection: component MP→product MP) based on the (either global or local) locations, infrastructures, and component sizes. The selected transportation modes are utilised to distribute the increased component orders from the located component MPs to product MPs (component order distribution: component MP

$\rightarrow$product MP) (+). The component order distributions indicate whether component MPs are closed (shutdown of component MP) or opened (start-up of component MP). The shutdown (valued by 0) and start-up (valued by 1) of component MPs are represented by (0/1) binary variables (binary variable for locational selection of component MP). If the component order distributions are increased, the start-up of component MPs is also increased (+). Otherwise, the shutdown of component MPs is decreased (-). The frequent change of component MP locations increases costs of shutdown (to keep the existing ones for the future operation e.g. fixed cost, permanent labour cost, depreciation, etc.) (+), and start-up (e.g. labour and waste costs, etc.) (+). These costs (locational selection cost of component MP) are also influenced in proportion to currency depreciation of component MPs (+). After that, integer transportation lot-sizes (integer lot-size: component MP$\rightarrow$product MP) are determined to indicate integer number of roundtrips (integer number of roundtrips: component MP $\rightarrow$product MP). They are less frequent when the integer lot-sizes are larger (-) and the component order distributions are smaller (+). However, the integer lot-sizes are no larger than the component order distributions. To assure full service level (service level: component MP$\rightarrow$product MP), the value of multiplication of integer roundtrips (+) and integer lot-sizes (+) (total component order distribution: component MP$\rightarrow$product MP) is no less than component volume (-). This mechanism is similar to the two other sub-modules as shown in Figures 3-13 and 3-14.

The component demand module: component MP$\rightarrow$product MP eventually returns five outputs. They are (1) component order distribution: component MP$\rightarrow$product MP, (2) integer lot-size: component MP$\rightarrow$product MP, (3) integer number of roundtrips: component MP$\rightarrow$product MP, (4) service level: component MP$\rightarrow$product MP, and (5) locational selection cost of component MP. The first three outputs are used for the modules of component manufacturing and warehousing, and component distribution. The rest of the outputs can be optimised as follows. The service level is full (100%) when the located component MPs are capable of fully satisfying the component orders to product MPs. The locational selection cost of component MPs can be minimised when component MP locations are similar to those in the previous period. If component MP locations are unchanged, they do not incur the shutdown and start-up costs involved.

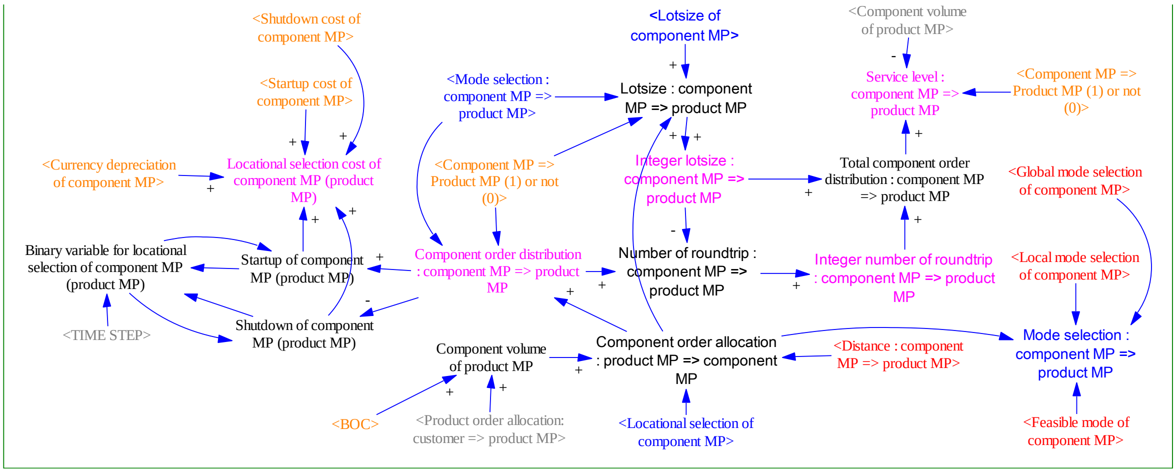


Figure 3-12 Component demand module: component MP → product MP

In Figure 3-13, the component demand module: component DC → product MP returns five outputs. They are (1) component order distribution: component DC → product MP, (2) integer lot-size: component DC → product MP, (3) integer number of roundtrips: component DC → product MP, (4) service level: component DC → product MP, and (5) locational selection cost of component DC. The first three outputs are used for other related modules, while the rest of the outputs can be optimised as follows. The service level is full (100%) when the located component DCs are capable of fully satisfying the component orders to product MPs. The locational selection cost of component DCs can be minimised when component DC locations are similar to those in the previous period. If component DC locations are unchanged, they do not incur the shutdown and start-up costs involved.

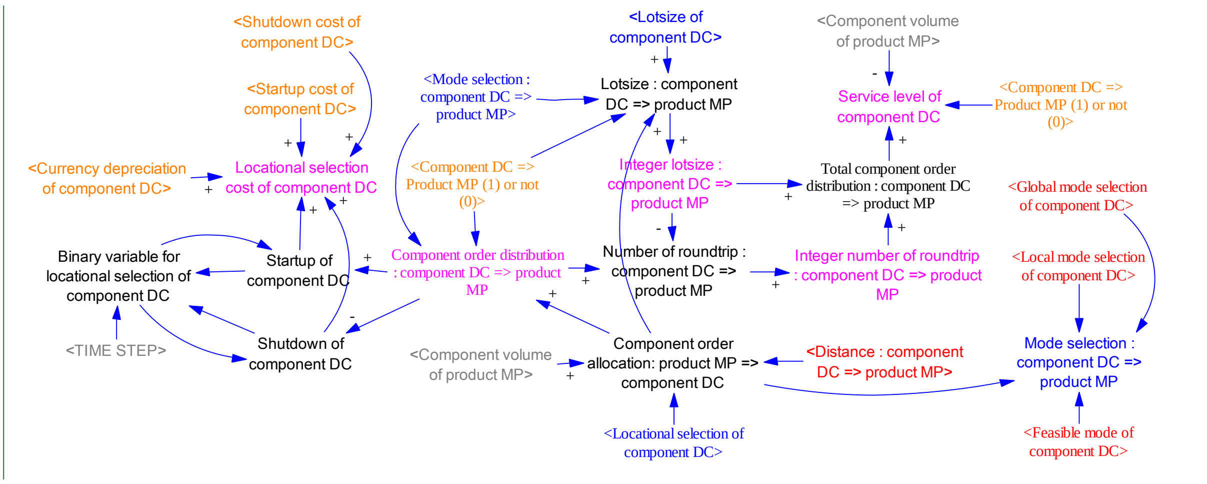


Figure 3-13 Component demand module: component DC → product MP

In Figure 3-14, the component demand module: component MP→component DC returns five outputs. They are (1) component order distribution: component MP→ component DC, (2) integer lot-size: component MP→component DC, (3) integer number of roundtrips: component MP→component DC, (4) service level: component MP→component DC, and (5) locational selection cost of component MP. The first three outputs are used for the modules of component manufacturing and warehousing, and component distribution. The rest of the outputs can be optimised as follows. The service level is full (100%) when the located component MPs are capable of fully satisfying the component orders to component DCs. The locational selection cost of component MPs can be minimised when component MP locations are similar to those in the previous period. If component MP locations are unchanged, they do not incur the shutdown and start-up costs involved.

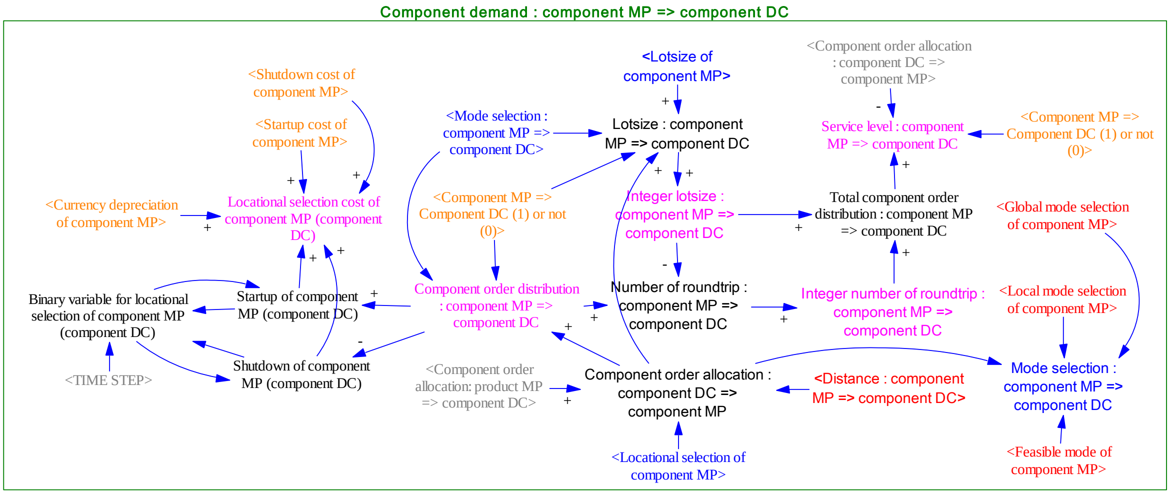


Figure 3-14 Component demand module: component MP→component DC

3.2.5 Component manufacturing and warehousing module

The component manufacturing and warehousing module aims to give feedback on the costs of energy, labour, and inventory holding, preparation time, and environmental impact of energy consumption. These feedbacks contribute to decision-making process in the three sub-modules of component demand as shown in Figures 3-15 to 3-17.

If component MP→product MP in the component demand module is selected, component MPs require numerous resources (i.e. energy, labour, space, and time) for manufacturing components to support product MPs as shown in Figure 3-15. The consumption of these resources is greater when component orders (component order distribution: component MP→product MP) are increased (+). The increased component orders cause (1) more energy consumption, (2) longer total preparation time, and (3) higher safety stocks. Firstly, the higher energy consumption leads to greater cost (energy price: component MP→product MP) (+) and environmental impact (energy EI: component MP→product MP) (+). The annual increase in energy price is aggravated by its growth rate (+) and higher currency depreciation of component MPs (+). The environmental impact of energy consumption is also worsened when energy source that generates more pollution is used (+). The pollution emission is indicated by environmental impact driver of energy consumption (energy EI driver) based on SLCA database of Manmek et al. (2008). To reduce the cost of energy and environmental impact, energy consumption can be improved by actions such as technological development. Secondly, the longer total preparation time increases labour cost (labour cost: component MP→product MP) (+). The increase in labour cost is aggravated by its growth rate (+) and higher currency depreciation of component MPs (+). In addition, total preparation time can be longer when lot-sizes (integer lot-sizes: component MP→ product MP) are smaller. The smaller lot-sizes lengthen setup unit time (-) which takes longer preparation unit time (+), and longer total preparation time (+). On the other hand, larger lot-sizes cause longer production time (+) and longer preparation time (preparation time: component MP→product MP) (+). Thirdly, the larger safety stocks increase inventory-holding cost (component holding cost: component MP→product MP) (+). The increase in component holding cost is aggravated by higher service factor (+), standard deviation of component volume (+), percentage of inventory holding cost (+), component unit price (+),currency depreciation of component MPs (+), and longer lead time (+), given that the lead-time is the sum of preparation time and transportation time. The lead-time of component MPs is dominated by the longest lead-time. This mechanism is similar to the two other sub-modules as shown in Figures 3-16 and 3-17.

The component manufacturing module: component MP→product MP eventually returns five outputs. They are (1) energy price: component MP→product MP, (2) energy EI: component MP→product MP, (3) labour cost: component MP→product MP, (4) component holding cost: component MP→product MP, and (5) preparation time: component MP→product MP. The five outputs can be optimised through two decisions of (1) component order distribution: component MP→product MP, and (2) integer lot-sizes: component MP→product MP as follows. The component orders are manufactured in component MP locations having more efficient energy consumption, lower energy unit price and its growth rate, lower wage rate and its growth rate, lower percentage of inventory holding cost, and lower currency depreciation, consuming greener energy, and taking shorter lead-time. The shorter lead-time is incurred by smaller lot-sizes (shorter preparation time). The smaller lot-sizes also reduce component holding cost (lower component safety stocks); however, it raises the labour cost (frequent setups). To trade-off these conflicts, lot-sizes are optimally determined. It should be noted that all of these preferences may not be available within one location, so they are traded-off to select the best-fitted locations of component MPs.

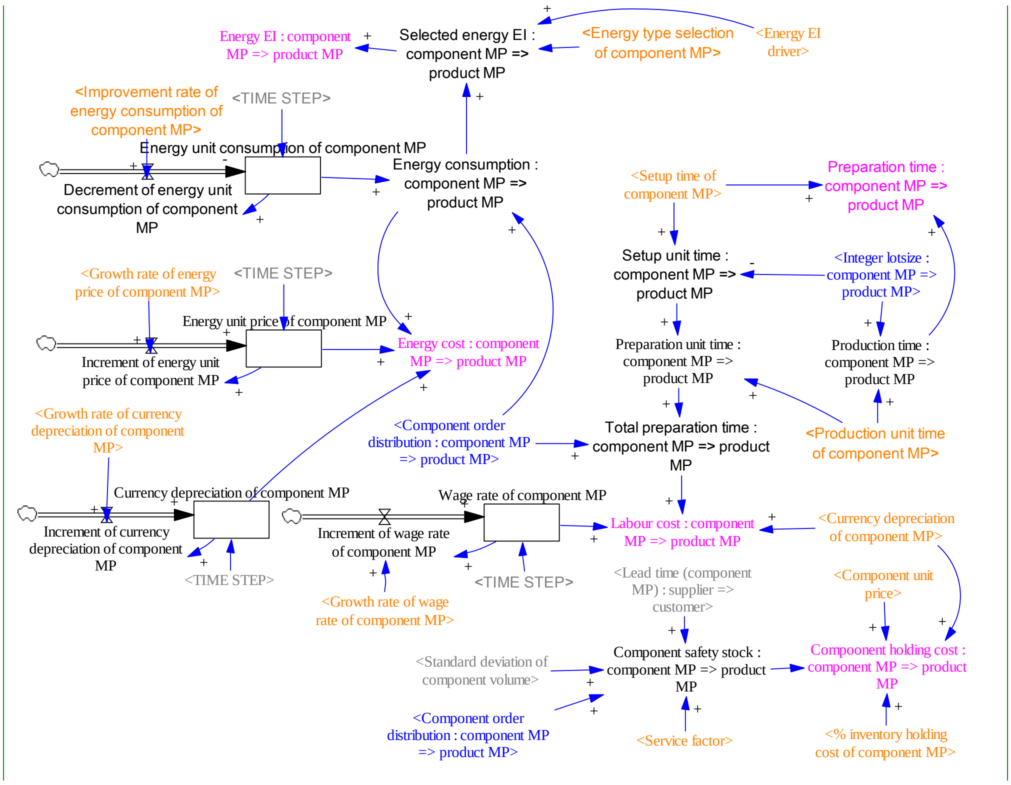


Figure 3-15 Component manufacturing module: component MP→product MP

In Figure 3-16, the component warehousing module: component DC→product MP returns five outputs. They are (1) energy price: component DC→product MP, (2) energy EI: component DC→product MP, (3) labour cost: component DC→product MP, (4) component holding cost: component DC→product MP, and (5) preparation time: component DC→product MP. The five outputs can be optimised through two decisions including (1) component order distribution: component DC→product MP, and (2) integer lot-sizes: component DC→product MP as follows. The component orders are warehoused in component DC locations that have higher energy efficiency, lower energy unit price and its growth rate, lower wage rate and its growth rate, lower percentage of inventory holding cost, and lower currency depreciation, consuming greener energy, and taking shorter lead time. The shorter lead-time is achieved by smaller lot-sizes (shorter preparation time). The smaller lot-sizes also reduce component holding cost (lower component safety stocks); however, it raises the labour cost (frequent setups). To trade-off these conflicts, lot-sizes are optimally determined. It should be noted that all of these preferences may not be available within one location, so they are traded-off to select the best-fitted locations of component DCs.

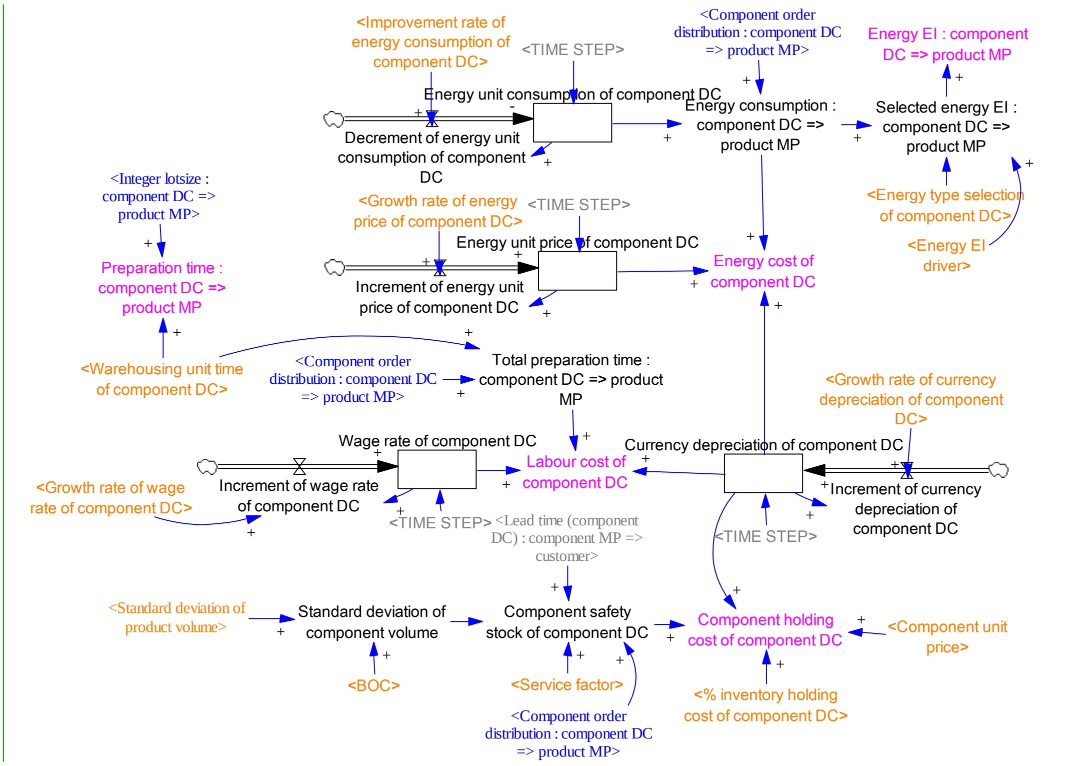


Figure 3-16 Component warehousing module: component DC→product MP

In Figure 3-17, the component manufacturing module: component MP→component DC returns five outputs. They are (1) energy price: component MP→component DC, (2) energy EI: component MP→component DC, (3) labour cost: component MP→component DC, (4) component holding cost: component MP→component DC, and (5) preparation time: component MP→component DC. The five outputs can be optimised through the two decisions of (1) component order distribution: component MP→component DC, and (2) integer lot-sizes: component MP→component DC as follows. The component orders are manufactured in component MP locations that have higher energy efficiency, lower energy unit price and its growth rate, lower wage rate and its growth rate, lower percentage of inventory holding cost, and lower currency depreciation, consuming greener energy, and taking shorter lead-time. The shorter lead-time is achieved by smaller lot-sizes (shorter preparation time). The smaller lot-sizes also reduce component holding cost (lower component safety stocks); however, it raises the labour cost (frequent setups). To trade-off these conflicts, lot-sizes are optimally determined. It is also noticeable that all of these preferences may not be found within one location, so they are traded-off to select the best-fitted locations of component MPs.

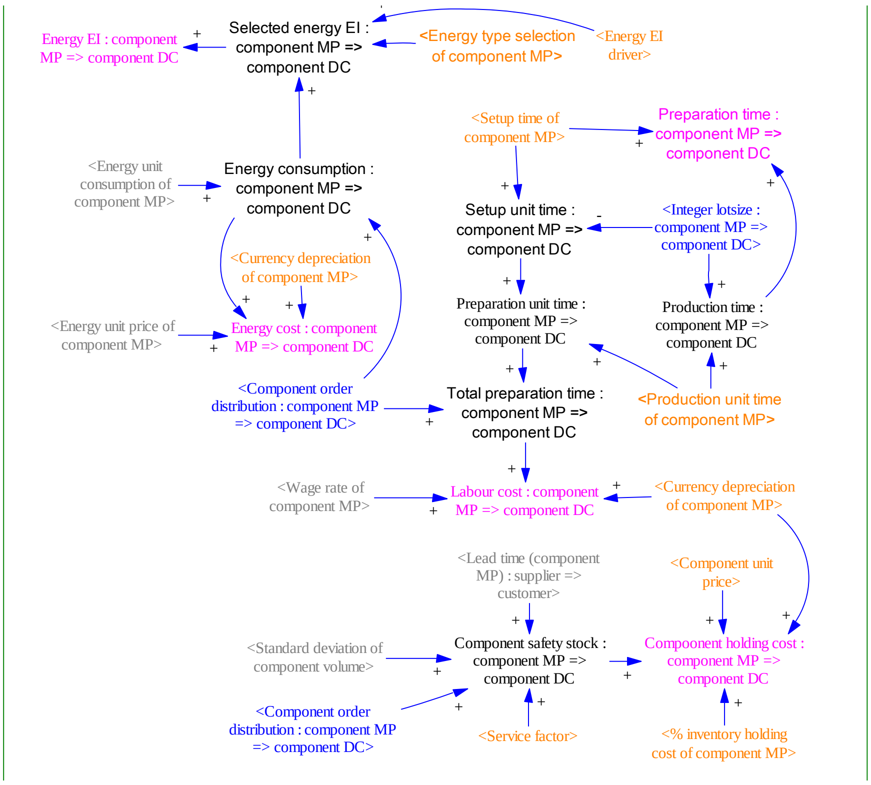


Figure 3-17 Component manufacturing module: component MP $\rightarrow$ component DC

3.2.6 Component distribution module

The component distribution module aims to give feedback on the transportation cost, time, environmental impact, and importation cost. These feedbacks contribute to the decision-making process in the three sub-modules of component demand, and locational selections of product MPs as shown in Figures 3-18 to 3-20.

If component MP $\rightarrow$ product MP in the component demand module is selected, component MPs distribute component orders to product MPs (component order distribution: component MP$\rightarrow$product MP) by utilising individual transportation modes as shown in Figure 3-18. The individual transportation modes have specific freight rates, emissions, and speeds. They significantly influence (1) transportation cost (transportation cost: component MP$\rightarrow$product MP), (2) time (transportation time: component MP$\rightarrow$product MP), and (3) environmental impact (mode EI: component MP $\rightarrow$product MP). Firstly, transportation cost is related to the variable cost and fixed unit cost of transportation, product orders, and currency depreciation of component MPs. The higher transportation cost hence arises from higher variable cost (+) and fixed unit cost (+), larger product orders (+), and higher currency depreciation of component MPs (+). The higher transportation variable cost is caused by growth rate of fuel price (+), higher ratio of fuel unit cost to transportation unit cost (+), longer distance (+), and heavier-weight components (+), given that component weight is the value of multiplication of component orders and Bill of Materials (BOM) of components. The higher transportation fixed unit cost is caused by smaller lot-sizes (integer lot-size: component MP$\rightarrow$product MP) in the case that transportation fixed cost is constant (not dependent on time). Secondly, transportation time is dependent on distance, speed, and number of roundtrips (integer number of roundtrips: component MP$\rightarrow$product MP). Therfore, it is greater when distance is longer (+), speed is slower (-), and roundtrips are frequent (+). Thirdly, mode EI is influenced by the distance, component weight, transportation capacity, and mode type. Hence, it becomes worse when the distance is longer (+), component weight is heavier (+), transportation capacity is higher (+), and transportation mode that consumes more fuel and emits more pollution is utilised (+). The pollution emission is indicated by environmental impact driver of transportation (mode EI driver) based on SLCA database of Manmek et al. (2008). The higher transportation capacity is to support larger component orders (+) and production capacity (+), and smaller lot-sizes (-) requiring a greater number of transportation modes. This mechanism is similar to the two other sub-modules as shown in Figures 3-19 and 3-20.

The component distribution module: component MP$\rightarrow$product MP eventually returns three outputs. They are (1) transportation cost: component MP$\rightarrow$product MP, (2) transportation time: component MP$\rightarrow$product MP, and (3) mode EI: component MP$\rightarrow$ product MP. The three outputs can be optimised through three decisions including (1) component order distribution: component MP$\rightarrow$product MP, (2) integer lot-sizes: component MP$\rightarrow$product MP, and (3) integer number of roundtrips: component MP$\rightarrow$

product MP as follows. The preferred locations of component MPs that are closer to product MPs have a lower growth rate of fuel price, lower ratio of fuel unit cost to transportation unit cost, and lower currency depreciation. All of these preferences may not be practically available within one location, so they are traded-off to select the best-fitted locations of component MPs. The preferred locations of product MPs are exempt from component import duty. The located component MPs distribute component orders to the located product MPs by utilising cheaper, faster, and greener transportation modes with larger lot-sizes. Unfortunately, cheaper and greener transport methods are slower; on the other hand, faster transport has a higher freight rate and environmental impact. To trade-off these conflicts, transportation modes are optimally selected.

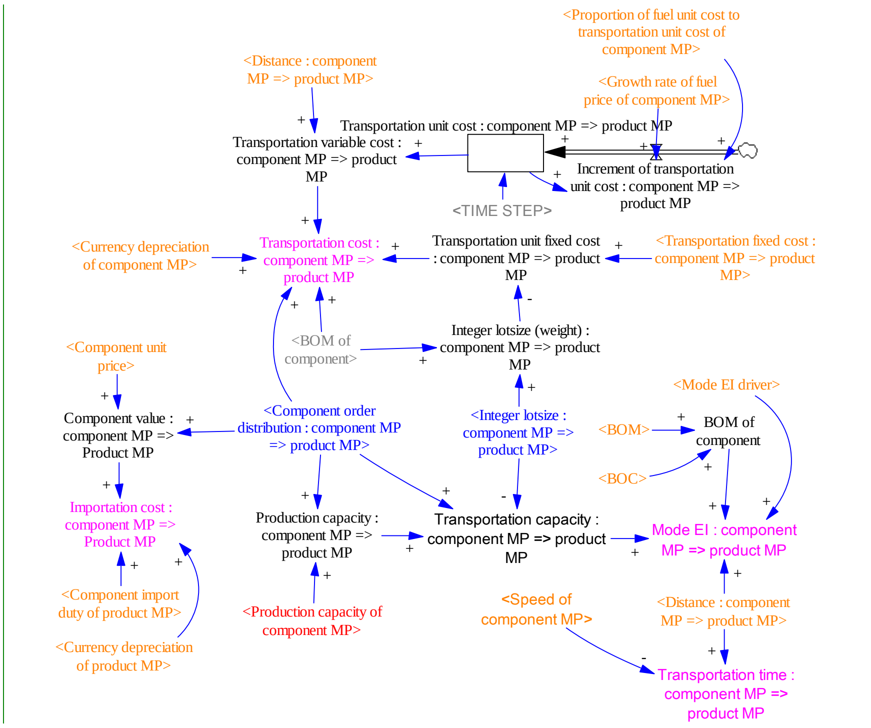


Figure 3-18 Component distribution module: component MP→product MP

In Figure 3-19, the component distribution module: component DC→product MP returns three outputs. They are (1) transportation cost: component DC→product MP, (2) transportation time: component DC→product MP, and (3) mode EI: component DC →product MP. The three outputs can be optimised through three decisions including (1) component order distribution: component DC→product MP, (2) integer lot-sizes: component DC→product MP, and (3) integer number of roundtrips: component DC→ product MP as follows. The preferred locations of component DCs that are closer to product MPs are exempt of import duty of components (referred to Figure 3-18), have lower growth rate of fuel price, lower ratio of fuel unit cost to transportation unit cost, and lower currency depreciation. All of these preferences may not be practically available within one location, so they are traded-off to select the best-suited locations of component DCs. The preferred locations of product MPs are exempt from component import duty. The located component DCs distribute component orders to the located product MPs by utilising cheaper, faster, and greener transport methods with larger lot-sizes. Unfortunately, cheaper and greener transport methods are slower, while faster transport has a higher freight rate and environmental impact. To trade-off these conflicts, transportation modes are optimally selected.

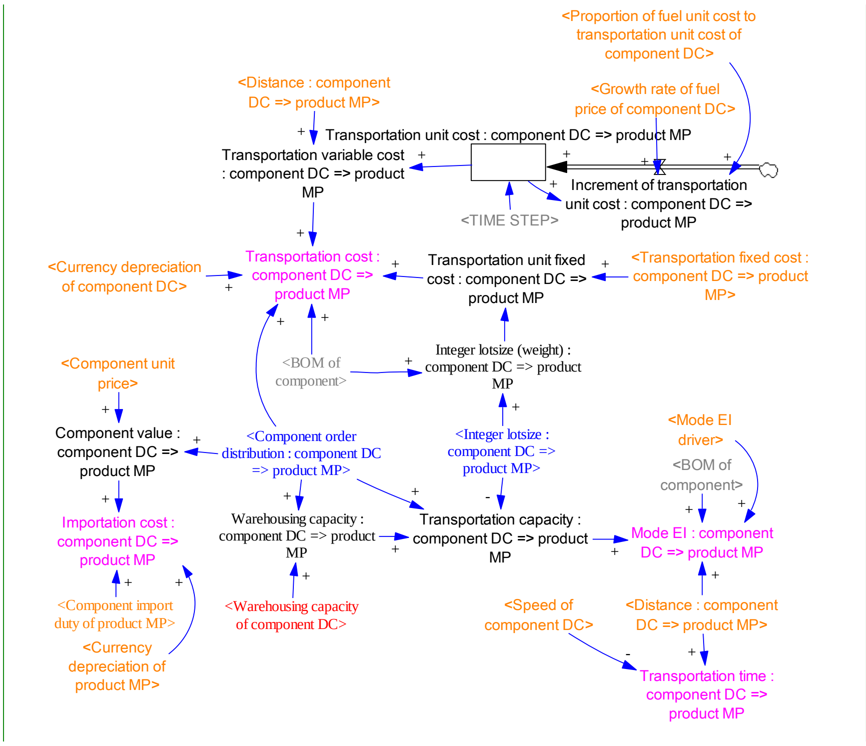


Figure 3-19 Component distribution module: component DC $\rightarrow$ product MP

In Figure 3-20, the component distribution module: component MP $\rightarrow$ component DC returns four outputs. They are (1) transportation cost: component MP $\rightarrow$ component DC, (2) transportation time: component MP $\rightarrow$ component DC, (3) mode EI: component MP $\rightarrow$ component DC, and (4) importation cost: component MP $\rightarrow$ component DC. The three outputs can be optimised through three decisions including (1) component order distribution: component MP $\rightarrow$ component DC, (2) integer lot-sizes: component MP $\rightarrow$ component DC, and (3) integer number of roundtrips: component MP $\rightarrow$ component DC as follows. The preferred locations of component MPs that are closer to component

DCs have a lower growth rate of fuel price, lower ratio of fuel unit cost to transportation unit cost, and lower currency depreciation. All of these preferences may not be practically available within one location, so they are traded-off to select the best-fitted locations of component MPs. The preferred locations of component DCs are those exempt from component import duty. The located component MPs distribute component orders to the located component DCs by utilising cheaper, faster, and greener transport with larger lot-sizes. Unfortunately, cheaper and greener transport is slower; however, faster transport has a higher freight rate and environmental impact. To trade-off these conflicts, transportation modes are optimally selected.

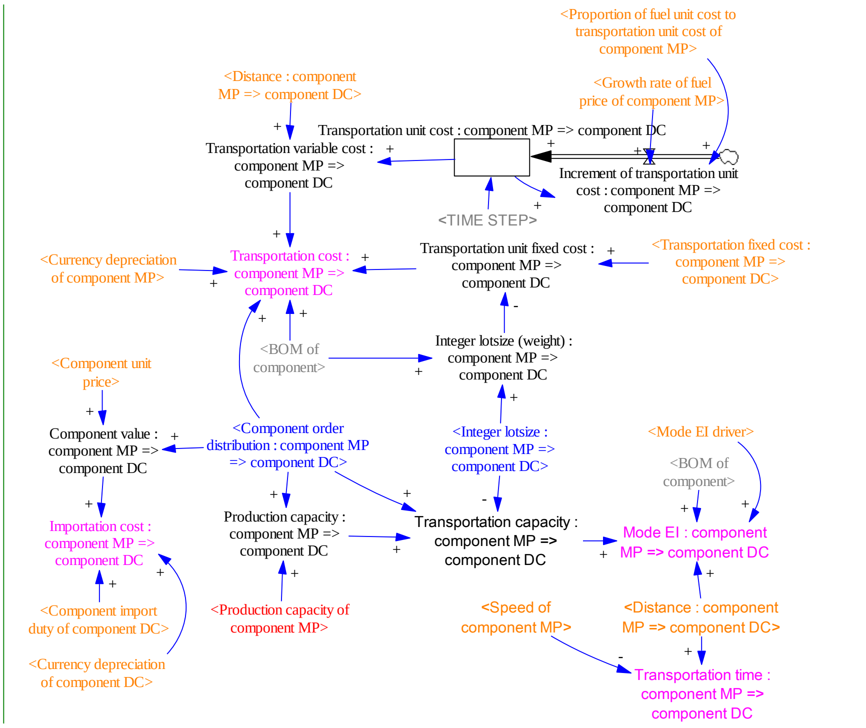


Figure 3-20 Product distribution module: component MP → component DC

3.2.7 Material demand module

The material demand module aims to decide the sources of supply (i.e. suppliers) and material order allocations, along with their transportation modes and lot-sizes. Suppliers supply materials to either product MPs (Figure 3-21) or component MPs (Figure 3-22).

If supplier → product MP is selected, Suppliers supply materials to product MPs as shown in Figure 3-21. Suppliers are selected (selection of supplier) with material volume allocated as ordered by product MPs (material order allocation: supplier→ product MP). The material volume is converted from product order allocations in proportion to product MPs and Bill of Materials (BOM) accordingly. It is annually increased by its growth rate (+), so material orders are increased (+). Subsequently, feasible transportation modes are selected (mode selection: supplier→product MP) based on (either global or local) locations, infrastructures, and material sizes. The selected transportation modes are utilised to distribute the increased material orders from the selected suppliers MPs to product MPs (material order distribution: supplier→ product MP) (+). The material order distributions indicate whether suppliers‟ contracts are initiated (initiation of supplier‟s contract) or terminated (termination of supplier‟s contract). The initiation (valued by 1) and termination (valued by 0) of suppliers‟ contracts are represented by (0/1) binary variables (binary variable for supplier selection). If the material order distributions are increased, the contract initiation is expanded (+). Otherwise, the contract termination is contracted (-). The frequent change of suppliers increases the costs of contract initiation (e.g. legal contract cost, tender cost, etc.) (+) and termination (excluding partners from the ordering plan as a percentage of order value) (+). These costs (supplier selection cost) are also proportionally influenced by currency depreciation of suppliers (+). After that, integer transportation lot-sizes (integer lot-size: supplier→product MP) are determined to indicate integer number of roundtrips needed (integer number of roundtrips: supplier→ product MP). They are less frequent when the integer lot-sizes are larger (-) and the material order distributions are smaller (+). However, the integer lot-sizes are no more than the material order distributions. To assure full service level (service level: supplier →product MP), the value of multiplication of integer roundtrips (+) and integer lot-sizes (+) (total material order distribution: supplier→product MP) is no less than material volume (-).This mechanism is similar to another sub-module as shown in Figure 3-22.

The material demand module: supplier→product MP eventually returns five outputs. They are (1) material order distribution: supplier→product MP, (2) lot-size: supplier→ product MP, (3) integer number of roundtrips: supplier→product MP, (4) service level: supplier→product MP, and (5) supplier selection cost. The first three outputs are used for the modules of material procurement, and material distribution. The rest of the outputs can be optimised as follows. The service level is full (100%) when the selected suppliers are capable of fully supplying material orders to product MPs. The supplier selection cost can be minimised when suppliers are similar to those in the previous period. If suppliers are unchanged, they do not incur the contract initiation and termination costs involved.

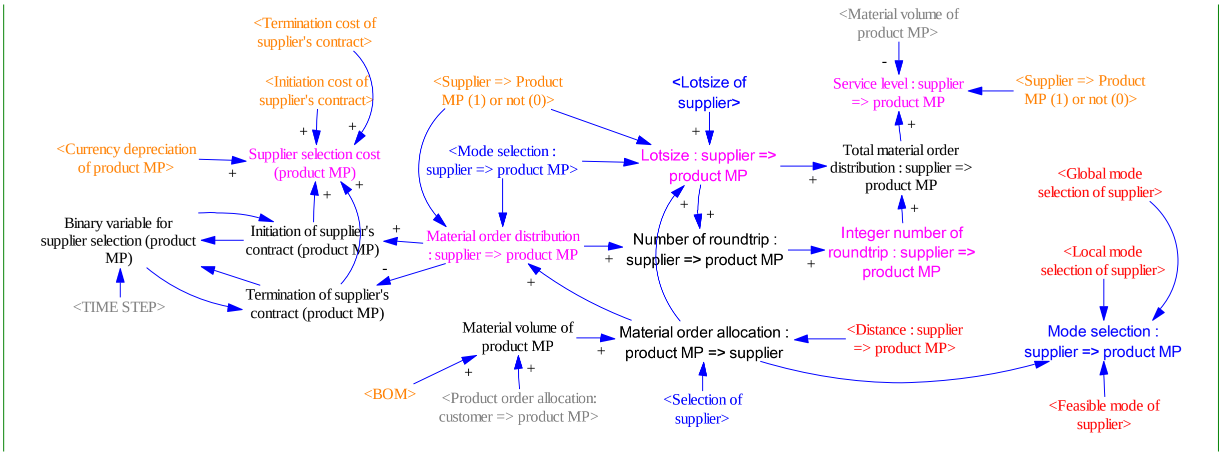


Figure 3-21 Material demand module: supplier→product MP

In Figure 3-22, the material demand module: supplier→component MP returns five outputs. They are (1) material order distribution: supplier→component MP, (2) lot-size: supplier→component MP, (3) integer number of roundtrips: supplier→component MP, (4) service level: supplier→component MP, and (5) supplier selection cost. The first three outputs are used for other related modules, while the rest of the outputs can be optimised as follows. The service level is full (100%) when the selected suppliers are capable of fully supplying material orders to product MPs. The supplier selection cost can be minimised when suppliers are similar to those in the previous period. If suppliers are unchanged, they do not incur the contract initiation and termination costs involved.

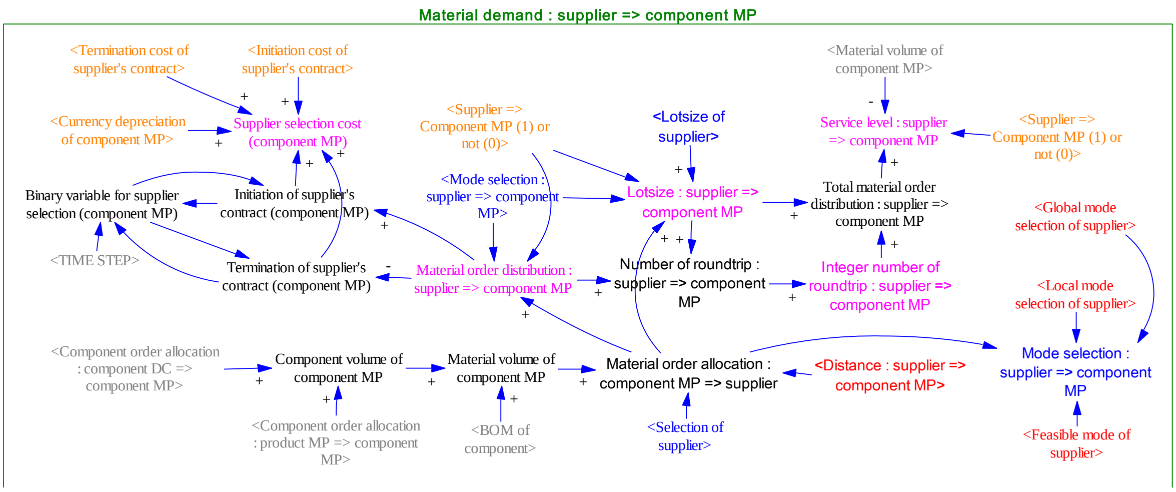


Figure 3-22 Material demand module: supplier→component MP

3.2.8 Material procurement module

The material procurement module aims to give feedback on the material cost, preparation time, and environmental impact. These feedbacks contribute to decision-making process in the two sub-modules of material demand as shown in Figures 3-23 and 3-24.

If supplier→product MP in the material demand module is selected, product MPs procure materials from suppliers as shown in Figure 3-23. The material procurement is charged for materials, takes preparation time, and impacts the environment. These factors are worsened when material orders (material order distribution: supplier→ product MP) are increased (+) and lot-sizes (lot-size: supplier→product MP) are larger (+). The increased material orders cause higher material cost (material cost of product MP) (+) and a worse environmental impact (material EI: supplier→product MP) (+), while the larger lot-sizes cause longer preparation time (preparation time: supplier→ product MP) (+). The higher material cost is also caused by higher currency depreciation of suppliers (+). The environmental impact of material is negatively aggravated when materials with higher pollution level are extracted for product manufacturing (+). The pollution level is indicated by the environmental impact driver of material extraction (material EI driver) based on SLCA database of Manmek et al. (2008). This mechanism is similar to another sub-module as shown in Figure 3-24.

The material procurement module: supplier→product MP eventually returns three outputs. They are (1) material cost of product MP, (2) preparation time: supplier→ product MP, and (3) material EI: supplier→product MP. The three outputs can be optimised through two decisions including (1) material order distribution: supplier→ product MP, and (2) lot-size: supplier→product MP as follows. The material orders are procured from suppliers offering lower-price materials, having higher currency depreciation, consuming greener materials, and utilising smaller lot-sizes. All of these preferences may not be practically available within one supplier, so they are traded-off to select the best-suited suppliers.

In Figure 3-24, the material procurement module: supplier→component MP eventually returns three outputs. They are (1) material cost of component MP, (2) preparation time: supplier→component MP, and (3) material EI: supplier→component MP. The three outputs can be optimised through two decisions including (1) material order distribution: supplier→component MP, and (2) lot-size: supplier→component MP as follows. The material orders are procured from suppliers offering lower-price materials, and utilising smaller lot-sizes. All of these preferences may not be practically available within one supplier, so they are traded-off to select the best-fitted suppliers.

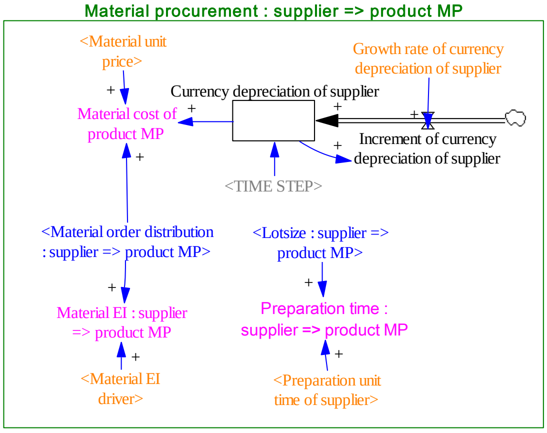


Figure 3-23 Material procurement module: supplier→product MP

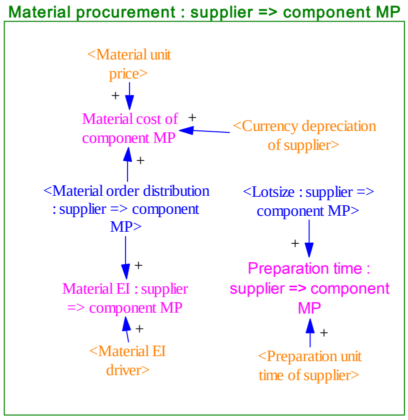


Figure 3-24 Material procurement module: supplier→component MP

3.2.9 Material distribution module

The material distribution module aims to give feedback on the transportation cost, time, environmental impact, and importation cost. These feedbacks contribute to decision-making process in the three sub-modules of material demand as shown in Figures 3-25 and 3-26.

If supplier→product MP in the material demand module is selected, suppliers distribute material orders to product MPs (material order distribution: supplier→product MP) by utilising individual transportation modes as shown in Figure 3-25. The individual transportation modes have specific freight rates, emissions, and speeds. They significantly influence (1) transportation cost (transportation cost: supplier→product MP), (2) time (transportation time: supplier→product MP), and (3) environmental impact (mode EI: supplier→product MP). Firstly, transportation cost is comprised of variable cost and fixed unit cost, so higher transportation cost arises from higher variable cost (+) and fixed unit cost (+), and heavier-weight materials (material orders) (+). The higher transportation variable cost is caused by growth rate of fuel price (+), higher ratio of fuel unit cost to transportation unit cost (+), and longer distance (+). The higher transportation fixed unit cost is caused by smaller lot-sizes (integer lot-size:

supplier→product MP) in the case where transportation fixed cost is constant (not dependent on time). Secondly, transportation time is dependent on distance, speed, and number of roundtrips (integer number of roundtrips: supplier→product MP). It is hence extended when distance is longer (+), speed is slower (-), and roundtrips are frequent (+). Thirdly, EI of transportation mode is influenced by the distance, material weight, transportation capacity, and mode type. Therefore, it becomes worse when distance is longer (+), material weight is heavier (+), transportation capacity is higher (+), and mode type that consumes more fuel and emits more pollution is utilised (+). The pollution emission is indicated by the environmental impact driver of transportation (mode EI driver) based on SLCA database of Manmek et al. (2008). The higher transportation capacity is to support larger material orders (+) and production capacity (+), and smaller lot-sizes (-) requiring a greater amount of transportation. This mechanism is similar to the two other sub-modules as shown in Figure 3-26.

The material distribution module: supplier→product MP eventually returns three outputs. They are (1) transportation cost: supplier→product MP, (2) transportation time: supplier→product MP, and (3) mode EI: supplier→product MP. The three outputs can be optimised through three decisions of (1) material order distribution: supplier→product MP, (2) integer lot-sizes: supplier→product MP, and (3) integer number of roundtrips: supplier→product MP as follows. The preferred suppliers are closer to product MPs and have a stronger currency exchange rate. All of these preferences may not be practically available within one location, so they are traded-off to select the best-suited suppliers. The preferred product MPs are exempt from material import duty. The selected suppliers distribute material orders to the located product MPs by utilising cheaper, faster, and greener transport with larger lot-sizes. Unfortunately, cheaper and greener transport is slower; otherwise, faster transport has a higher freight rate and environmental impact. To trade-off these conflicts, transportation modes are optimally selected.

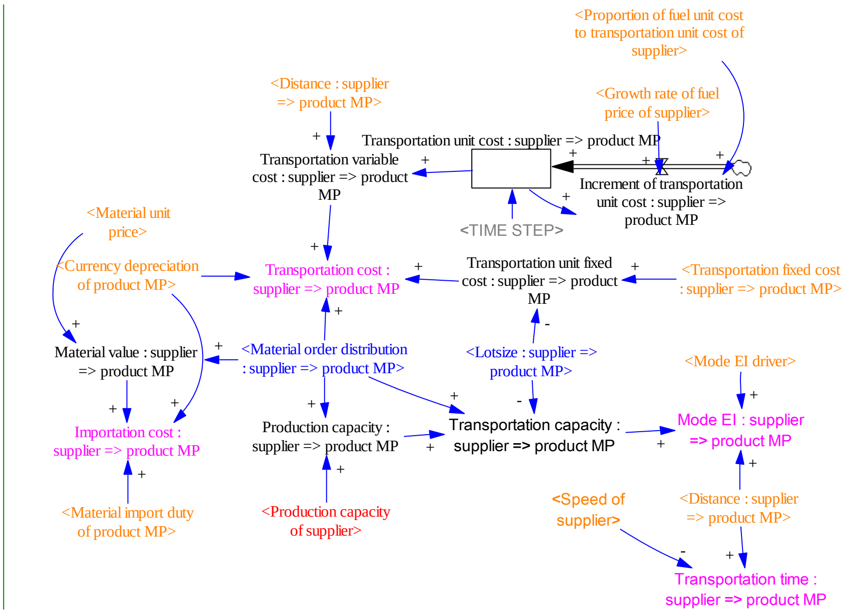


Figure 3-25 Material distribution module: supplier→product MP

In Figure 3-26, the material distribution module: supplier→component MP eventually returns three outputs. They are (1) transportation cost: supplier→component MP, (2) transportation time: supplier→component MP, and (3) mode EI: supplier→component MP. The three outputs can be optimised through three decisions of (1) material order distribution: supplier→component MP, (2) integer lot-sizes: supplier→component MP, and (3) integer number of roundtrips: supplier→component MP as follows. The preferred suppliers are closer to component MPs and have a stronger currency exchange rate. All of these preferences may not be practically available within one location, so they are traded-off to select the best-suited suppliers. The preferred component MPs are exempt from material import duty. The selected suppliers distribute material orders to the located component MPs by utilising cheaper, faster, and greener transport with larger lot-sizes. Unfortunately, cheaper and greener transport is slower; alternatively, faster transport has a higher freight rate and environmental impact. To trade-off these conflicts, transportation modes are optimally selected.

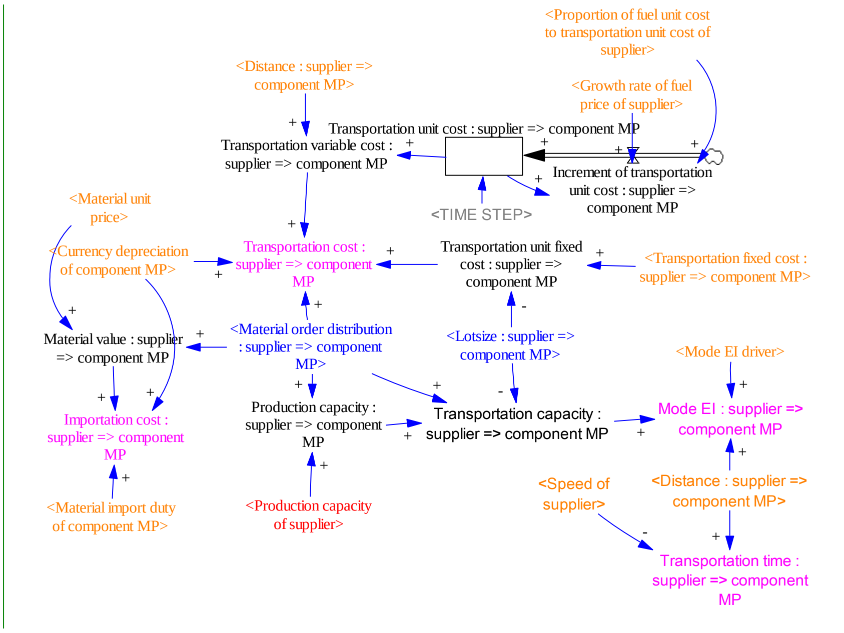


Figure 3-26 Material distribution module: supplier→component MP

The nine generic modules generate outputs related to the three objectives (cost, lead time, and environmental impact). Firstly, the SCND cost is incurred by initiation and termination of supplier contracts, shutdown and start-up of facilities, material purchasing, energy consumption, labour employment, inventory holding, transportation, and importation. Secondly, the SCND lead time is counted from when a customer places an order to a supplier until that customer receives that order. This time duration covers material procurement, component manufacturing, warehousing, and distribution, and product manufacturing, warehousing, and distribution. Thirdly, the SCND environmental impact is incurred by material extraction, manufacturing process, and transportation. These environmental impacts are calculated by using Simplified Life Cycle Assessment (SLCA) database of Manmek et al. (2008). These outputs are formulated into mathematical equations in the next step (the third step of the development of generic DSS), namely system formulation.

3.3 System formulation

The nine generic modules, which were conceptualised as causal loop diagrams in section 3.2, are formulated into mathematical equations related to the three objectives (cost, lead time, and environmental impact). The system formulation undergoes three main steps including multi-objective function, fuzzy membership function, and Pareto-optimal function as shown in Figure 3-27. The causal loop diagrams of nine generic modules are mathematically formulated into three-objective functions as described in Appendix A. The individual objective functions are optimised as single-objective decisions to determine their upper and lower bounds. They are used for converting the three-objective functions into a fuzzy membership function (Zimmermann, 1978) to address the vagueness in target values of each objective (goals). The fuzzy membership function is eventually converted into Pareto-optimal function by using a weighted max-min operator (Lin, 2004) to obtain the Pareto-optimal solution for a multi-objective decision.

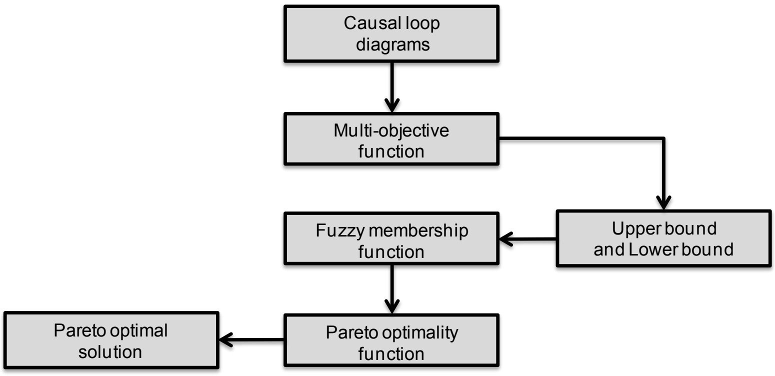


Figure 3-27 Procedure of system formulation

3.3.1 Multi-objective function

The indices, input parameters, constraints, decision variables, and outputs which are used to formulate a multi-objective function are denoted below.

Indices:

i	Index of candidate suppliers; $i = 1,....I$
k	Index of locations of candidate component manufacturing plants; $k = 1,....K$
l	Index of locations of candidate component distribution centres; $l = 1,....L$
m	Index of locations of candidate product manufacturing plants; $m = 1,....M$
n	Index of locations of candidate product distribution centres; $n = 1,....N$
o	Index of customers; $o = 1,....O$
p	Index of materials; $p = 1,....P$
q	Index of components; $q = 1,....Q$

r	Index of products; $r = 1,....R$
s	Index of candidate transportation modes; $s = 1,....S$
t	Index of planning periods; $t = 1,....T$
u,v	Index of objective functions; $u = 1,....U$; $v = 1,....V$; $U = V$

Input parameters:

PD_{ort}	Product volume: amount of the *r*-th product ordered by the *o*-th customer over the *t*-th planning period
BOM_{pr} ,	Bill of materials for a unit product: amount of the *p*-th material required to manufacture a unit of the *r*-th product
BOM_{qr}	Bill of components for a unit product: amount of the *q*-th component required to manufacture a unit of the *r*-th product
BOM_{pq}	Bill of material for a unit component: amount of the *p*-th material required to manufacture a unit of the *q*-th component
w_v	Relative weight of the *v*-th objective

Constraints:

SL	Service level: probability of not stocking out during lead time
$\max C_{ip}$	Supplier"s production capacity: maximum amount of the *p*-th material procured from the *i*-th supplier
$\max C_{kq}$	Component manufacturing plant"s production capacity: maximum amount of the *q*-th component manufactured in the *k*-th location of component manufacturing plant
$\max C_{lq}$	Component distribution centre"s warehousing capacity: maximum amount of the *q*-th component warehoused in the *l*-th location of component distribution centre
$\max C_{mr}$	Product manufacturing plant"s production capacity: maximum amount of the *r*-th product manufactured in the *m*-th location of product manufacturing plant
$\max C_{nr}$	Product distribution centre"s warehousing capacity: maximum amount of the *r*-th product warehoused in the *n*-th location of product distribution centre
$\min C_{ip}$	Minimum order quantity of supplier: minimum amount of the *p*-th material ordered by the *i*-th supplier

$\min C_{kq}$ Minimum order quantity of component manufacturing plant: minimum amount of the *q*-th component ordered to the *k*-th component manufacturing plant

$\min C_{lq}$ Minimum order quantity of component distribution centre: minimum amount of the *q*-th component ordered to the *l*-th component distribution centre

$\min C_{mr}$ Minimum order quantity of product manufacturing plant: minimum amount of the *r*-th product ordered to the *m*-th product manufacturing plant

$\min C_{nr}$ Minimum order quantity of product distribution centre: minimum amount of the *r*-th product ordered to the *n*-th product distribution centre

Decision variables:

C_{impstu} Material order allocation from product manufacturing plant to supplier: amount of the *p*-th materials allocated from the *m*-th product manufacturing plant to the *i*-th supplier by utilising the *s*-th transportation mode over the *t*-th planning period when the *u*-th objective is optimised

C_{ikpstu} Material order allocation from component manufacturing plant to supplier: amount of the *p*-th materials allocated from the k-th component manufacturing plant to the *i*-th supplier by utilising the *s*-th transportation mode over the *t*-th planning period when the *u*-th objective is optimised

C_{kmqstu} Component order allocation from product manufacturing plant to component manufacturing plant: amount of the *q*-th component allocated from the *m*-th product manufacturing plant to the *k*-th component manufacturing plant by utilising the *s*-th transportation mode over the *t*-th planning period when the *u*-th objective is optimised

C_{klqstu} Component order allocation from component distribution centre to component manufacturing plant: amount of the *q*-th component allocated from the *l*-th component distribution centre to the *k*-th component manufacturing plant by utilising the *s*-th transportation mode over the *t*-th planning period when the *u*-th objective is optimised

C_{lmqstu} Component order allocation from product manufacturing plant to component distribution centre: amount of the *q*-th component allocated from the *m*-th product manufacturing plant to the *l*-th component distribution centre by utilising the *s*-th transportation mode over the *t*-th planning period when the *u*-th objective is optimised

C_{morstu} Product order allocation from customer to product manufacturing plant: amount of the *r*-th product allocated from the *o*-th customer to the *m*-th product manufacturing plant by utilising the *s*-th transportation mode over the *t*-th planning period when the *u*-th objective is optimised

C_{mnrstu} Product order allocation from product distribution centre to product manufacturing plant: amount of the *r*-th product allocated from the *n*-th product distribution centre to the *m*-th product manufacturing plant by utilising the *s*-th transportation mode over the *t*-th planning period when the *u*-th objective is optimised

C_{norstu} Product order allocation from customer to product distribution centre: amount of the *r*-th product allocated from the *o*-th customer to the *n*-th product distribution centre by utilising the *s*-th transportation mode over the *t*-th planning period when the *u*-th objective is optimised

T_{impstu} Transportation lot size from supplier to product manufacturing plant: amount of the *p*-th material delivered from the *i*-th supplier to the *m*-th product manufacturing plant per round-trip using the *s*-th transportation mode over the *t*-th planning period when the *u*-th objective is optimised

T_{ikpstu} Transportation lot size from supplier to component manufacturing plant: amount of the *p*-th material delivered from the *i*-th supplier to the *k*-th component manufacturing plant per round-trip using the *s*-th transportation mode over the *t*-th planning period when the *u*-th objective is optimised

T_{kmqstu} Transportation lot size from component manufacturing plant to product manufacturing plant: amount of the *q*-th component delivered from the *k*-th component manufacturing plant to the *m*-th product manufacturing plant per round-trip using the *s*-th transportation mode over the *t*-th planning period when the *u*-th objective is optimised

T_{klqstu} Transportation lot size from component manufacturing plant to component distribution centre: amount of the *q*-th component delivered from the *k*-th component manufacturing plant to the *l*-th component distribution centre per round-trip using the *s*-th transportation mode over the *t*-th planning period when the *u*-th objective is optimised

T_{lmqstu} Transportation lot size from component distribution centre to product manufacturing plant: amount of the *q*-th component delivered from the *l*-th component distribution centre to the *m*-th product manufacturing plant per round-trip using the *s*-th transportation mode over the *t*-th planning period when the *u*-th objective is optimised

T_{morstu} Transportation lot size from product manufacturing plant to customer: amount of the *r*-th product delivered from the *m*-th product manufacturing plant to the *o*-th customer per round-trip using the *s*-th transportation mode over the *t*-th planning period when the *u*-th objective is optimised

T_{mnrstu} Transportation lot size from product manufacturing plant to product distribution centre: amount of the *r*-th product delivered from the *m*-th product manufacturing plant to the *n*-th product distribution centre per round-trip using the *s*-th transportation mode over the *t*-th planning period when the *u*-th objective is optimised

T_{norstu} Transportation lot size from product distribution centre to customer: amount of the *r*-th product delivered from the *n*-th product distribution centre to the *o*-th customer per round-trip using the *s*-th transportation mode over the *t*-th planning period when the *u*-th objective is optimised

S_{itu} Binary variable = $\begin{cases} 1, & \text{if the } i\text{-th supplier is selected over the } t\text{-th planning period when the } u\text{-th objective is optimised} \\ 0, & \text{otherwise} \end{cases}$

F_{ktu} Binary variable = $\begin{cases} 1, & \text{if the } k\text{-th component manufacturing plant is selected over the } t\text{-th planning period when the } u\text{-th objective is optimised} \\ 0, & \text{otherwise} \end{cases}$

F_{ltu} Binary variable = 1, if the *l*-th component distribution centre is selected over the *t*-th planning period when the *u*-th objective is optimised; 0, otherwise

F_{mtu} Binary variable = 1, if the *m*-th product manufacturing plant is selected over the *t*-th planning period when the *u*-th objective is optimised; 0, otherwise

F_{ntu} Binary variable = 1, if the *n*-th product distribution centre is selected over the *t*-th planning period when the *u*-th objective is optimised; 0, otherwise

Outputs:

$$z_{ut} \quad \text{Objective value} = \begin{cases} \text{Cost} & \text{, if } u = 1 \\ \text{Lead time} & \text{, if } u = 2 \\ \text{Environmental impact} & \text{, if } u = 3 \end{cases}$$

The three-objective functions are formulated as a multi-objective function (z_{ut}). They are traded-off through twenty-one decision variables (Eq. 1) including non-negative order distribution (C_{impstu}, C_{ikpstu}, C_{kmqstu}, C_{klqstu}, C_{lmqstu}, C_{morstu}, C_{mnrstu}, C_{norstu}) (Eq. 2), non-negative transportation lot sizes (T_{impstu}, T_{ikpstu}, T_{kmqstu}, T_{klqstu}, T_{lmqstu}, T_{morstu}, T_{mnrstu}, T_{norstu}) (Eq. 3), binary variables for either termination or initiation of supplier contracts (S_{itu}) (Eq. 4), binary variables for either shutdown or start-up of facility locations (F_{ktu}, F_{ltu}, F_{mtu}, F_{ntu}) (Eq. 5).

$$\min Z_{ut}\begin{pmatrix} C_{impstu}, C_{ikpstu}, C_{kmqstu}, C_{klqstu}, C_{lmqstu}, C_{morstu}, C_{mnrstu}, C_{norstu}, \\ T_{impstu}, T_{ikpstu},, T_{kmqstu}, T_{klqstu}, T_{lmqstu}, T_{morstu}, T_{mnrstu}, T_{norstu}, \\ S_{itu}, F_{ktu}, F_{ltu}, F_{mtu}, F_{ntu} \end{pmatrix} \tag{1}$$

subject to:

$$C_{impstu}, C_{ikpstu}, C_{kmqstu}, C_{klqstu}, \quad ;\forall i,k,l,m,n,p,q,r,t,u \quad (2)$$

$$C_{lmqstu}, C_{morstu}, C_{mnrstu}, C_{norstu} \geq 0$$

$$T_{impstu}, T_{ikpstu}, T_{kmqstu}, T_{klqstu}, \quad ;\forall i,k,l,m,n,p,q,r,t,u \quad (3)$$

$$T_{lmqstu}, T_{morstu}, T_{mnrstu}, T_{norstu} \geq 0$$

$$S_{itu} \in \{0, 1\} \quad ;\forall i,t,u \quad (4)$$

$$F_{ktu}, F_{ltu}, F_{mtu}, F_{ntu} \in \{0, 1\} \quad ;\forall k,l,m,n,t,u \quad (5)$$

The trade-offs between the three-objective functions are constrained by product volume (Eq. 6), component volume (Eq. 7), material volume (Eq. 8), mass balance (Eq. 9 and Eq. 10), and transportation capacity (Eq. 11 to Eq. 15).

The constraint of Eq. 6 ensures that the amount of products ordered by customers is fully satisfied.

$$\sum_{m,o,s}^{M,O,S} C_{morstu} + \sum_{n,o,s}^{N,O,S} C_{norstu} \geq \sum_{o}^{O} PD_{otr} \quad ;\forall r,t,u \quad (6)$$

The constraint of Eq. 7 ensures that the amount of components ordered by product manufacturing plants is fully satisfied.

$$\sum_{k,m,s}^{K,M,S} C_{kmqstu} + \sum_{l,m,s}^{L,M,S} C_{lmqstu} \geq \sum_{o,r}^{O,R} \left(PD_{otr} \times BOM_{qr}\right) \quad ;\forall q,t,u \quad (7)$$

The constraint of Eq. 8 ensures that the amount of materials ordered by product manufacturing plants and component manufacturing plants is fully satisfied

$$\sum_{i,m,s}^{I,M,S} C_{impstu} + \sum_{i,k,s}^{I,K,S} C_{ikpstu} \geq \sum_{o,r}^{O,R} \left(PD_{otr} \times BOM_{pr}\right) \quad ;\forall p,t,u \quad (8)$$

The constraint of Eq. 9 ensures that component inflows into component distribution centres are equal to component outflow from component distribution centres.

$$\sum_{l,m,s}^{L,M,S} C_{lmqstu} = \sum_{k,l,s}^{K,L,S} C_{klqstu} \quad ;\forall q,t,u \quad (9)$$

The constraint of Eq. 10 ensures that product inflows into product distribution centres are equal to product outflow from product distribution centres.

$$\sum_{n,o,s}^{N,O,S} C_{norstu} = \sum_{m,n,s}^{M,N,S} C_{mnrstu} \quad ;\forall r,t,u \quad (10)$$

The constraint of Eq. 11 ensures that the amount of materials delivered by suppliers per round-trip is no less than their minimum order requirements and no more than their production capacity.

$$\min C_{ip} \leq \sum_{m,s}^{M,S} T_{impstu} + \sum_{k,s}^{K,S} T_{ikpstu} \leq \max C_{ip} \qquad ;\forall i,p,t,u \qquad (11)$$

The constraint of Eq. 12 ensures that the amount of components delivered by component manufacturing plants per round-trip is no less than their minimum order requirements and no more than their production capacity.

$$\min C_{kq} \leq \sum_{m,s}^{M,S} T_{kmqstu} + \sum_{l,s}^{L,S} T_{klqstu} \leq \max C_{kq} \qquad ;\forall k,q,t,u \qquad (12)$$

The constraint of Eq. 13 ensures that the amount of components delivered by component distribution centres per round-trip is no less than their minimum order requirements and no more than their warehousing capacity.

$$\min C_{lq} \leq \sum_{m,s}^{M,S} T_{lmqstu} \leq \max C_{lq} \qquad ;\forall l,q,t,u \qquad (13)$$

The constraint of Eq. 14 ensures that the amount of products delivered by product manufacturing plants per round-trip is no less than their minimum order requirements and no more than their production capacity.

$$\min C_{mr} \leq \sum_{o,s}^{O,S} T_{morstu} + \sum_{n,s}^{N,S} T_{mnrstu} \leq \max C_{mr} \qquad ;\forall m,r,t,u \qquad (14)$$

The constraint of Eq. 15 ensures that the amount of products delivered by product distribution centres per round-trip is no less than their minimum order requirements and no more than their warehousing capacity.

$$\min C_{nr} \leq \sum_{o,s}^{O,S} T_{norstu} \leq \max C_{nr} \qquad ;\forall n.r,t,u \qquad (15)$$

In a period of time, the three-objective functions (z_u) are individually optimised as single-objective decisions including the minimisation of cost ($\text{Min } Z_1$), lead time ($\text{Min } Z_2$), and environmental impact ($\text{Min } Z_3$). The optimum values of individual objectives are used to find their corresponding values for other objectives. The maximum and minimum values of individual objectives are determined as upper and lower bounds of individual objectives as shown in Figure 3-28.

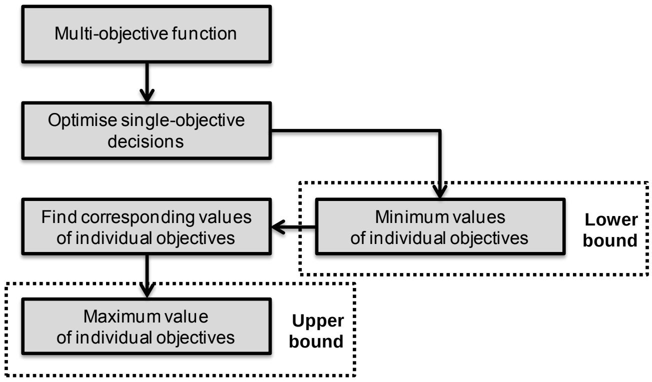


Figure 3-28 Determination of objective upper and lower bounds

The single-objective decision with cost minimisation generates the minimum value of cost (a_1^*). The minimum value of cost is used to find its corresponding values for lead time (b_1) and environmental impact (c_1). With a similar procedure, the single-objective decision with lead time minimisation generates the minimum value of lead time (b_2^*) and its corresponding values of cost (a_2) and environmental impact (c_2). The single-objective decision with environmental impact minimisation generates the minimum value of environmental impact (c_3^*) and its corresponding values of cost (a_3) and lead time (b_3). Amongst the corresponding values of individual objectives, their maximum values are set as upper bounds (UB_v). On the other hand, the minimum values of individual objectives are lower bounds (LB_v) as shown in Table 3-1. The upper and lower bounds of individual objectives are used for converting the multi-objective function into a fuzzy membership function in the next sub-section.

Table 3-1 Upper and lower bounds of individual objectives

	Z_1	Z_2	Z_3
Min Z_1	a_1^*	b_1	c_1
Min Z_2	a_2	b_2^*	c_2
Min Z_3	a_3	b_3	c_3^*
UB_v	Max $(a_1^*, a_2, a_3) = UB_1$	Max $(b_1, b_2^*, b_3) = UB_2$	Max $(c_1, c_2, c_3^*) = UB_3$
LB_v	Min $(a_1^*, a_2, a_3) = a_1^* = LB_1$	Min $(b_1, b_2^*, b_3) = b_2^* = LB_2$	Min $(c_1, c_2, c_3^*) = c_3^* = LB_3$

3.3.2 Fuzzy membership function

The multi-objective function, which was formulated in section 3.3.1, is converted into a fuzzy membership function (Zimmermann, 1978) (Eq. 16 and Figure 3-29) aiming to address the vagueness in target values that exist in the individual objectives over the planning periods. The fuzzy membership function is restricted by upper (UB_{vt}) and lower (LB_{vt}) bounds of the three objectives.

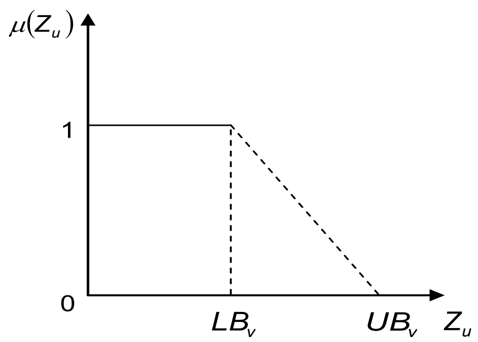


Figure 3-29 Fuzzy membership function

The constraint of Eq. 16 ensures that the individual objective values are no more than their upper bounds (UB_{vt}) and no less than their lower bounds (LB_{vt}).

$$\mu_{vt}(Z_{ut}) = \begin{cases} 1 & ; Z_{ut} \le LB_{vt} \\ \dfrac{UB_{vt} - Z_{ut}}{UB_{vt} - LB_{vt}} & ; UB_{vt} < Z_{ut} < LB_{vt} \\ 0 & ; Z_{ut} \ge UB_{vt} \end{cases} \quad ; \forall u, v, t \qquad (16)$$

where Z_{ut} refers to

$$\min Z_{ut} \begin{pmatrix} C_{impstu}, C_{ikpstu}, C_{kmqstu}, C_{klqstu}, C_{lmqstu}, C_{morstu}, C_{mnrstu}, C_{norstu}, \\ T_{impstu}, T_{ikpstu}, T_{kmqstu}, T_{klqstu}, T_{lmqstu}, T_{morstu}, T_{mnrstu}, T_{norstu}, \\ S_{itu}, F_{ktu}, F_{ltu}, F_{mtu}, F_{ntu} \end{pmatrix}$$

The fuzzy membership function returns fuzzy membership values (closeness degrees) of individual objectives over the planning periods. They measure how close objective values are to their target values. The closeness of objective values is maximised by a Pareto-optimal function which is derived from the fuzzy membership function in the next sub-section.

3.3.3 Pareto-optimal function

The fuzzy membership function, which was formulated in section 3.3.2, is converted into a Pareto-optimal function (Eq. 17). It aims to maximise the degree of closeness of any objective resulting in the decrease in the closeness degrees of the rest of the objectives. The closeness degrees of objectives can be functioned with max-min or weighted max-min operator to return the satisfaction degree.

$$\text{Max } \lambda_t \qquad ;\forall v,t \qquad (17)$$

The max-min operator (Zimmermann, 1978) is used when the multi-objectives have identical relative weights. The satisfaction degree with max-min operator is not more than the closeness degrees of the three objectives (Eq. 18) and in the unit interval of real numbers (Eq. 19).

$$\lambda_t \le \mu_{v\,t}(Z_{u\,t}) \qquad ;\forall v,t \qquad (18)$$

$$0 \le \lambda_t \le 1 \qquad (19)$$

The weighted max-min operator (Lin, 2004) is used when the multi-objectives have different relative weights. The satisfaction degree with weighted max-min operator is no more than the degree of closeness for the three objectives (Eq. 20) and is a non-negative real number (Eq. 21). The relative objective weights are in the unit interval of real numbers (Eq. 22) and their summation must be one (Eq. 23).

$$w_v \lambda_t \le \mu_{v\,t}(Z_{u\,t}) \qquad ;\forall v,t \qquad (20)$$

$$\lambda_t \ge 0 \qquad (21)$$

$$0 \le W_v \le 1 \qquad ;\forall v \qquad (22)$$

$$\sum_v^V W_v = 1 \qquad ;\forall v \qquad (23)$$

The results from the system formulation step are functions of multi-objective, fuzzy membership, and Pareto-optimality. They are subsequently configured into Vensim software version 5.4d as the fourth step for the development of generic DSS. The configured system can generate the baseline solution and result, optimal solutions and results of single objective decisions.In addition, the Pareto-optimal solution and result of multi-objective decision can also be generated. The Pareto-optimal solutions and results are generated by using the Powell algorithm (an add-on of Vensim optimiser) with multiple starting points. The optimal result (outputs and their relative decision variables) are eventually found. Then, the proposed system is verified and validated in the chapter 4.

3.4 Concluding remarks

This chapter has illustrated the development of methodology frameworks and generic DSS based on multi-objective optimisation for an environmentally sustainable supply chain network design. The development of generic DSS undergoes six steps including system understanding, conceptualisation, formulation, configuration, verification, and validation.

To understand the proposed system, it is modelled with an integrated design of supply and facility networks based on eight entities and nine generic modules.

- The eight entities are (1) suppliers, (2) manufacturing plants, (3) distribution centres or warehouses, (4) customers, (5) products, (6) components, (7) materials, and (8) transportation modes.
- The nine generic modules include (1) product demand, (2) product manufacturing and warehousing, (3) product distribution, (4) component demand, (5) component manufacturing and warehousing, (6) component distribution, (7) material demand, (8) material procurement and warehousing, and (9) material distribution modules.

The nine generic modules are conceptualised with causal loop diagrams aiming to support the decision-making process of sources of supply, facility locations, transportation modes and lot-size. These decisions are based on minimisation of cost, lead time, and environmental impact across the supply chain.

- The best-suited sources of supply and their optimal order quantity allocations are capable of fully satisfying their downstream members with lower-cost of termination and initiation, shorter preparationtime, lower-price of materials, lower-cost of transportation, exemption from import duty, shorter distance travel, and utilising faster methods of transport.
- The best-suited facility locations and their optimal order quantity allocations are capable of fully satisfying their downstream members, contributing to lower-cost of facility shutdown and start-up, labour, inventory holding, warehousing, and transportation, using more efficient forms of energy, with shorter preparation

time, exemption from import duty, shorter distance travel, and utilising faster methods of transport.

- The optimal transportation lot sizes are determined through the tradeoff decisions between preparation time, inventory holding, freight rates, and environmental impact.
- The appropriate transportation modes (i.e. air, road, rail, and sea) are selected through the tradeoff decisions between travelling time, freight rates, and environmental impact.

The causal loop diagrams are formulated into mathematical, multi-objective, fuzzy membership, and Pareto-optimal functions. These mathematical functions are configured into Vensim software version 5.4d and optimised with the Powell algorithm which is verified and validated with various industrial case studies in chapter 4.

CHAPTER 4
CASE STUDIES

The research methodology in chapter 3 outlines the research methodology framework to develop a generic Decision Support System (DSS) for an environmentally sustainable Supply Chain Network Design (SCND). In chapter 3, the first four steps (i.e. system understanding, conceptualisation, formulation, and configuration) are explained. The last two steps, namely system verification and validation, are demonstrated in this chapter. The demonstration of system verification aims to ensure that the first four steps are correctly developed. The verified system is subsequently implemented in various industrial cases as the system validation. They include (1) a cryogenic storage tank manufacturing company, (2) an automotive part manufacturing company, (3) a roof sheet manufacturing company, and (4) a power boat manufacturing company.

The demonstrations of system verification and validation consist of eleven steps as shown in Figure 4-1. The generic DSS is developed as an individual DSS for each industrial case. It has specific SCND problems (stated in the first step), assumptions (defined in the second step), and generic modules (determined in the third step). The individual DSS is applied for a baseline decision in the fourth step and single-objective decisions in the fifth step. Each of the single-objective decisions generates conflicting outputs (i.e. objective values), so they are traded off as the multi-objective decision. This requires upper bounds (UBs) and lower bounds (LBs) of individual objectives (determined in the sixth step) to formulate a fuzzy membership function, and relative objectives weights (emphasised in the seventh step) to formulate a Pareto optimality function. It may return the Pareto optimal satisfaction degree with an infinite number of iterations, so the number of iterations is restricted in the eighth step. The Pareto optimal satisfaction degree contributes to the Pareto-optimal result (i.e. configuration and its relative outputs), which is revealed in the ninth step. The Pareto-optimal result is analysed when its parameter uncertainties are fed to the individual DSS with different values (sensitivity analysis) in the tenth step. In the last step, the Pareto-optimal result is compared to that of the baseline and three single-objective decisions, along with those discussed as the system validation.

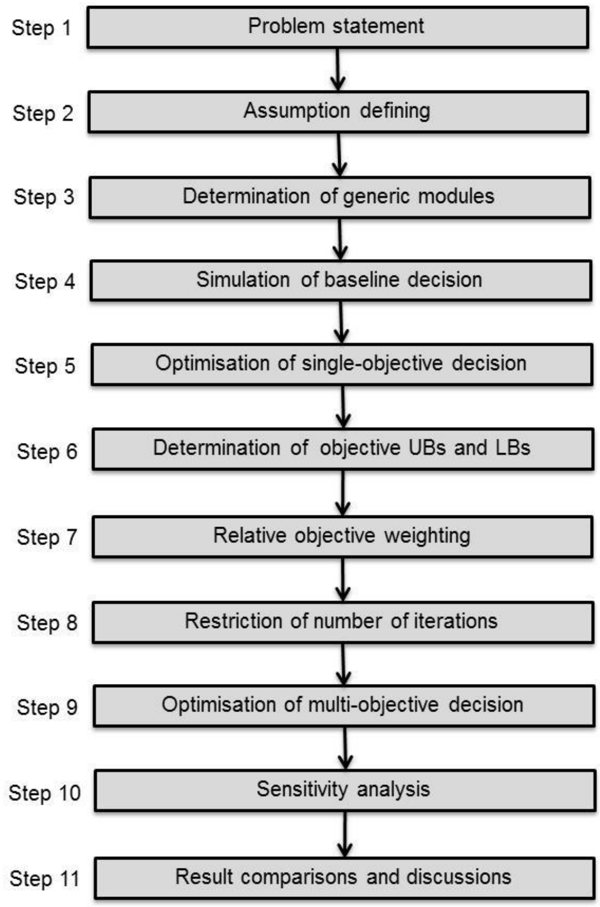


Figure 4-1 Eleven steps of system verification and validation

4.1 Cryogenic storage tank manufacturing company

The individual Decision Support System (DSS) for environmentally sustainable Supply Chain Network Design (SCND) of the cryogenic storage tank manufacturing company is verified and validated by following the eleven steps as shown in Figure 4-1. It demonstrates step-by-step system verification and validation as follows.

Step 1: Problem statement

The SCND problems are first stated in order to understand existing and desired situation of an industrial case. In this industrial case, the specialised company of cryogenic storage tanks has one location of component manufacturing plant (component MP) in Thailand, two locations of component warehouses (component DCs) in Thailand and Taiwan, and two locations of product assembly plants (product MPs) in Thailand and Taiwan. They manufacture, store, and assemble components into three product models for four customers in Thailand 1 to 3, and Taiwan. The three product models require nine material types procured from nine local suppliers in Thailand 1 to 9, and three global suppliers in US and Germany 1 and 2 as presented in Figure 4-1-1. The procured materials are promptly delivered to the component MP whenever ordered with a Make to Stock (MTS) policy. The component MP subsequently manufactures components which are assembled into products by product MPs whenever products are ordered (the so-called Make to Order: MTO). It is not required to hold the procured materials, manufactured components and assembled products as inventory.

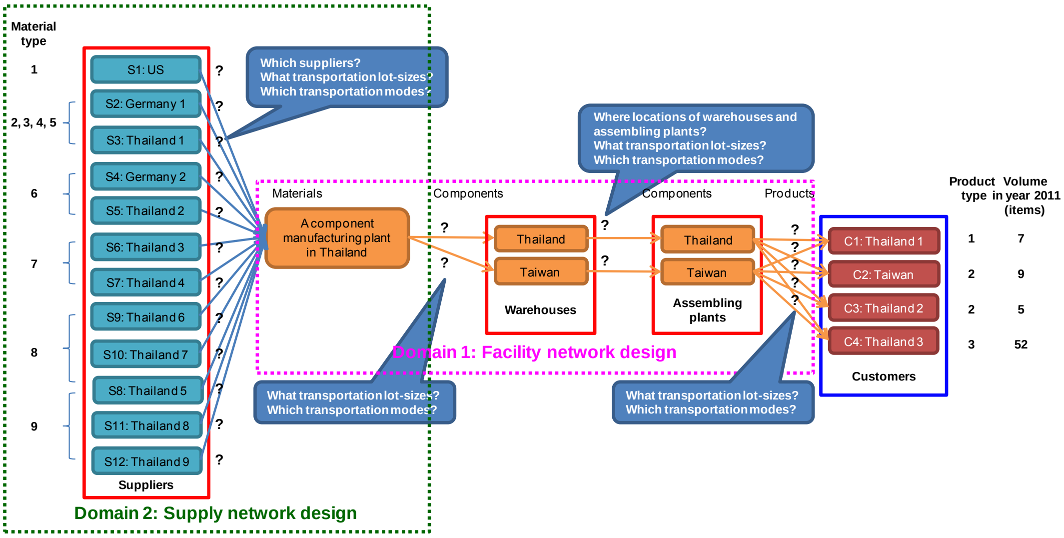


Figure 4-1-1 Supply chain networks of cryogenic storage tank manufacturing company

The supply chain networks of cryogenic storage tank manufacturing company (Figure 4-1-1) involve two strategic decisions (domains). They include designs of facility networks and supply networks. The first domain (Facility Network Design: FND) determines where locations (Thailand and Taiwan) of warehouse and assembly plant are the best-fitted. Thailand and Taiwan have a different economic competitiveness including currency exchange rates, fuel and electricity costs, and wage rates (Appendix B). Firstly, the Taiwanese Dollar (TWD) is less depreciated than the Thai Baht (THB). Secondly, Taiwan has lower costs of fuel and electricity, but their growth rates are higher than those of Thailand. Thirdly, Thailand has a lower wage rate, but its growth rate is higher than that of Taiwan. The product assembly plant in Taiwan uses automated machines and equipment to reduce the workforce and labour cost. The use of automated machines and equipment also shortens production time. Accordingly, the three differences in economic competitiveness are traded-off to select the most economic, responsive, and green facility locations.

The latter domain (Supply Network Design: SND) determines which suppliers are the best-fitted. Suppliers offering lower-price materials are farther from the component manufacturing plant. Alternatively, suppliers who are closer to the component manufacturing plant offer higher-price materials. For example, suppliers in Germany offer lower-price materials, but the distance is much longer than local suppliers (Appendix B). However, the material prices are dependent on suppliers" economic competitiveness, especially currency exchange rates. For example, the Euro is more depreciated than the THB. The greater depreciation of the Euro causes higher-price materials in the long-term. These conflicts cause the need for trade-offs between currency depreciation rates, material prices and transportation distances to select the most economic, responsive, and green suppliers.

Both of the FND and SND (Supply Chain Network Design: SCND) determine which transportation modes and what lot-sizes are optimal. Firstly, cheaper and greener transportation modes have slower speeds; alternatively, faster transport consumes more fuel. Greater fuel consumption causes higher freight rates and more environmental impact. Secondly, larger lot-sizes contribute to reduction in manufacturing cost due to infrequent setups, and less transportation cost and environmental impact due to infrequent roundtrips, but produce a longer lead time. These conflicts cause the need for trade-offs between cost, lead time, and environmental impact to determine appropriate transportation modes and lot-sizes.

In summary, the SCND problems of the cryogenic storage tank manufacturing company involve the strategic decisions (domains) of FND and SND. They include several conflicts of three objectives (i.e. cost, lead time, and environmental impact). These conflicts are however solved under numerous assumptions which are defined in the next step (referred to Figure 4-1).

Step 2: Assumption defining

The assumptions are defined as the second step in aiming to reduce complication of the SCND problems, which were stated in the first step. Certain assumptions concerning the cryogenic storage tank manufacturing company are made based on the discussions with the company officials as follows.

- There is no standard deviation of product volume since MTO strategy is implemented in component manufacturing plant and product assembly plants.
- There is no preparation unit time of suppliers since MTS strategy is implemented in suppliers.
- A component warehouse is located in the same location as the product assembly plant. That means when the location of the component warehouse is Thailand, the location of the product assembly plant is Thailand.
- There is no improvement in energy consumption at the component manufacturing plant and product assembly plants since there is no action plan to improve energy consumption.
- Thailand and Taiwan use the same environmental impact driver of energy consumption (Manmek et al., 2008).
- Candidate transportation modes include air inter-continental, truck 16 ton B250, truck 40 ton B250, train B250, and sea ship B250 (BUWAL250, 1996).
- There are no costs of shutting down and starting up any component warehouses.
- There are no costs of terminating and initiating any contracts for any suppliers.

These assumptions support the individual DSS to specify their relative parameters. They are input into generic modules which are determined based on the SCND problems of the cryogenic storage tank manufacturing company in the next step (referred to Figure 4-1).

Step 3: Determination of generic modules

The generic modules are determined based on the SCND problems and assumptions, which were stated in the first two steps. The SCND problems of the cryogenic storage tank manufacturing company involve the strategic decisions (domains) of FND and SND. Each of them has individual supply chain entities which are specified as follows.

1) Facility Network Design (FND)

The FND of cryogenic storage tank manufacturing company covers seven entities which are indexed as follows.

- Component MP (*k* = 1) is located in Thailand;
- Component DCs (*l* = 1 and 2) are located in Thailand and Taiwan;
- Product MPs (*m* = 1 and 2) are located in Thailand and Taiwan;
- Customers (*o* = 1,…,4) are in Thailand 1, Taiwan, Thailand 2, and Thailand 3;
- Products (*r* = 1,…,3) include product model 1 to 3.
- Components (*q* = 1,...,3) include component set of product model 1 to 3;
- Transportation modes (*s* = 1,...,5) include air, 16-ton truck (T16), 40-ton truck (T40), rail, and sea

These seven entities involve six generic modules of the individual DSS. They are (1) product demand, (2) product manufacturing and warehousing, (3) product distribution, (4) component demand, (5) component manufacturing and warehousing, and (6) component distribution (Figure 3-2). These six generic modules are input with numerous parameters as shown in Appendix B. They contribute to the optimum values of eight decision variables including (1) locational selection of product MPs, (2) transportation mode selection and (3) transportation lot-sizes utilised for delivering products from the located product MP to customers, (4) locational selection of component DCs, (5) transportation mode selection and (6) transportation lot-sizes utilised for delivering components from the located component DC to the located product MP, (7) transportation mode selection and (8) transportation lot-sizes utilised for delivering components from the component MP to the located component DC.

2) Supply Network Design (SND)

The SND of the cryogenic storage tank manufacturing company covers five entities which are indexed as follows.

- Component MP (*k* = 1) is located in Thailand,
- Suppliers (*i* = 1,...,12) are in the United States (US), Germany 1, Thailand 1, Germany 2, and Thailand 2 to 9,
- Components (*q* = 1,...,3) include component set of product model 1 to 3,
- Materials (*p* = 1,...,9) include material type 1 (glass), 2 (low nickel ferro), 3 (low nickel ferro), 4 (copper), 5 (copper), 6 (low nickel ferro), 7 (no nickel ferro), 8 (low nickel ferro), and 9 (no nickel ferro), and
- Transportation modes (*s* = 1,...,5) include air, 16-ton truck (T16), 40-ton truck (T40), rail, and sea.

These five entities involve three generic modules of the individual DSS. They are (1) material demand, (2) material procurement and warehousing, and (3) material distribution (Figure 3-2). These three generic modules are input with numerous parameters as shown in Appendix B. They contribute to the optimum values of four decision variables including (1) supplier selection, (2) transportation mode selection, and (3) transportation lot-sizes utilised for delivering materials from the selected suppliers to the component MP.

The nine generic modules, which were determined above for environmentally sustainable SCND of the cryogenic storage tank manufacturing company, are formally tested as a system validation before applied for the baseline decision in the next step (referred to Figure 4-1). The formal tests of structure confirmation, parameter confirmation, dimensional consistency, and extreme-condition are demonstated in Appendix C.

Step 4: Simulation of baseline decision

The baseline decision aims to simulate the nine generic modules, which were determined in the third step, with the existing decision variables. They generate baseline cost, lead time, and environmental impact for the ten years of planning period as the baseline outputs. This step presents baseline supply chain networks and their relative outputs as follows.

1) Baseline supply chain networks

The baseline decision locates facilities (i.e. component manufacturing plant, component warehouse, and product assembly plant) in Thailand since Thailand has a much lower wage rate than Taiwan as shown in Figure 4-1-2. The manufactured components, warehoused components, and assembled products are locally delivered by utilising 40-ton trucks, whereas sea mode is utilised for international transportation. These utilised transportation modes contribute to lower transportation cost and environmental impact, however, there is a lengthened lead time. The lengthened lead time is improved by minimal lot-sizes (i.e. 1 item).

In addition, the baseline decision selects suppliers offering lower-price materials. The selected suppliers deliver nine material types locally by utilising 40-ton trucks with maximal lot-sizes (i.e. 48 tons). They contribute to reduction in transportation cost and environmental impact. Otherwise, air mode with minimal lot-sizes is globally utilised to shorten lead time. As shown in Figure 4-1-2, suppliers in Germany are selected to supply the material types 2 to 6 by utilising air mode with lot-sizes of 12 tons, whereas the rest of the material types are procured from local suppliers by utilising 40-ton trucks with lot-sizes of 48 tons.

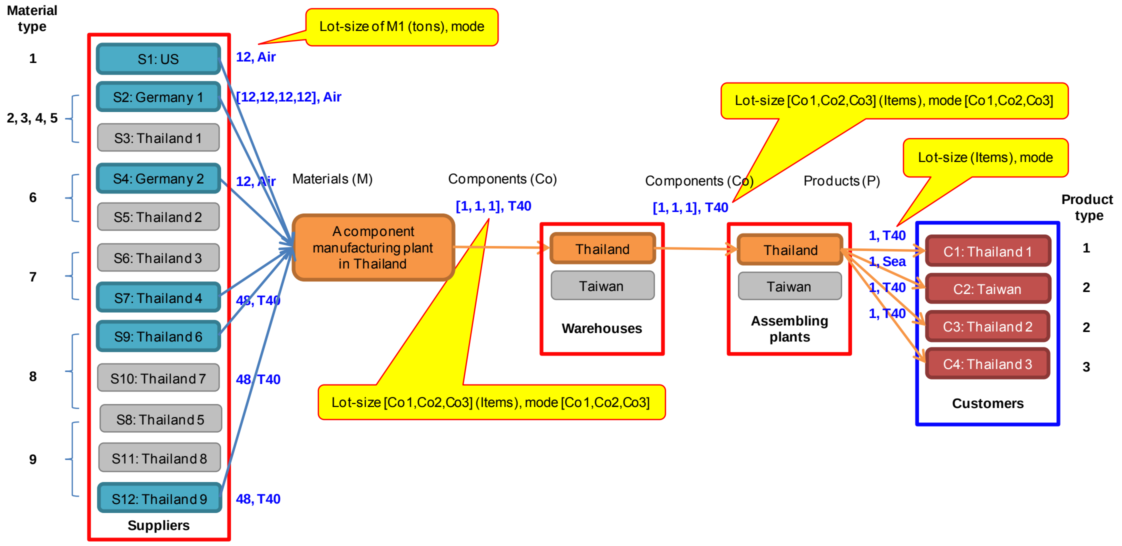


Figure 4-1-2 Baseline supply chain networks

2) Outputs of baseline decision

Based on the baseline configuration, the individual DSS return the baseline cost, lead time, and environmental impact along the supply chain for the ten years of planning period as shown in Table 4-1-1. The baseline cost tends to increase annually due to the growth rates of energy price, fuel price, wage rate, and currency depreciation. In contrast, the baseline lead time and environmental impact are constant because their utilised transportation modes and lot-sizes are not changed over the ten years of planning period. The baseline outputs are averaged by the summation of baseline outputs over the ten years of planning period and divided by ten as shown in the last row of Table 4-1-1. The baseline cost, lead time, and environmental impact respectively are 1.762 Million Thai Baht (M THB) per item, 0.223 years, and 781 points per item on average.

Table 4-1-1 Baseline outputs

Planning year	Baseline decision		
	Cost (M THB per item)	Lead time (years)	Environmental impact (x 1,000 points per item)
2011	0.991	0.223	0.757
2012	1.111	0.223	0.776
2013	1.245	0.223	0.789
2014	1.386	0.223	0.778
2015	1.552	0.223	0.778
2016	1.750	0.223	0.783
2017	1.976	0.223	0.788
2018	2.226	0.223	0.784
2019	2.520	0.223	0.785
2020	2.863	0.223	0.789
Average	**1.762**	**0.223**	**0.781**

It is noticeable that the individual DSS for environmentally sustainable SCND of the cryogenic storage tank manufacturing company is capable of explaining behaviour of the baseline supply chain networks and their relative outputs. They are used for comparing to the results of three single-objective and multi-objective decisions in the eleventh step.

Step 5: Optimisation of single-objective decisions

The single-objective decisions aim to optimise an objective without consideration of other objectives. For example, the lowest cost is aimed, whereas the other two objectives (i.e. lead time and environmental impact) are not considered. This step presents the optimisation of three single-objective decisions including minimisation of cost, lead time, and environmental impact as follows.

1) Cost minimisation

The cost minimisation aims to reduce cost along the supply chain over the ten years of planning period. Based on the cost minimisation, the individual DSS suggests decision variables which contribute to the lowest cost. These suggestions and their contribution are provided and discussed as follows.

1.1) Supply chain networks based on cost minimisation

The individual DSS based on cost minimisation suggests three configurations over the ten years of planning period as shown in Figures 4-1-3a to 4-1-3c. The three configurations locate facilities in Thailand. Thailand has a much lower wage rate than Taiwan contributing to reduction in manufacturing and warehousing costs. The manufactured components and assembled products are delivered with maximal lot-sizes. The maximal lot-sizes contribute to reduction in manufacturing cost due to infrequent setups, and transportation cost due to infrequent roundtrips. The transportation cost is also reduced by utilising cheaper transport (i.e. rail and sea modes). Although rail mode is a cheaper transport, it is not locally utilised for short distances (e.g. 5 kilometres). In the case of short distances, 40-ton trucks are hence utilised instead. For global transport, sea (the cheapest) mode is utilised. As shown in Figure 4-1-3a to 4-1-3c, the component manufacturing plant in Thailand utilises rail mode for delivering the 3-rd component with a lot-size of 52 items to the component warehouse in Thailand. The component warehouse in Thailand utilises 40-ton trucks for delivering the 3-rd component with a lot-size of 52 items to the product assembly plant in Thailand. The product assembly plant in Thailand utilises 40-ton trucks for delivering the 3-rd product with a lot-size of 52 items to customers in Thailand 3.

The three configurations utilise cheaper transport (i.e. 40-ton trucks and sea mode) with maximal lot-sizes (i.e. 48 tons) over the ten years of planning period, but suppliers are different. In the first two years, suppliers offering lower-price materials are selected as shown in Figure 4-1-3a. After that, the 8-th material type is procured from suppliers in Thailand 7 having shorter-distance transportation (Figure 4-1-3b). The shorter distance offsets a growth rate of transportation cost incurred by the growth rate of fuel price. It overcomes a growth rate of material cost incurred by the growth rate of currency depreciation of suppliers in Thailand 6. In year 2019, material types 2 to 6 are procured from suppliers in Thailand (Figure 4-1-3c). Their materials are cheaper than those of suppliers in Germany. The cheaper materials are caused by the growth rate of Thai Baht (THB) depreciation slower than that of the Euro.

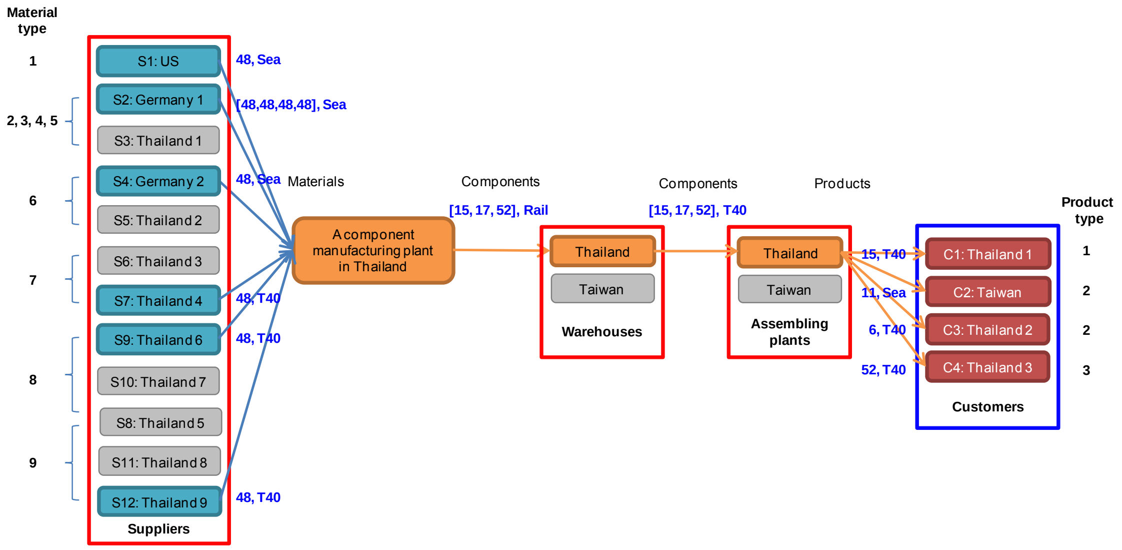


Figure 4-1-3a Supply chain networks based on cost minimisation in year 2011 and 2012 (the 1-st configuration)

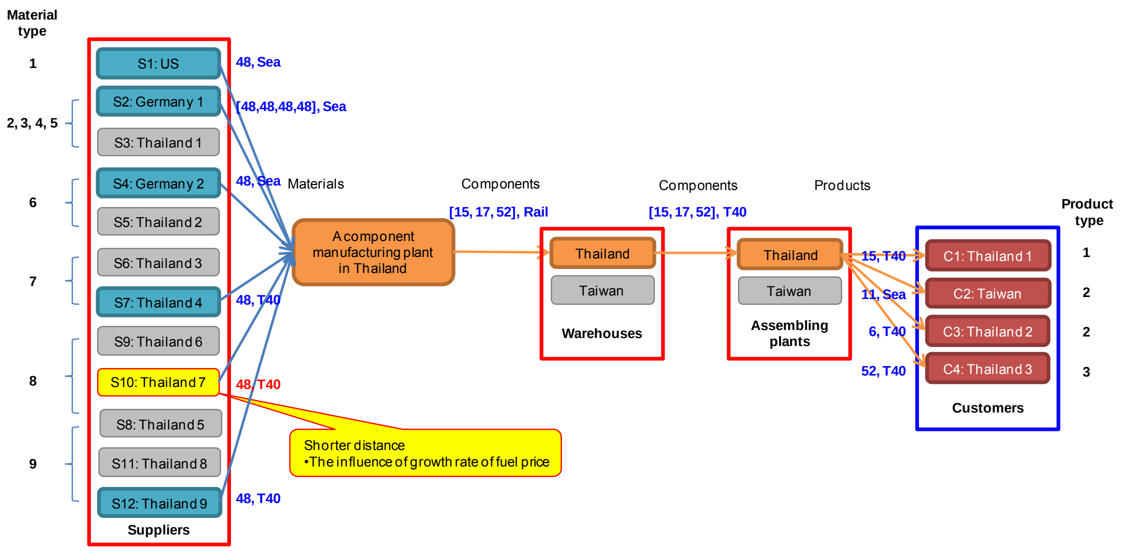


Figure 4-1-3b Supply chain networks based on cost minimisation in year 2013 and 2018 (the 2-nd configuration)

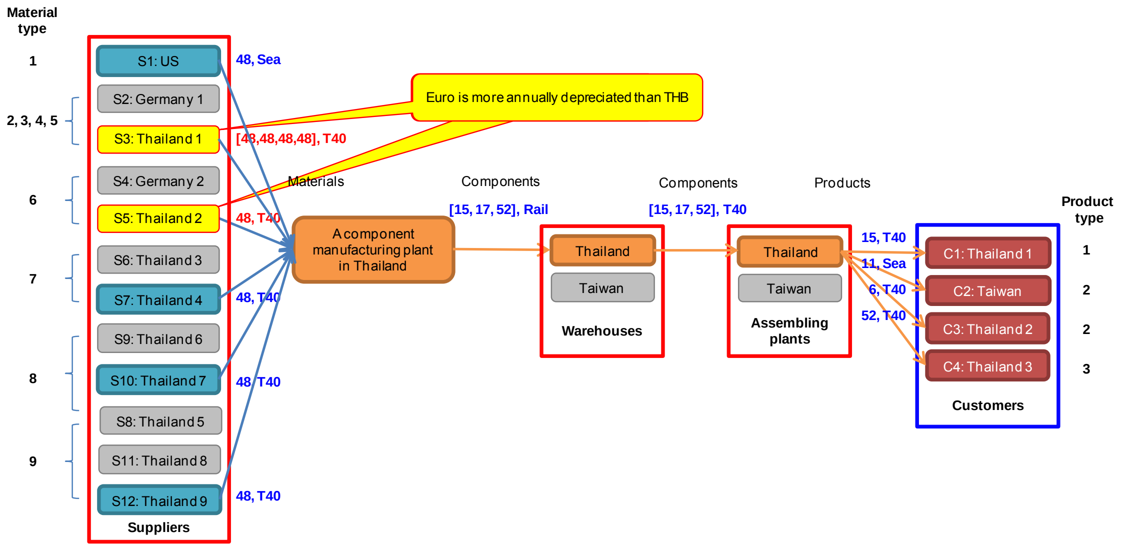


Figure 4-1-3c Supply chain networks based on cost minimisation in year 2019 and 2020 (the 3-rd configuration)

The three configurations generate the lowest cost in different time durations due to the influence of economic competitiveness as shown in Table 4-1-2. The frequent reconfigurations over the ten years of planning period are impractical. One of the three configurations is therefore selected as the cheapest configuration in the long-term. It is measured by the product cost on average (the summation of product cost over the ten years of planning period and divided by ten) as shown in the last row of Table 4-1-2. It reveals that supply chain networks of the cryogenic storage tank manufacturing company are long-term designed with either the 1-st (Figure 4-1-3a) or 2-nd (Figure 4-1-3b) configuration which generates the lowest product cost on average.

Table 4-1-2 Product cost of candidate economic configurations

Planning year	Product cost (THB per item)		
	Configuration 1	Configuration 2	Configuration 3
2011	**895,333**	895,334	918,018
2012	**1,002,622**	1,002,622	1,023,000
2013	1,120,134	**1,120,134**	1,138,000
2014	1,241,749	**1,241,749**	1,257,000
2015	1,385,471	**1,385,470**	1,397,000
2016	1,557,651	**1,557,649**	1,566,000
2017	1,754,427	**1,754,425**	1,759,000
2018	1,968,587	**1,968,584**	1,969,000
2019	2,223,087	2,223,084	**2,218,000**
2020	2,519,638	2,519,634	**2,509,000**
Average	**1,566,870**	**1,566,869**	**1,575,402**

1.2) Outputs of cost minimisation

Based on the 2-nd (cheapest) configuration, the individual DSS returns the lowest product cost and its corresponding values of lead time and environmental impact for the ten years of planning period as shown in Table 4-1-3. The cost and lead time tend to be increasing annually. The annual growth of cost is influenced by the growth rates of energy price, fuel price, wage rate, and currency depreciation. The annual growth of lead time is influenced by the growth rate of product volume which enlarges transportation lot-sizes; otherwise, the environmental impact is fairly constant because it is calculated based on maximal lot-sizes over the ten years of planning period. The last row of Table 4-1-3 reveals the outputs on average of cost minimisation. The lowest value of cost is 1.567 M THB per item, whereas its relative lead time and environmental impact respectively are valued at 3.229 years, and 670 points per item.

Table 4-1-3 Outputs of cost minimisation

Planning year	Cost minimisation		
	Cost (M THB per item)	Lead time (years)	Environmental impact (x 1,000 points per item)
2011	0.895	2.806	0.654
2012	1.003	2.989	0.667
2013	1.120	3.115	0.677
2014	1.242	3.139	0.665
2015	1.385	3.206	0.664
2016	1.558	3.273	0.669
2017	1.754	3.340	0.673
2018	1.968	3.407	0.668
2019	2.222	3.474	0.668
2020	2.519	3.542	0.670
Average	**1.567**	**3.229**	**0.668**

2) Lead time minimisation

The lead time minimisation aims to shorten the longest lead time of the supply chain as a critical path over the ten years of planning period. Based on the lead time minimisation, the individual DSS suggests decision variables which contribute to the shortest lead time. These suggestions and contribution are revealed and discussed as follows.

2.1) Supply chain networks based on lead time minimisation

The individual DSS based on lead time minimisation suggests a single configuration over the ten years of planning period as shown in Figure 4-1-4. The suggested configuration locates facilities in Taiwan. Taiwan uses automated machines and equipment contributing to shorten production time. Total production time is less when lot-sizes are smaller. The smaller lot-sizes cause a shorter lead time. The lead time is also shortened by utilising faster transport (i.e. 16-ton trucks and air mode). The faster transportation modes are, however, incapable of delivering large product volume, so 40-ton trucks and sea mode are utilised respectively instead for local and global transport. As shown in Figure 4-1-4, the component manufacturing plant in Thailand utilises sea mode for delivering the 3-rd component with a lot-size of 1 item to the component warehouse in Taiwan. The component warehouse in Taiwan utilises 40-ton trucks for delivering the 3-rd component with a lot-size of 1 item to the product assembly plant in Thailand. The product assembly plant in Taiwan utilises sea mode for delivering the 3-rd product with a lot-size of 1 item to customers in Thailand 3.

The critical lead time of the suggested configuration is incurred by procuring the 1-st material type since there is a long distance between suppliers in the United States (US) and the component manufacturing plant in Thailand. This can be shortened by utilising air mode with a minimal lot-size (i.e. 12 tons). This air mode is also utilised for other global suppliers in order to avoid lengthening the critical lead time. Otherwise, 40-ton trucks as a slower transportation mode are locally utilised as it does not have impact on the critical lead time.

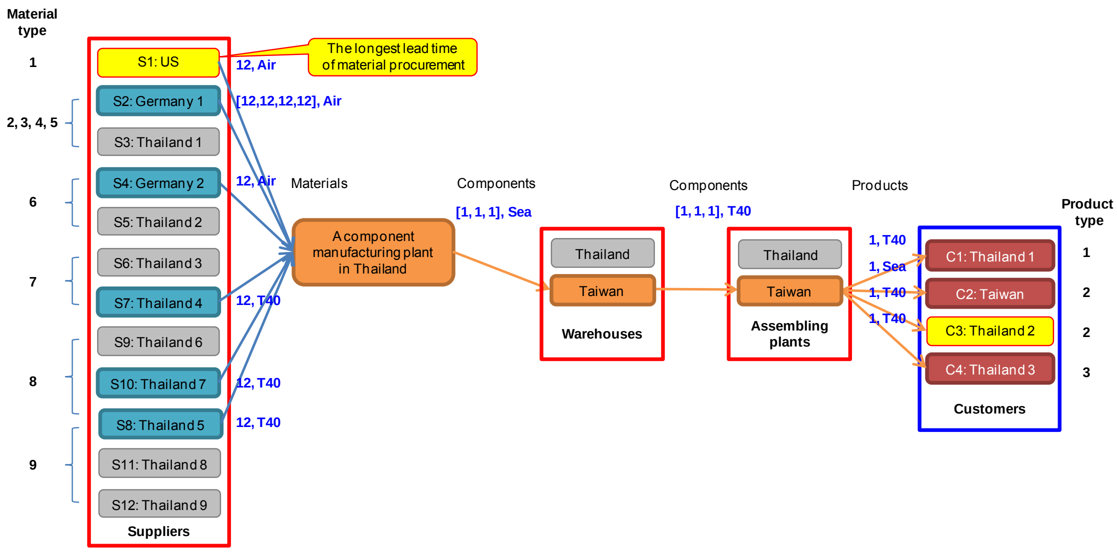


Figure 4-1-4 Supply chain networks based on lead time minimisation for the ten years of planning period

2.2) Outputs of lead time minimisation

Based on the fastest configuration, the individual DSS returns the shortest lead time and its corresponding values of cost and environmental impact for the ten years of planning period as shown in Table 4-1-4. The cost and environmental impact tend to increase annually. The annual growth of cost is influenced by the growth rates of energy price, fuel price, wage rate, and currency depreciation. On the other hand, the lead time is steadily constant and the environmental impact is fairly constant. In contrast, the baseline lead time and environmental impact are constant because their utilised transportation modes and lot-sizes are not changed over the ten years of planning period. The last row of Table 4-1-4 reveals the outputs on average of lead time minimisation. The shortest value of lead time is 0.216 years, whereas its relative cost and environmental impact are 2.273 M THB per item and 1,157 points per item respectively.

Table 4-1-4 Outputs of lead time minimisation

Planning year	Lead time minimisation		
	Cost (M THB per item)	Lead time (years)	Environmental impact (x 1,000 points per item)
2011	1.603	0.216	1.108
2012	1.711	0.216	1.136
2013	1.835	0.216	1.156
2014	1.963	0.216	1.143
2015	2.108	0.216	1.149
2016	2.279	0.216	1.161
2017	2.468	0.216	1.173
2018	2.672	0.216	1.174
2019	2.910	0.216	1.181
2020	3.181	0.216	1.188
Average	**2.273**	**0.216**	**1.157**

3) Environmental impact minimisation

The environmental impact minimisation aims to reduce environmental impact along the supply chain over the ten years of planning period. Based on the environmental impact minimisation, the individual DSS suggests decision variables which contribute to the lowest environmental impact. These suggestions and contribution are provided and discussed as follows.

3.1) Supply chain networks based on environmental impact minimisation

The individual DSS based on environmental impact minimisation suggests a single configuration over the ten years of planning period as shown in Figure 4-1-5. The suggested configuration locates facilities in Thailand. Thailand has much shorter total distance than Taiwan contributing to reduction in environmental impact. The manufactured components and assembled products are delivered with maximal lot-sizes. The maximal lot-sizes contribute to improvement in the environmental impact of transportation due to infrequent roundtrips. The environmental impact of transportation is also improved by utilising greener transport (i.e. rail and sea modes). Although rail mode is a greener form of transport, it is not locally utilised for short distances (e.g. 5 kilometres). In the case of short distances, 40-ton trucks aare utilised instead. For global transport, sea (the greenest) mode is utilised. As shown in Figure 4-1-5, the component manufacturing plant in Thailand utilises rail mode for delivering the 3-rd component with a lot-size of 52 items to the component warehouse in Thailand. The component warehouse in Thailand utilises 40-ton trucks for delivering the 3-rd component with a lot-size of 52 items to the product assembly plant in Thailand. The product assembly plant in Thailand utilises 40-ton trucks for delivering the 3-rd product with a lot-size of 52 items to customers in Thailand 3.

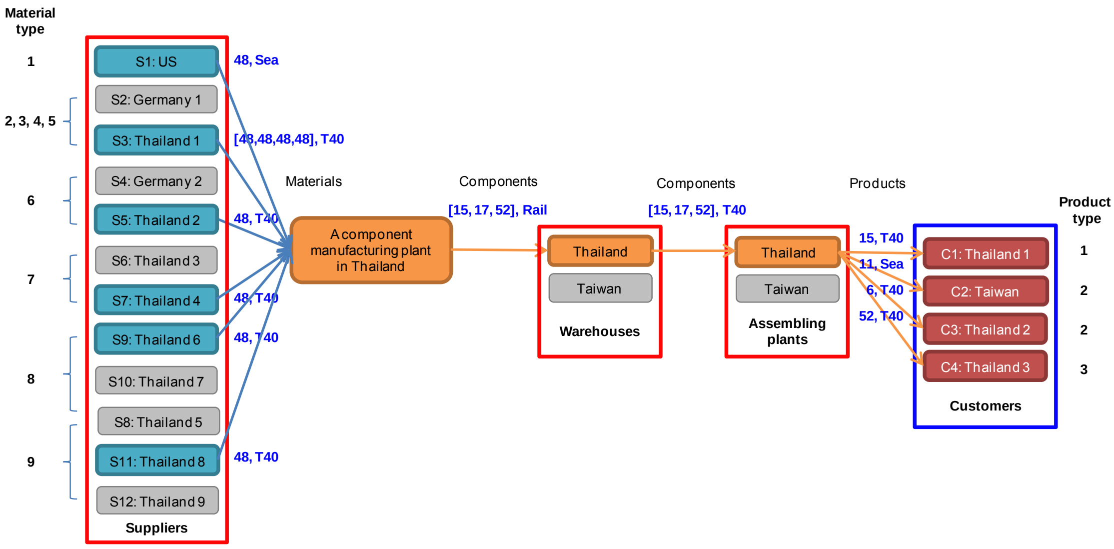


Figure 4-1-5 Supply chain networks based on environmental impact minimisation for the ten years of planning period

The suggested configuration selects suppliers closer to the component manufacturing plant in Thailand and utilises greener transport (i.e. 40-ton trucks and sea modes) with maximal lot-sizes (i.e. 40 tons) over the ten years of planning period as shown in Figure 4-1-5. The 1-st material types are procured from suppliers in the United States (US) by utilising sea mode with a lot-size of 48 tons. 40-ton trucks with lot-sizes of 48 tons are utilised for the rest of the material types procured from local suppliers.

3.2) Outputs of environmental impact minimisation

Based on the greenest configuration, the individual DSS returns the lowest environmental impact and its corresponding values of cost and lead time for the ten years of planning period as shown in Table 4-1-5. The cost and lead time tend to increase annually. The annual growth of cost is influenced by the growth rates of energy price, fuel price, wage rate, and currency depreciation. The annual growth of lead time is influenced by the growth rate of product volume which increases transportation lot-sizes; otherwise, the environmental impact is fairly constant because it is calculated based on maximal lot-sizes over the ten years of planning period. The last row of Table 4-1-5 reveals the outputs on average of environmental impact minimisation. The lowest value of environmental impact is 667 points per item, whereas its relative cost and lead time are valued at 1.576 M THB per item and 3.229 years.

Table 4-1-5 Outputs of environmental impact minimisation

Planning year	Environmental impact minimisation		
	Cost (M THB per item)	**Lead time (years)**	**Environmental impact (x 1,000 points per item)**
2011	0.919	2.806	**0.653**
2012	1.024	2.989	**0.667**
2013	1.139	3.115	**0.676**
2014	1.258	3.139	**0.665**
2015	1.399	3.206	**0.663**
2016	1.567	3.273	**0.668**
2017	1.759	3.340	**0.673**
2018	1.970	3.407	**0.667**
2019	2.219	3.474	**0.668**
2020	2.510	3.542	**0.669**
Average	**1.576**	**3.229**	**0.667**

It is noticeable that the three single-objective decisions suggest different configurations. The optimal configuration based on an objective contributes to the optimum value of that objective, whereas it is in conflict with the other two objectives. The conflicts of three objectives are traded off by using the multi-objective decision. It requires upper and lower bounds of individual objectives which are determined in the next step (referred to Figure 4-1).

Step 6: Determination of objective upper and lower bounds

The upper (UB_{vt}) and lower (LB_{vt}) bounds of individual objectives over the planning periods (*t*) are determined as input parameters of the fuzzy membership function (Zimmermann, 1978) (Eq. 1). It returns the fuzzy membership values (or degrees of closeness) of individual objectives (μ_{vt}) aiming to measure how close the objective values (Z_{ut}) to their target values (LB_{vt}) are.

$$\mu_{vt}(Z_{ut}) = \begin{cases} 1 & ; Z_{ut} \le LB_{vt} \\ \dfrac{UB_{vt} - Z_{ut}}{UB_{vt} - LB_{vt}} & ; UB_{vt} < Z_{ut} < LB_{vt} \\ 0 & ; Z_{ut} \ge UB_{vt} \end{cases} \qquad ; \forall u, v, t \qquad (1)$$

The optimum values of cost (*u, v* = 1), lead time (*u, v* = 2), and environmental impact (*u, v* = 3) are determined as Lower Bounds (LB_{vt}). Their corresponding values of the other two objectives, which return maximum values, are determined as Upper Bounds (UB_{vt}).

1.1) Upper and lower bounds of cost objective

Over the ten years of planning period, the lower bound of cost objective is caused by the cost minimisation, whereas the upper bound of cost objective returns the maximum cost. It is derived from the cost values of lead time minimisation and environmental impact minimisation as shown in Table 4-1-6a.

Table 4-1-6a Upper and lower bounds of cost objective

Planning year (*t*)	Cost (M THB per item)				
	Cost minimisation	Lead time minimisation	Environmental impact minimisation	Upper bound	Lower bound
2011	0.895	1.603	0.919	**1.603**	**0.895**
2012	1.003	1.711	1.024	**1.711**	**1.003**
2013	1.120	1.835	1.139	**1.835**	**1.120**
2014	1.242	1.963	1.258	**1.963**	**1.242**
2015	1.385	2.108	1.399	**2.108**	**1.385**
2016	1.558	2.279	1.567	**2.279**	**1.558**
2017	1.754	2.468	1.759	**2.468**	**1.754**
2018	1.968	2.672	1.970	**2.672**	**1.968**
2019	2.222	2.910	2.219	**2.910**	**2.222**
2020	2.519	3.181	2.510	**3.181**	**2.519**
Average	**1.567**	**2.273**	**1.576**	**2.273**	**1.565**

1.2) Upper and lower bounds of lead time objective

Over the ten years of planning period, the lower bound of lead time objective is caused by the lead time minimisation, whereas the upper bound of lead time objective returns the maximum lead time. It is derived from the lead time values of cost minimisation and environmental impact minimisation as shown in Table 4-1-6b.

Table 4-1-6b Upper and lower bounds of lead time objective

Planning year (*t*)	Lead time (years)				
	Cost minimisation	Lead time minimisation	Environmental impact minimisation	Upper bound	Lower bound
2011	2.806	0.216	2.806	**2.806**	**0.216**
2012	2.989	0.216	2.989	**2.989**	**0.216**
2013	3.115	0.216	3.115	**3.115**	**0.216**
2014	3.139	0.216	3.139	**3.139**	**0.216**
2015	3.206	0.216	3.206	**3.206**	**0.216**
2016	3.273	0.216	3.273	**3.273**	**0.216**
2017	3.340	0.216	3.340	**3.340**	**0.216**
2018	3.407	0.216	3.407	**3.407**	**0.216**
2019	3.474	0.216	3.474	**3.474**	**0.216**
2020	3.542	0.216	3.542	**3.542**	**0.216**
Average	**3.229**	**0.216**	**3.229**	**3.229**	**0.216**

1.3) Upper and lower bounds of environmental impact objective

Over the ten years of planning period, the lower bound of environmental impact objective is caused by the environmental impact minimisation, whereas the upper bound of environmental impact objective returns the maximum environmental impact. It is derived from the environmental impact values of cost minimisation and lead time minimisation as shown in Table 4-1-6c.

Table 4-1-6c Upper and lower bounds of environmental impact objective

Planning year (t)	Environmental impact (x 1,000 points per item)				
	Cost minimisation	Lead time minimisation	Environmental impact minimisation	Upper bound	Lower bound
2011	0.654	1.108	0.653	**1.108**	**0.653**
2012	0.667	1.136	0.667	**1.136**	**0.667**
2013	0.677	1.156	0.676	**1.156**	**0.676**
2014	0.665	1.143	0.665	**1.143**	**0.665**
2015	0.664	1.149	0.663	**1.149**	**0.663**
2016	0.669	1.161	0.668	**1.161**	**0.668**
2017	0.673	1.173	0.673	**1.173**	**0.673**
2018	0.668	1.174	0.667	**1.174**	**0.667**
2019	0.668	1.181	0.668	**1.181**	**0.668**
2020	0.670	1.188	0.669	**1.188**	**0.669**
Average	**0.668**	**1.157**	**0.667**	**1.157**	**0.667**

The upper and lower bounds of the three objectives (i.e. cost, lead time, and environmental impact) are used to formulate the fuzzy membership function. It is subsequently converted into the Pareto optimality function which requires relative weights of individual objectives. They are emphasised in the next step (referred to Figure 4-1).

Step 7: Relative objective weighting

The relative weights of objectives (W_v) are emphasised to convert the fuzzy membership function (Eq. 1) into the Pareto optimality function (Zimmermann, 1978) (Eq. 2) with weighted max-min operator (Lin, 2004) (Eq. 3). This conversion aims to maximise the closeness degree of any objective resulting in the decrease in the closeness degrees of some other objectives.

$$\text{Max } \lambda_t \tag{2}$$

$$w_v \lambda_t \leq \mu_{vt}(Z_{ut}) \qquad ;\forall v, t \tag{3}$$

The relative weights of objectives (W_v) are in the unit interval of real numbers in which individual objectives are relatively emphasised by decision makers. The highest important objective is weighted with the highest value relative to that of other objectives; otherwise, the lowest value is applied. Decision makers of the cryogenic storage tank company pay much attention to lead time (v = 2), followed by cost (v = 1) in order to achieve mass customisation as an organisational strategy. On the other hand, there is little attention to environmental impact (v = 3) because environmental regulations and consciousness in Thailand are not strong. Accordingly, the company emphasises cost, lead time, and environmental impact with relative weights at 0.4, 0.5, and 0.1 respectively (*W* [0.4, 0.5, 0.1]). The relative objective weights are used to formulate the Pareto optimality function. It is optimised with a number of iterations using Powell algorithm and eventually returns the satisfaction degree. It may be greater when the number of iterations is increased. The infinitely increased number of iterations is, however, impractical, so the number of iterations is restricted in the next step (referred to Figure 4-1).

Step 8 Restriction of number of iterations

The number of iterations is appropriately restricted by a test of the hypothesis that the population mean (μ_0) is compared to the sample mean (μ) whose observations (x_j) are independent and identically distributed (i.i.d.). The mean comparison is tested with the *t* statistic since the population variance (σ^2) is unknown and estimated from the i.i.d. sample observations. The *t* – test gives the ability to erroneously reject and fail to reject the test hypothesis with probabilities no greater than α and β respectively (Mace, 1964). Accordingly, the number of iterations for the satisfaction degree (the summation of Pareto-optimal satisfaction degree over the ten years of planning period and divided by ten) is restricted by using the *t* – test.

The satisfaction degree is incrementally generated as a series shown in Figure 4-1-6, so the series is transformed into the i.i.d. observations by the difference (Δ_j) between the satisfaction degree (x_j) and its predecessor (x_{j-1}) in Eq. 4 (Greiner, 1996). The population mean of the difference in satisfaction degree is tested with null and research hypotheses which are identified in Eq. 5 and Eq. 6 respectively. The hypothesis testing is based on the *t* statistic which enables restriction of the number of iterations in Eq. 7.

$$\Delta_j = x_j - x_{j-1} \quad (4)$$

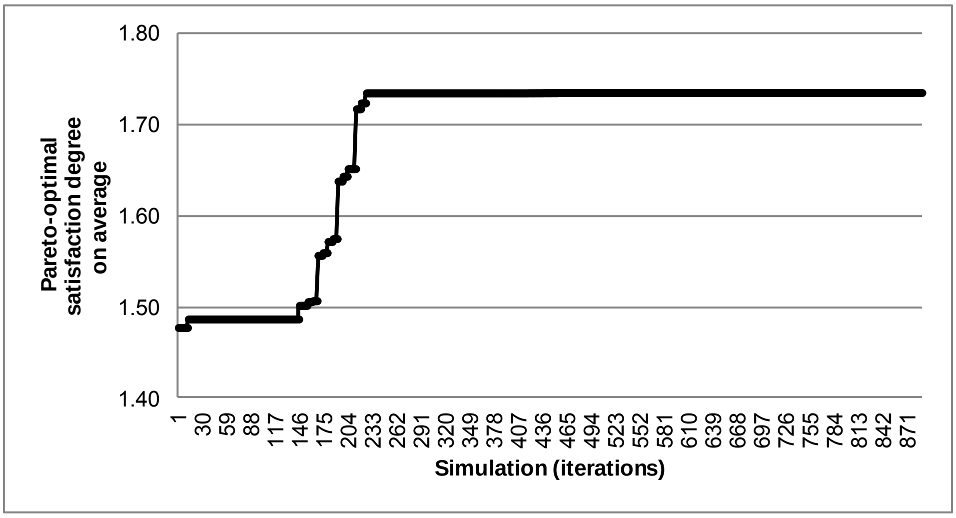


Figure 4-1-6 Pareto-optimal satisfaction degree

The null hypothesis (Eq. 5) claims that the unknown long-term mean of the difference in satisfaction degree (μ) is exactly equal to the known reference of the difference in satisfaction degree ($\mu_0 = 0$).

$$H_0 : \quad \mu \quad = \quad 0 \tag{5}$$

The research hypothesis (Eq. 6) claims that the unknown long-term mean of the difference in satisfaction degree (μ) is different from the known reference of the difference in satisfaction degree ($\mu_0 = 0$).

$$H_1 : \quad \mu \quad \neq \quad 0 \tag{6}$$

The number of iterations is derived from the *t* statistic for the population mean (Eq. 7). It is based on 95% significant level of the test (α) and 95% power of the test (β), and input with the known reference of the difference in satisfaction degree ($\mu_0 = 0$), the known sample mean of the difference in satisfaction degree ($\mu = 0.00058$), and its estimated standard deviation ($\hat{\sigma} = 0.00720$).

$$n \quad = \quad \left(\frac{(t_{\alpha,\,\text{n-1}} + t_{\beta,\,\text{n-1}})\,\hat{\sigma}}{\mu - \mu_0} \right)^2 \tag{7}$$

As a result, the number of iterations is returned at 1,998 by using Minitab software. At the 1,998-th iteration, the Pareto-optimal satisfaction degree is 1.74 which contributes to the Pareto-optimal outputs (i.e. the lowest cost, shortest lead time, and lowest environmental impact) as presented in Table 4-1-7. The shortest lead time (i.e. 0.223 years) is much closer to its target value (i.e. 0.216 years) at 96.60% because the objective of lead time is highly weighted with 0.5. The following closeness degrees are 78.60% of environmental impact and 75.40% of cost. The small difference in closeness degrees of cost and environmental impact is caused by their support for each other. The number of iterations of 1,998 is hence conducted to optimise the multi-objective decision in the next step (referred to Figure 4-1).

Table 4-1-7 Pareto-optimal outputs with 1,998 iterations

Output	Upper bound	Lower bound	Pareto-optimal value	Degree of closeness
Cost (M THB per item)	2.273	1.565	1.739	0.754
Lead time (years)	3.229	0.216	0.223	0.966
Environmental impact (x 1,000 points per item)	1.157	0.667	0.772	0.786

Step 9: Optimisation of multi-objective decision

The multi-objective decision aims to trade off multiple conflicting objectives (i.e. cost, lead time, and environmental impact). The three objectives are optimised with relative weights at 0.4, 0.5, and 0.1 (i.e. *W* [0.4, 0.5, 0.1]). The optimisation of the multi-objective decision applies system dynamics simulation with 1,998 iterations for finding the lowest cost, shortest lead time, and lowest environmental impact as the Pareto-optimal outputs. Based on the Pareto-optimal outputs, the individual DSS suggests decision variables which may cause several configurations over the ten years of planning period. Their relative outputs and utilities are computed to select the Pareto-optimal configuration in the long-term. The suggestions and computations are revealed as follows.

1) Supply chain networks based on multi-objective decision

The individual DSS based on the multi-objective decision suggests seven configurations over the ten years of planning period as shown in Figure 4-1-7a to 4-1-7g. The seven configurations locate facilities in Thailand. The component manufacturing plant in Thailand utilises a component warehouse in Thailand to temporarily store manufactured components. They are then assembled into product models 1 to 3 in the product assembly plant in Thailand. The located facilities in Thailand have a lower wage rate and shorter total distance than those in Taiwan. They utilise 40-ton trucks and sea mode respectively for local and global transport with minimal lot-sizes (i.e. 1 item). Except for the 3-rd product type in year 2020, its lot-size is maximal (i.e. 52 items) as shown in Figure 4-1-7g. The utilised transport supports reduction in cost transportation and environmental impact, whereas the minimal lot-sizes (i.e. 1 item) are utilised to get faster. The lot-size of the 3-rd product type is enlarged to maximum value to offset the growth rate of supply chain cost.

The seven configurations have different suppliers and transportation lot-sizes over the ten years of planning period. In the first two years, suppliers offering lower-price materials are selected as shown in Figure 4-1-7a. Global material procurement utilises air mode with minimal lot-sizes (i.e. 12 tons) aiming to shorten lead time. 40-ton trucks with maximal lot-sizes (i.e. 48 tons) are utilised for local material procurement aiming to improve cost and environmental impact (infrequent roundtrips). In year 2013, the 8-th material type is procured from suppliers in Thailand 7 with 40-ton trucks and maximal lot-sizes (Figure 4-1-7b). Suppliers in Thailand 7 have shorter-distance transportation which causes a slower growth rate of transportation cost incurred by the slower growth rate of fuel. This overcomes a growth rate of material price incurred by the faster growth rate of currency depreciation of suppliers in Thailand 6. With a similar reason as the first reconfiguration, the 9-th material type is procured from suppliers in Thailand 5 in year 2016 (Figure 4-1-7c). The third reconfiguration selects local suppliers to procure material types 2, 4, and 5 in year 2017 (Figure 4-1-7d). In the next year, material types 2 to 6 are procured from local suppliers as the fourth reconfiguration (Figure 4-1-7e). Local suppliers are selected because the Thai Baht (THB) is less depreciated annually than the Euro. The lesser THB depreciation causes lower-price materials in Thailand. In year 2019, all of the materials are procured with minimal lot-sizes (Figure 4-1-7f). The lowering of lot-sizes worsens environmental impact if there is no action to improve supply chain cost. This reconfiguration corresponds to the relative objective weights. In the last planning year, the 3-rd product model is delivered with maximal lot-size (i.e. 52 items). The enlargement of lot-size reduces cost and improves environmental impact, whereas the critical lead time is lengthened (Figure 4-1-7g).

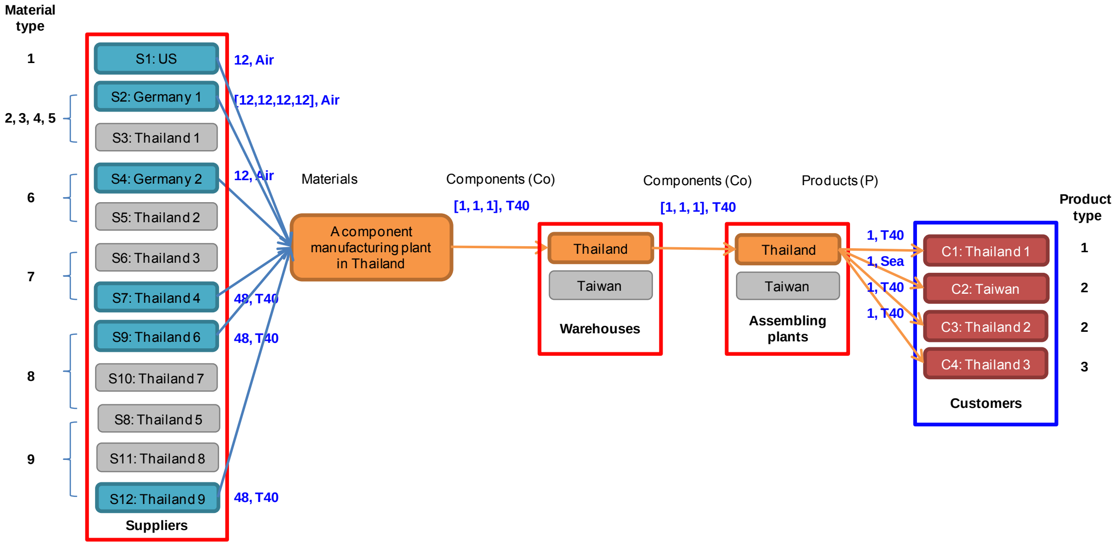


Figure 4-1-7a Supply chain networks based on W [0.4, 0.5, 0.1] in years 2011 and 2012 (the 1-st configuration)

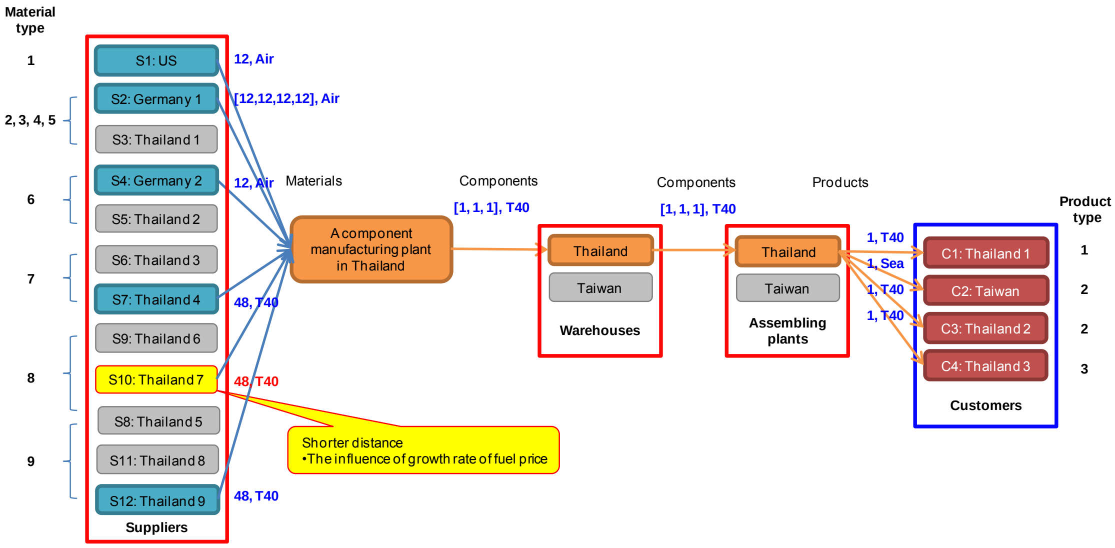


Figure 4-1-7b Supply chain networks based on W [0.4, 0.5, 0.1] from years 2013 to 2015 (the 2-nd configuration)

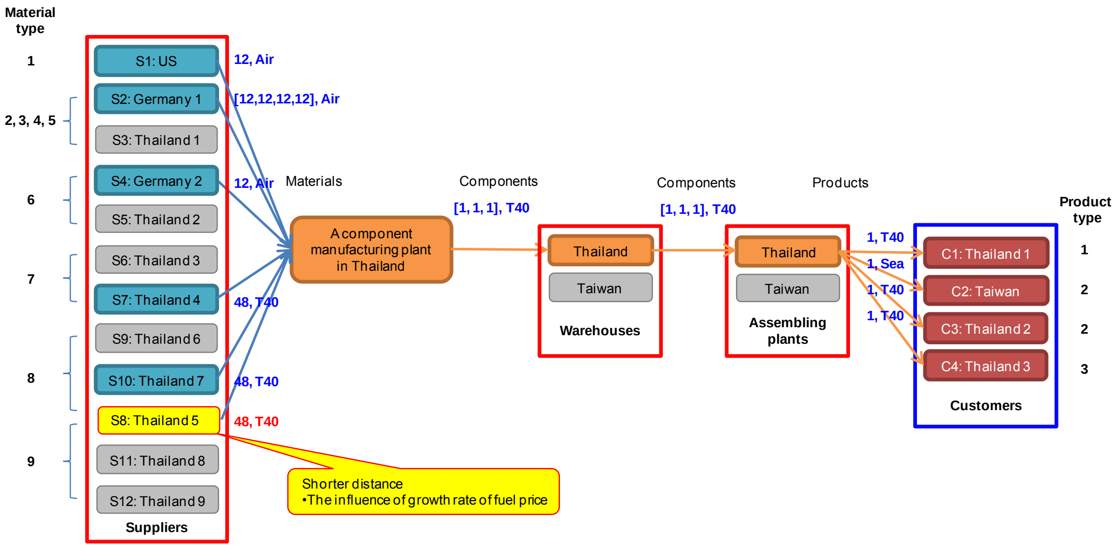


Figure 4-1-7c Supply chain networks based on *W* [0.4, 0.5, 0.1] in year 2016 (the 3-rd configuration)

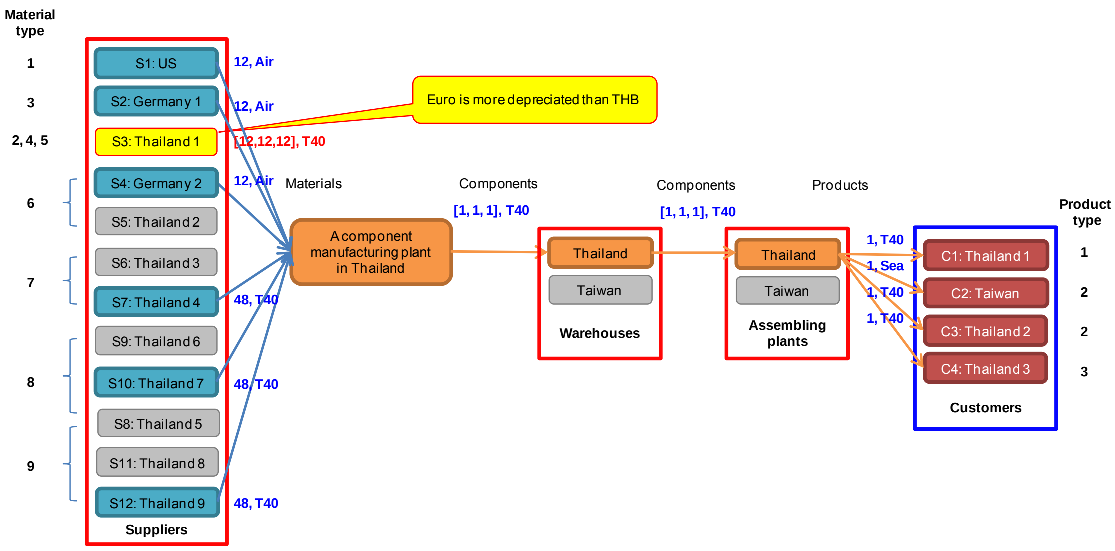


Figure 4-1-7d Supply chain networks based on *W* [0.4, 0.5, 0.1] in year 2017 (the 4-th configuration)

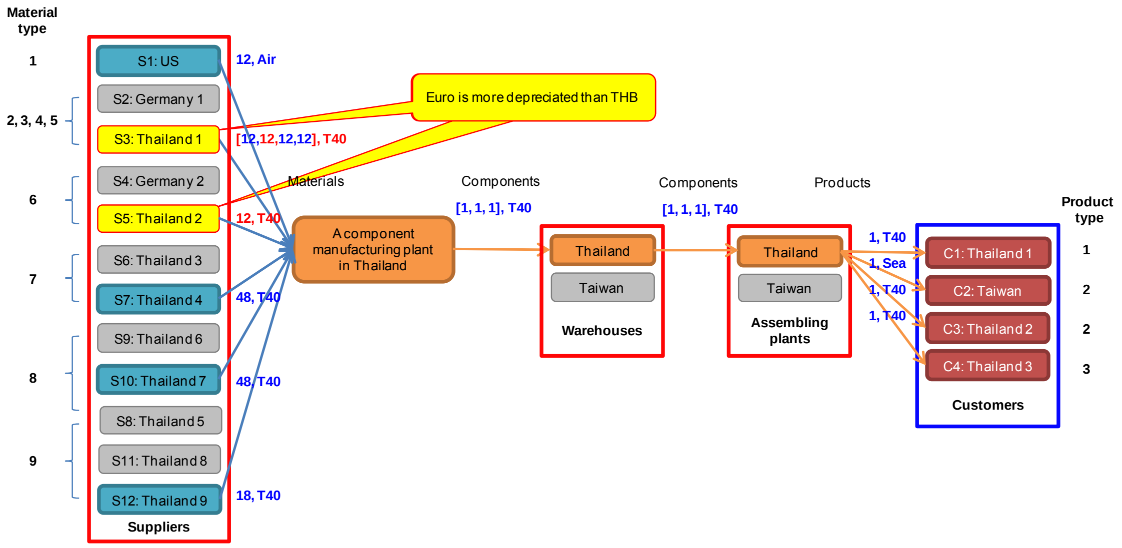


Figure 4-1-7e Supply chain networks based on *W* [0.4, 0.5, 0.1] in year 2018 (the 5-th configuration)

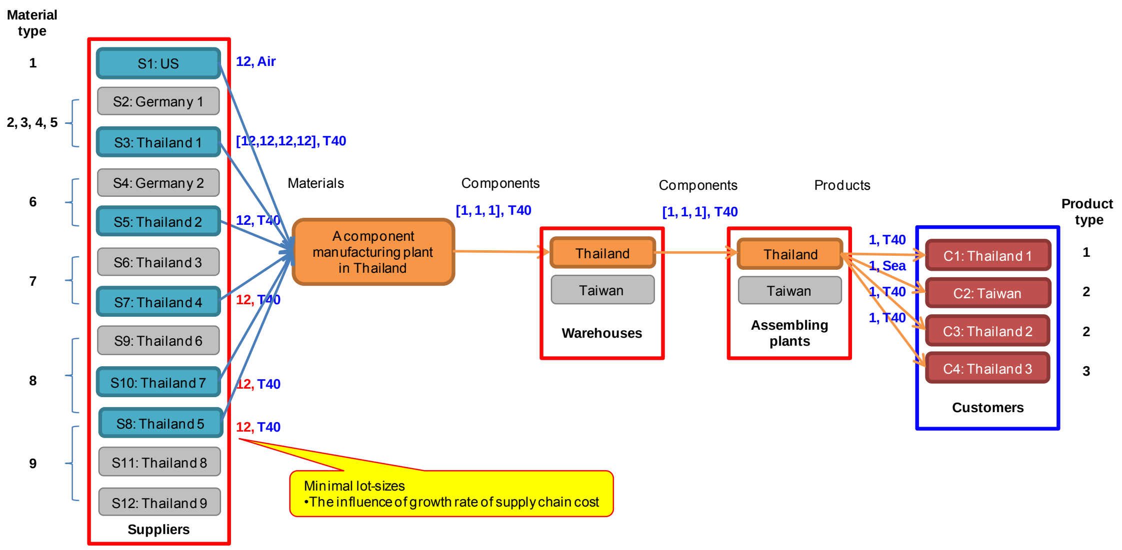


Figure 4-1-7f Supply chain networks based on *W* [0.4, 0.5, 0.1] in year 2019 (the 6-th configuration)

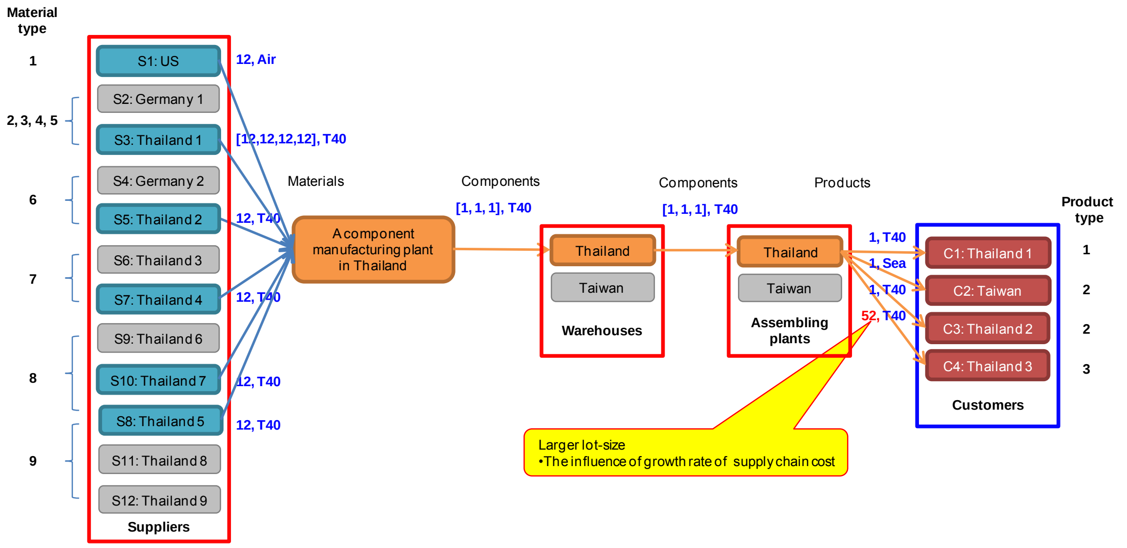


Figure 4-1-7g Supply chain networks based on *W* [0.4, 0.5, 0.1] in year 2020 (the 7-th configuration)

The seven configurations generate the Pareto-optimal outputs in different time durations. The frequent reconfigurations over the ten years of planning period are impractical. One of the seven configurations is therefore selected as the Pareto-optimal configuration in the long-term which generates the Pareto-optimal outputs.

2) Outputs of multi-objective decision

Based on the multi-objective decision, the individual DSS suggests seven configurations. Each of them has specific overall performance based on three attributes (i.e. cost, lead time, and environmental impact). The three attributes are in conflict with each other, have different scales, and relative weights, so the multiplicative utility function is applied (Thurston, 1991, Thurston et al., 1994, Hazelrigg, 1998, Callaghan and Lewis, 2000, Wan and Krishnamurty, 2001, Chen and Tseng, 2005). It normalises multi-attribute values (Z_v) into a common scale as the single attribute utility ($U_v(Z_v)$) (Eq. 8). Given that the multi-attributes are valued within their acceptable ranges between their acceptable minimum and maximum values ([$Z_{v,\min}$, $Z_{v,\max}$]), the single attribute utility is emphasised with its relative weights (W_v), and combined with an additive operator in order to return the overall utility (U) (Eq. 7).

$$U = \sum_{v}^{V} W_v U_v \left(Z_v \right) \tag{7}$$

where

$$U_v\left(Z_v\right) = \frac{Z_{v,\max} - Z_v}{Z_{v,\max} - Z_{v,\min}} \quad ;\forall v \tag{8}$$

In order to compute the overall utility for the seven configurations, three input parameters are determined. The first input parameter is three attribute values including cost (Z_1), lead time (Z_2), and environmental impact (Z_3) on average. They are individually generated by the seven configurations as shown in Table 4-1-8. The second input parameter is acceptable ranges of cost, lead time, and environmental impact, which were determined in the sixth step. They are [1.565, 2.723], [0.371, 5.536], and [0.667, 1.157], respectively. The third input parameter is relative weights of cost, lead time, and environmental impact, which were emphasised in the seventh step. They are 0.4, 0.5, and 0.1, respectively. The three input parameters support the computation of the overall utility for the seven configurations as presented in the last row of Table 4-1-8.

$$U = \left(0.4 \ x \ U_1\left(Z_1\right)\right) + \left(0.5 \ x \ U_2\left(Z_2\right)\right) + \left(0.1 \ x \ U_3\left(Z_3\right)\right) \tag{9}$$

where

$$U_1\left(Z_1\right) = \frac{2.723 - Z_1}{2.723 - 1.565} \tag{10}$$

$$U_2\left(Z_2\right) = \frac{5.536 - Z_2}{5.536 - 0.371} \tag{11}$$

$$U_3\left(Z_3\right) = \frac{1.157 - Z_3}{1.157 - 0.667} \tag{12}$$

Table 4-1-8 reveals that supply chain networks of the cryogenic storage tank manufacturing company is long-term designed with the 4-th configuration (Figure 4-1-7d) which generates the greatest overall utility (i.e. 0.8659). The 4-th configuration contributes to the Pareto-optimal cost at 1.764 M THB per item, lead time at 0.223 years, and environmental impact at 768 points per item on average.

Table 4-1-8 Overall utility of candidate Pareto-optimal configurations

Output	Configuration						
	1	2	3	4	5	6	7
Cost (Z_1) **(M THB per item)**	1.762	1.762	1.762	**1.764**	1.766	1.766	1.657
Lead time (Z_2) **(years)**	0.223	0.223	0.223	**0.223**	0.223	0.223	1.195
Environmental impact (Z_3) **(x 1,000 points per item)**	0.781	0.781	0.780	**0.768**	0.768	0.768	0.730
Overall utility (*U*)	**0.8646**	**0.8646**	**0.8646**	**0.8659**	**0.8651**	**0.8651**	**0.7727**

In summary, the individual DSS for environmentally sustainable SCND of the cryogenic storage tank manufacturing company is capable of making several decisions such as baseline, single-objective, and multi-objective decisions. They include a number of subjective and uncertain parameters. The subjectivity and uncertainty are, however, not incorporated into the individual DSS, so the sensitivity of parameters to the Pareto-optimal result is investigated and analysed in the next step (referred to Figure 4-1).

Step 10: Sensitivity analysis

The sensitivity analysis aims to examine the robustness of the individual DSS. The Pareto-optimal outputs (i.e. cost, lead time, and environmental impact) are investigated when the uncertain parameters are fed to the individual DSS with different values. The uncertain parameters include relative objective weights, minimum product order quantity, and product transportation capacity. They significantly influence decision variables of facility locations, suppliers, transportation modes and lot-sizes.

1) Relative objective weights

The relative weights of cost, lead time, and environmental impact are subjectively determined by decision makers. The subjective determination is caused by uncertain information. The highest important objective is weighted with the highest value; otherwise, the lowest value is applied. The application of relative objective weights is for the Pareto optimal function, so the Pareto-optimal outputs are significantly sensitive to a change in the relative objective weights. The sensitivity of the relative objective weights to the Pareto-optimal outputs are investigated in Figures 4-1-8a to 4-1-8c and analysed. The three figures vary in objective weight from 0.1 to 1.0, whereas its relative two objectives are relatively weighted with equal values. For example, the relative weights of lead time and environmental impact are 0.45 if the cost objective is weighted at 0.1 (Figure 4-1-8a).

Figure 4-1-8a reveals that the Pareto-optimal cost decreases when its relative weight increases. The increase in the relative weight of cost means more attention to cost reduction. It is optimised based on the higher weight of cost and suggested by the selections of cheaper facility locations and suppliers, the choosing of cheaper transportation modes (i.e. rail and sea modes), and the utilisation of larger lot-sizes as discussed in the optimisation of cost minimisation in the fifth step. These suggestions contribute to the lower Pareto-optimal cost; however, the Pareto-optimal cost is insensitive to some of the changed values of the relative weight of cost.

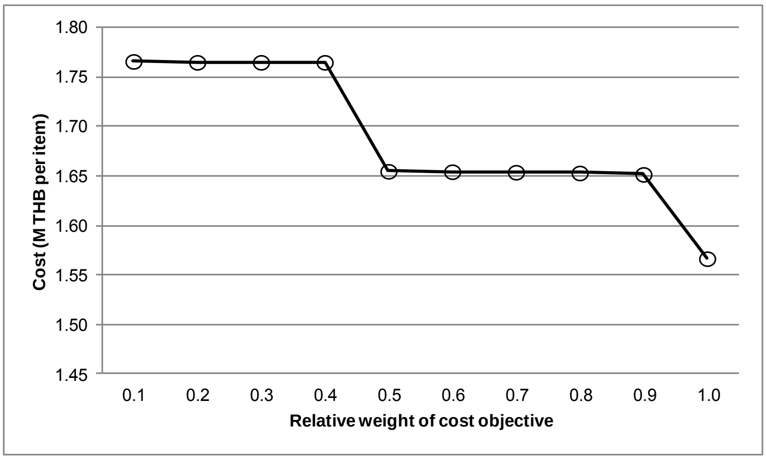


Figure 4-1-8a Sensitivity of relative weight of cost to the Pareto-optimal cost

Figure 4-1-8b reveals that the Pareto-optimal lead time decreases when its relative weight increases. The increase in the relative weight of lead time means more attention to lead time shortening. It is optimised based on the higher weight of lead time and suggested by the selections of more responsive facility locations and suppliers, the choosing of faster transportation modes (i.e. air mode), and the utilisation of smaller lot-sizes as discussed in the optimisation of lead time minimisation in the fifth step. These suggestions contribute to the shorter Pareto-optimal lead time; however, the Pareto-optimal lead time is insensitive to some of the changed values of the relative weight of lead time.

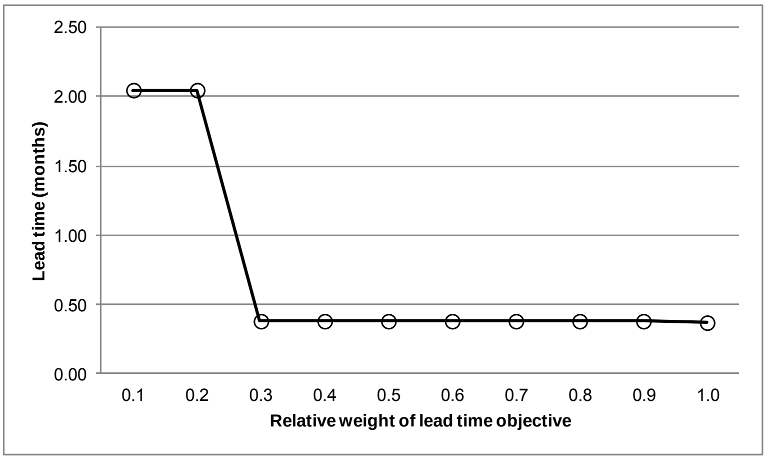


Figure 4-1-8b Sensitivity of relative weight of lead time to the Pareto-optimal lead time

Figure 4-1-8c reveals that the Pareto-optimal environmental impact decreases when its relative weight increases. The increase in the relative weight of environmental impact means more attention to improvement in environmental impact. It is optimised based on the higher weight of environmental impact and suggested by the selections of greener facility locations and suppliers, the choosing of greener transportation modes (i.e. rail and sea modes), and the utilisation of larger lot-sizes as discussed in the optimisation of environmental impact minimisation in the fifth step. These suggestions contribute to the lower Pareto-optimal environmental impact; however, the Pareto-optimal environmental impact is insensitive to some of the changed values of the relative weight of environmental impact.

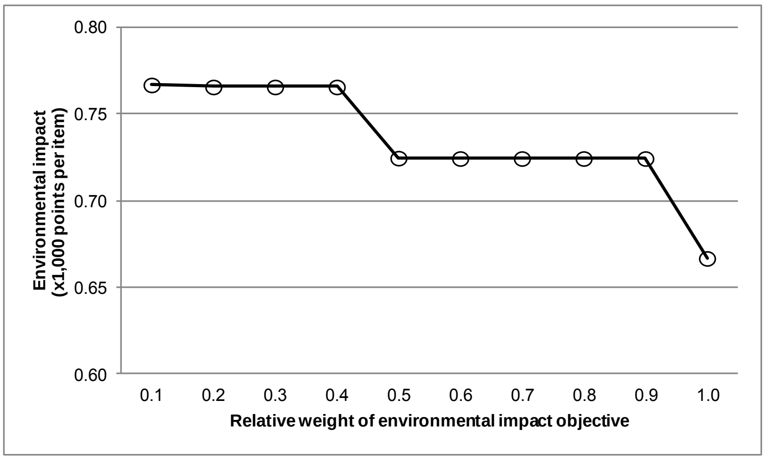


Figure 4-1-8c Sensitivity of relative weight of environmental impact to the Pareto-optimal environmental impact

It can be concluded from Figures 4-1-8a to 4-1-8c that the Pareto-optimal cost, lead time, and environmental impact are significantly sensitive to the change in relative objective weights. Their suitable determination is therefore necessary for achieving the organisational satisfaction.

2) Minimum product order quantity

The minimum product order quantity is the amount of products acceptable to the manufacturing company; however, it can be changed with negotiations. The minimum product order quantity significantly influences product transportation lot-size as its lower constraint. The product transportation lot-size is not less than the minimum product order quantity, so its change may have significant effects on the Pareto-optimal product transportation lot-size and its relative outputs. The sensitivity of the minimum product order quantity to the Pareto-optimal outputs based on *W* [0.4, 0.5, 0.1] are investigated in Figures 4-1-9 and analysed. Figure 4-1-9 reveals the increase in the minimum product order quantity from 1 to 10 items causes the larger Pareto-optimal product transportation lot-size which contributes to improvements in the Pareto-optimal cost and environmental impact, but the Pareto-optimal lead time is longer.

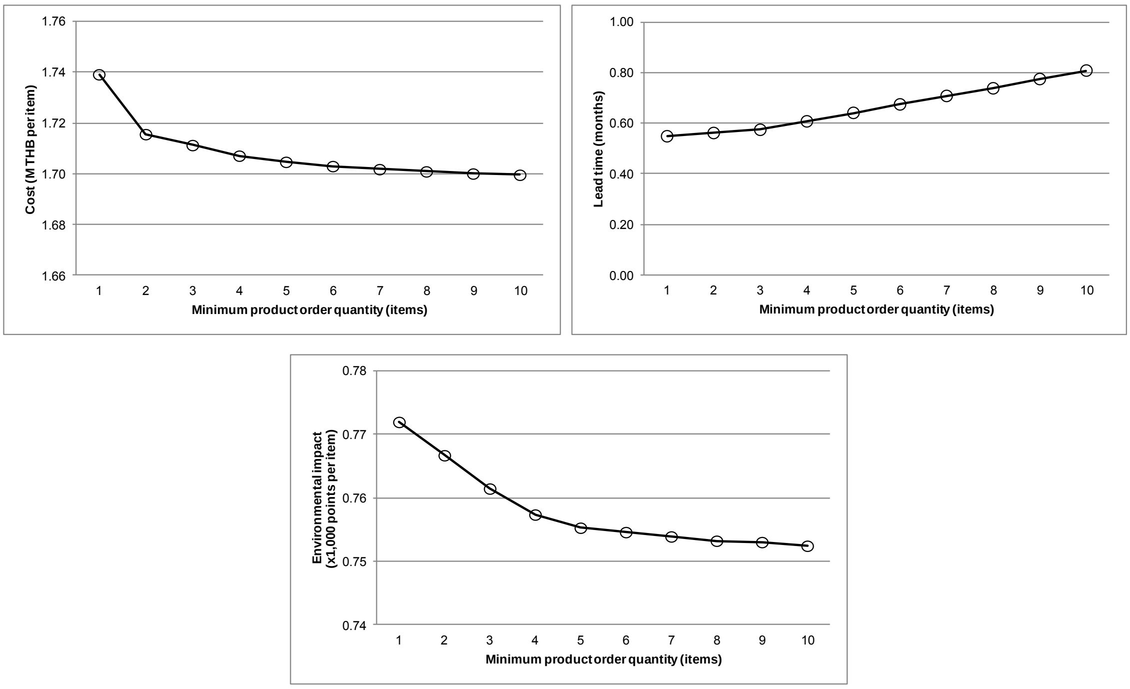


Figure 4-1-9 Sensitivity of minimum product order quantity to the Pareto-optimal outputs

In addition, the Pareto-optimal outputs are sensitive to minimum component and material order quantities. Their sensitivities have a similar mechanism to the sensitivity of minimum product order quantity (Figure 4-1-9). It can be concluded that the Pareto-optimal cost, lead time, and environmental impact are significantly sensitive to the change in minimum order quantities. Their suitable determination is necessary for achieving the organisational satisfaction.

3) Product transportation capacity

The product transportation capacity is assumed as infinite since the manufacturing company is capable of outsourcing unlimited transports from logistics providers. It is however required not more than the product transportation capacity. The assumption of product transportation capacity significantly influences product transportation lot-size as its upper constraint. A change in the required product transportation capacity may have significant effects on the Pareto-optimal product transportation lot-size and its relative outputs. The sensitivity of the required product transportation capacity to the Pareto-optimal outputs based on *W* [0.4, 0.5, 0.1] are investigated in Figures 4-1-10 and analysed. Figure 4-1-10 reveals the enlargement in the required product transportation capacity from -50% to +50% of production capacity is insensitive to the Pareto-optimal cost and lead time since the product transportation lot-size is optimally utilised by one item as minimum product order quantity. The utilised transportation lot-size of one item enlarges the unused transportation capacity which contributes to the worse Pareto-optimal environmental impact.

In addition, the Pareto-optimal environmental impact is sensitive to component and material transportation capacities. Their sensitivities have a similar mechanism to the sensitivity of product transportation capacity (Figure 4-1-10). It can be concluded that the Pareto-optimal environmental impact is sensitive, whereas the Pareto-optimal cost and lead time are insensitive to the change in transportation capacity. Its suitable determination is necessary for achieving the organisational satisfaction.

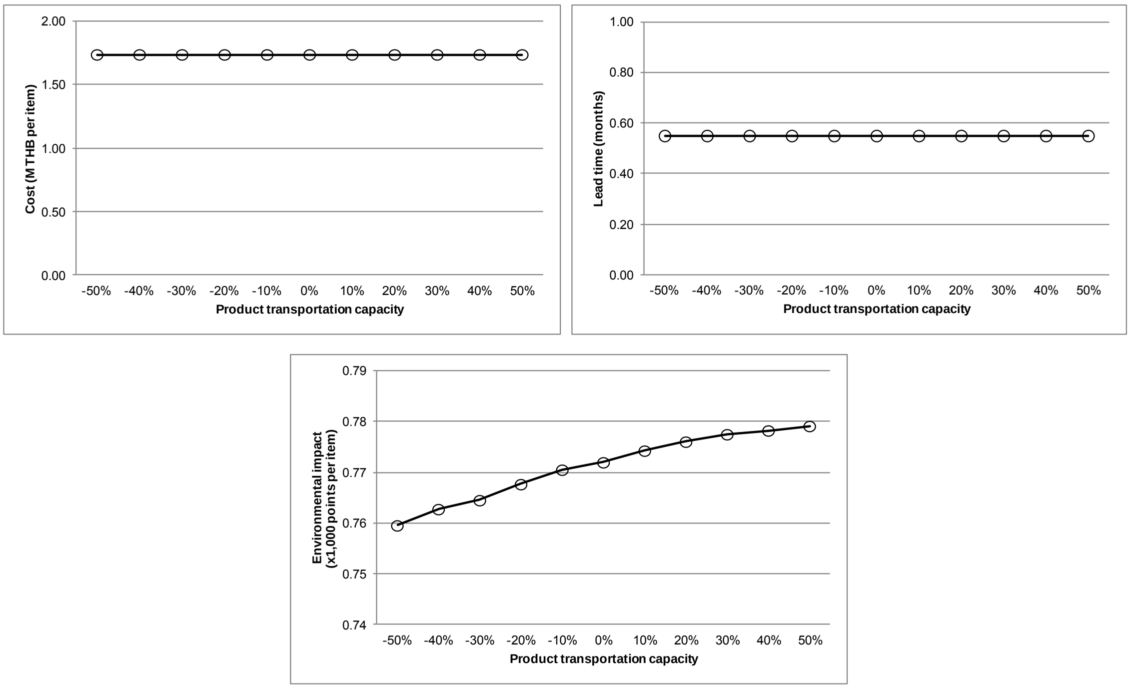


Figure 4-1-10 Sensitivity of product transportation capacity to the Pareto-optimal outputs

In summary, the individual DSS for environmentally sustainable SCND of the cryogenic storage tank manufacturing company is capable of returning reasonable results when the uncertain parameters (i.e. relative objective weights, minimum product order quantity, and product transportation capacity) are changed. Their corresponding results can also be predicted. These capabilities can imply that the generic DSS is sufficiently robust for the system validation in the next step (referred to Figure 4-1).

Step 11: Result comparisons and discussions

The results (i.e. outputs and their relative decision variables) of baseline, three single-objective, and multi-objective decisions are compared and discussed in order to demonstrate the potential of the individual DSS for industry implementation. This step provides three comparisons along with their discussions as follows.

1) Comparison of baseline and actual product cost in the base year

To demonstrate the first successful validation of the individual DSS, its product cost based on the baseline decision is compared to the actual product cost in the base year (year 2011). Figure 4-1-11 reveals that the individual DSS returns the baseline product cost at 0.991 Million Thai Baht (M THB) per item. It is differed by 2.31% when compared to the actual product cost (i.e. 1.01 M THB per item). The very small difference in product cost is considered a successful validation of the individual DSS.

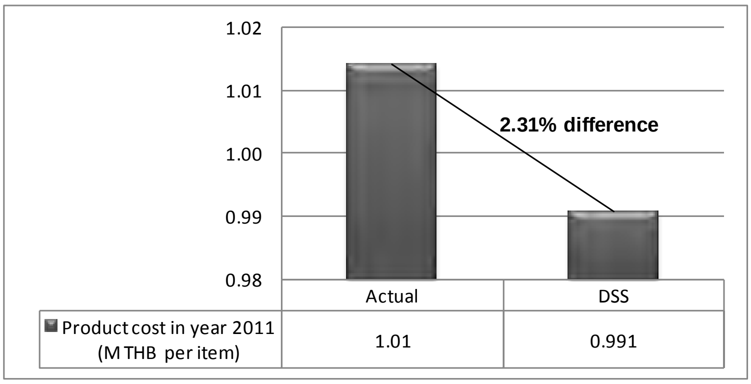


Figure 4-1-11 Product cost comparison in year 2011

2) Comparison of baseline and Pareto-optimal results

To demonstrate the second successful validation of the individual DSS, its outputs (on average) and decision variables based on the multi-objective decision with *W* [0.4, 0.5, 0.1] are compared to those based on the baseline decision. Table 4-1-9 reveals that the multi-objective decision generates the Pareto-optimal cost at 1.764 Million Thai Baht (M THB) per item, lead time at 0.223 years, and environmental impact at 768 points per item. The multi-objective decision is capable of little improvement to the baseline environmental impact (i.e. 781 points per item) by 1.65%, thereby worsening the baseline cost (i.e. 1.762 M THB per item) by 0.13%, whereas there is no difference in lead time (i.e. 0.223 years). The improvement in environmental impact is caused by selecting local suppliers (in Thailand 1 and 7) which have shorter-distance transportation and utilise 40-ton trucks (greener mode) of the multi-objective decision with *W* [0.4, 0.5, 0.1] (Figure 4-1-9d). The selected suppliers and utilised 40-ton trucks do not have any effect on the critical lead time, so there is no difference in lead time. On the other hand, the baseline decision selects suppliers (in Germany 1 and Thailand 6) offering lower-price materials, so the baseline cost is lower than the Pareto-optimal cost. Even if the Pareto-optimal outputs are conflicted with each other, they generate the better overall performance by 0.16% as shown in Table 4-1-9. The improvement in overall performance is, however, not sufficiently significant, so decision makers should select any decision which is appropriate for the cryogenic storage tank manufacturing plant.

Table 4-1-9 Comparisons of baseline and Pareto-optimal outputs and overall utility

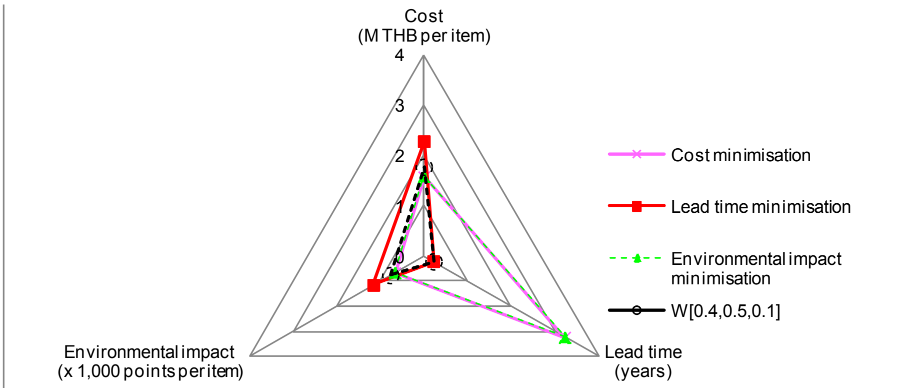
Output	Baseline decision	*W* [0.4, 0.5, 0.1]	% Improvement
Cost (M THB per item)	1.762	1.764	- 0.13%
Lead time (years)	0.223	0.223	0.00%
Environmental impact (x 1,000 points per item)	0.781	0.768	**1.65%**
Overall utility	**0.8646**	**0.8659**	**0.16%**

3) Comparison of single-objective and Pareto-optimal results

To demonstrate the third successful validation of the individual DSS, its outputs (on average) and decision variables based on the multi-objective decision with *W* [0.4, 0.5, 0.1] are compared to those based on the three single-objective decisions. Figure 4-1-12 reveals that the three single-objective decisions generate extreme values of individual objectives. For example, the single-objective decision with environmental impact minimisation generates the lowest environmental impact without consideration of cost and lead time as depicted in the triangle-dash line. The environmental impact minimisation (Figure 4-1-5) supports the cost minimisation (Figure 4-1-3b) since the individual DSS suggests facility locations in Thailand, suppliers having shorter-distance transportation, and greener transport with maximal lot-sizes. The greener transport modes consume lesser fuel and have a lower freight rate, although having slower speed. The maximal lot-sizes reduce transportation cost and environmental impact due to infrequent roundtrips. The three outputs of environmental impact minimisation consequently approach those of cost minimisation, but are conflicting with those of lead time minimisation as depicted in the cross-solid line. The lead time minimisation (Figure 4-1-4) suggests utilising the faster transport with minimal lot-sizes, especially the critical lead time. The faster transportation modes consume more fuel, however, having higher freight rates and more environmental impact. The minimal lot-sizes shorten preparation time, but increase transportation cost and environmental impact due to frequent roundtrips. These conflicts cause the need for multi-objective decision with *W* [0.4, 0.5, 0.1].

The three outputs of multi-objective decision with W [0.4, 0.5, 0.1] approach the shortest lead time by 99.80% as depicted in the circle-solid line of Figure 4-1-12. Its significant closeness is caused by three influences (Figure 4-1-7d). The first influence is the selection of facility locations and suppliers having shorter-distance transportation.

It contributes to reduction in transportation cost and environmental impact. The second and third influences are the selection of fastest transport (i.e. air mode) with minimal lot-size to shorten the critical lead time (incurred by global material procurement). On the other hand, some suppliers utilise the cheaper and greener transport with maximal lot-sizes to improve cost and environmental impact. The improvements in cost and environmental impact contribute to the greater degrees of closeness of the Pareto-optimal cost and environmental impact. They are, however, less than the closeness degree of the Pareto-optimal lead time. These degrees of closeness correspond to the relative weights of cost, lead time, and environmental impact. The correspondence is considered another successful validation of the individual DSS.



Output	Single-objective decision			*W* [0.4, 0.5, 0.1]	Degree of closeness
	Cost	Lead time	Environmental impact		
Cost (M THB per item)	**1.567**	2.273	1.576	1.764	0.719
Lead time (years)	3.229	**0.216**	3.229	0.216	0.998
Environmental impact (x 1,000 points per item)	0.668	1.157	**0.667**	0.768	0.794

Figure 4-1-12 Comparisons of single-objective and Pareto-optimal outputs

In summary, the individual DSS for environmentally sustainable SCND is successfully validated by the industrial case of cryogenic storage tank manufacturing company. The successful validation of the individual DSS is demonstrated with three comparisons along with their discussions. Firstly, there is a very small difference between baseline and actual product cost of 2.31% in the base year. Secondly, the individual DSS provides some suggestions that the baseline overall performance can be improved by 0.16% when the multi-objective decision with *W* [0.4, 0.5, 0.1] is implemented. The improvement in overall performance is, however, not sufficiently significant, so decision makers should select any decision which is appropriate for the company. Thirdly, there is correspondence between the degrees of closeness and relative weights of the Pareto-optimal cost, lead time, and environmental impact. These comparisons and discussions can imply that the individual DSS is successfully validated. The successful validation must be further demonstrated with various industrial cases. The further demonstrations are considered convincing evidence that the generic DSS is sufficiently effective for industry implementation. Accordingly, another three industrial cases are used to demonstrate the system validation in the next sections.

4.2 Automotive part manufacturing company

The automotive part manufacturing company in Thailand is the second industrial case. It is used to demonstrate step-by-step the system verification and validation by following the eleven steps as shown in Figure 4-1.

Step 1: Problem statement

The multinational and medium-sized company of automotive parts has one location of manufacturing plant (product MP) in Thailand. It manufactures six product models which include three models of oil pumps, two models of water pumps, and one models of front case assembly. The six product models are provided for four local customers and four global customers in Japan, Indonesia and Malaysia. Their demand (i.e. product volume) is annually growing at 10.9% as a prediction, whereas their demand fluctuation (i.e. standard deviation) is 1% of the growth of product volume. In addition, the six product models require twelve material types procured from thirteen local suppliers and one global supplier in Malaysia as presented in Figure 4-2-1. The procured materials are promptly delivered to the product MP whenever ordered as Make to Stock (MTS).

The supply chain networks of automotive part manufacturing company (Figure 4-2-1) involve two strategic decisions (domains) including designs of facility networks and supply networks. The first domain (Facility Network Design: FND) does not determine the locations of product manufacturing plant, whereas the latter domain (Supply Network Design: SND) determines which suppliers are the best-fittedSuppliers offering lower-price materials are farther from the product manufacturing plant. Alternatively, suppliers who are closer to the product manufacturing plant offer higher-price materials. For example, suppliers in Thailand 2 offer lower-price materials, but the distance is longer than suppliers in Thailand 1 (Appendix D). The longer distance increases transportation cost, time, and environmental impact. These conflicts cause the need for a trade-off between material prices and transportation distances for selecting the best-fitted suppliers.

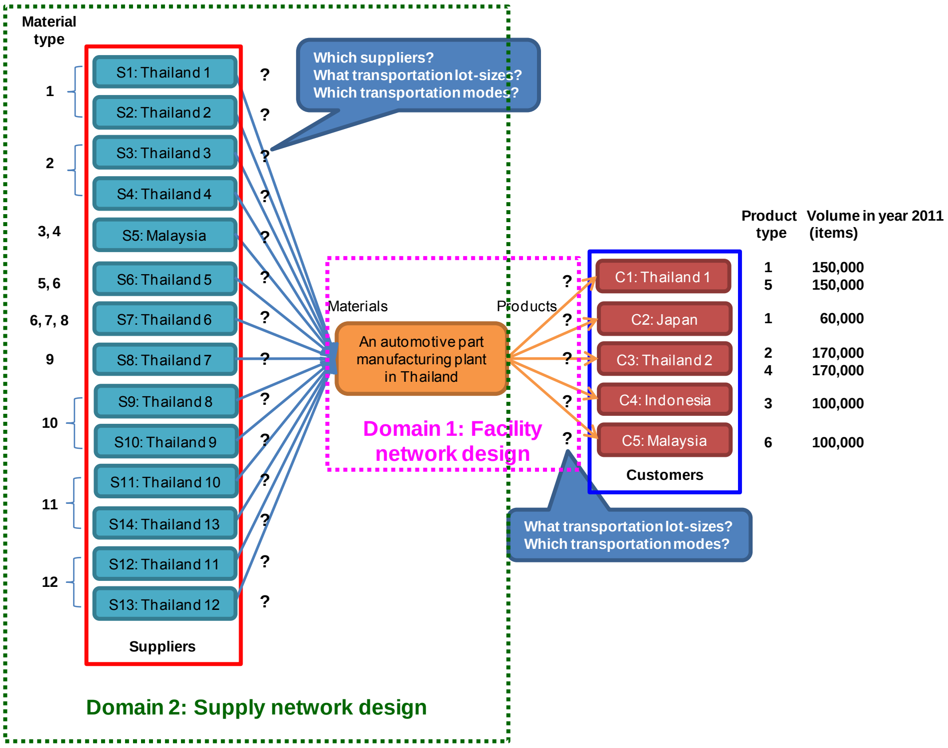


Figure 4-2-1 Supply chain networks of automotive part manufacturing company

Both of the FND and SND (Supply Chain Network Design: SCND) determine which transportation modes and what lot-sizes are optimal. Firstly, cheaper and greener transportation modes have slower speeds; alternatively, faster transport consumes more fuel. Greater fuel consumption causes higher freight rates and more environmental impact. Secondly, larger lot-sizes contribute to reduction in manufacturing cost due to infrequent setups, less transportation cost and environmental impact due to infrequent roundtrips, but produce a longer lead time and higher-cost inventory holding. These conflicts cause the need for trade-offs between cost, lead time, and environmental impact to determine appropriate transportation modes and lot-sizes.

In summary, the SCND problems of the automotive part manufacturing company involve the strategic decisions (domains) of FND and SND. They include several conflicts of three objectives (i.e. cost, lead time, and environmental impact). These conflicts are however solved under numerous assumptions which are defined in the next step (referred to Figure 4-1).

Step 2: Assumption defining

The assumptions are defined as the second step in aiming to reduce complication of the SCND problems, which were stated in the first step. Certain assumptions concerning the automotive part manufacturing company are made based on the discussions with the company officials as follows.

- Candidate transportation modes include air inter-continental, truck 16 ton B250, truck 40 ton B250, and sea ship B250 (BUWAL250, 1996).
- There are no costs of terminating and initiating any contracts for any suppliers.

These assumptions support the individual DSS to specify its relative parameters. They are input into generic modules which are determined based on the SCND problems of the automotive part manufacturing company in the next step (referred to Figure 4-1).

Step 3: Generic module determination

The generic modules are determined based on the SCND problems and assumptions, which were stated in the first two steps. The SCND problems of the automotive part manufacturing company involve the strategic decisions (domains) of FND and SND. Each of them has individual supply chain entities which are specified as follows.

1) Facility Network Design (FND)

The FND of automotive part manufacturing company covers four entities which are indexed as follows.

- Product MP (m = 1) is located in Thailand;
- Customers (o = 1,…,5) are in Thailand 1, Japan, Thailand 2, Indonesia, and Malaysia;
- Products (r = 1,…,6) include product model 1 to 6.
- Transportation modes (s = 1,...,5) include air, 16 ton-truck (T16), 40-ton truck (T40), and sea

These four entities involve three generic modules of the individual DSS. They are (1) product demand, (2) product manufacturing and warehousing, (3) product distribution (Figure 3-2). These three generic modules are input with numerous parameters as shown in Appendix D. They contribute to the optimum values of three decision variables including (1) transportation mode selection and (2) transportation lot-sizes utilised for delivering products from the product MP to customers.

2) Supply network design (SND)

The SND of automotive part manufacturing company covers five entities which are indexed as follows.

- Product MP (*m* = 1) is located in Thailand,
- Suppliers (*i* = 1,...,14) are in Thailand 1 to 4, Malaysia, and Thailand 5 to 13,
- Products (*r* = 1,...,6) include product model 1 to 6,
- Materials (*p* = 1,...,12) include material type 1 and 2 (aluminium), 3 and 4 (iron), 5 to 12 (steel), and
- Transportation modes (*s* = 1,...,5) include air, 16 ton-truck (T16), 40-ton truck (T40), and sea.

These five entities involve three generic modules of the individual DSS. They are (1) material demand, (2) material procurement and warehousing, and (3) material distribution (Figure 3-2). These three generic modules are input with numerous parameters as shown in Appendix D. They contribute to the optimum values of four decision variables including (1) supplier selection, (2) transportation mode selection, and (3) transportation lot-sizes utilised for delivering materials from the selected suppliers to the product MP.

The six generic modules, which were above determined for environmentally sustainable SCND of the automotive part manufacturing company, are applied to simulate the baseline decision in the next step (referred to Figure 4-1).

Step 4: Simulation of baseline decision

The baseline decision selects suppliers offering lower-price materials, and utilises cheaper and greener transport (i.e. 40-ton trucks and sea mode) with minimal lot-sizes for material procurement and product distribution. The cheaper and greener transportation modes support lower transportation cost and environmental impact, whereas the minimal lot-sizes cause improvements in lead time and safety stocks. As shown in Figure 4-2-2, suppliers in Thailand 2 are selected to supply the 1-st material type by utilising 40-ton trucks with a lot-size of 12 tons. 40-ton trucks are also utilised for delivering product models 1 and 5 to customers in Thailand 1 with lot-sizes of 7858 and 8000 items respectively. Based on the baseline configuration, the individual DSS returns the baseline cost, lead time, and environmental impact respectively are 578.20 Thai Baht (THB) per item, 4.58 weeks and 0.674 points per item on average.

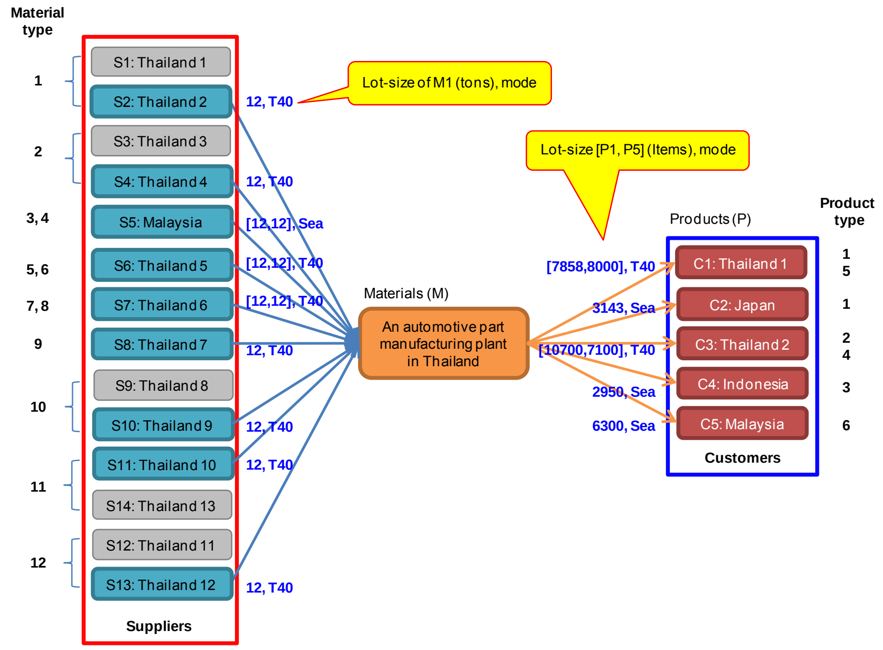


Figure 4-2-2 Baseline supply chain networks

It is noticeable that the individual DSS for environmentally sustainable SCND of the automotive part manufacturing company is capable of explaining behaviour of the baseline supply chain networks and their relative outputs. They are used for comparing to the results of three single-objective and multi-objective decisions in the eleventh step.

Step 5: Optimisation of single-objective decisions

The single-objective decisions aim to optimise an objective without consideration of other objectives. This step presents the optimisation of three single-objective decisions including minimisation of cost, lead time, and environmental impact as follows.

1) Cost minimisation

The individual DSS based on cost minimisation suggests a single configuration over the ten years of planning period as shown in Figure 4-2-3. The suggested configuration selects suppliers offering lower-price materials, and utilises cheaper transport (i.e. 40-ton trucks and sea mode) with smaller lot-sizes. The cheaper transportation modes support lower transportation cost, whereas the smaller lot-sizes cause reduction in safety stocks influencing inventory holding cost. These suggestions contribute to the lowest cost at 560.80 THB per item, whereas its relative lead time and environmental impact respectively are valued at 5.47 weeks and 0.672 points per item on average.

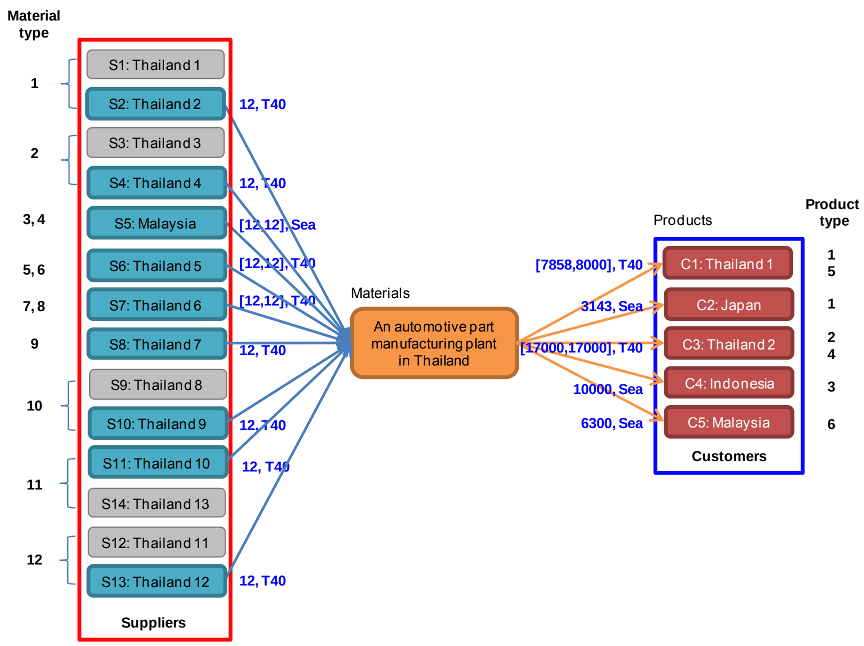


Figure 4-2-3 Supply chain networks based on cost minimisation for the ten years of planning period

2) Lead time minimisation

The individual DSS based on lead time minimisation suggests a single configuration over the ten years of planning period as shown in Figure 4-3-4. The critical lead time of the suggested configuration is incurred by procuring material types 3 and 4 from suppliers in Malaysia and delivering the 6-th product type to customers in Malaysia. It is shortened by utilising air (the fastest) mode with minimal lot-sizes (i.e. 12 tons of materials and 6,300 items of products). To avoid lengthening the critical lead time, this air mode with lot-sizes of 12 tons is globally utilised whereas 40-ton trucks are locally utilised as it does not impact on the critical lead time. These suggestions contribute to the shortest lead time at 4.01 weeks, and its relative cost and environmental impact respectively are valued at 625.90 THB per item and 0.862 points per item on average.

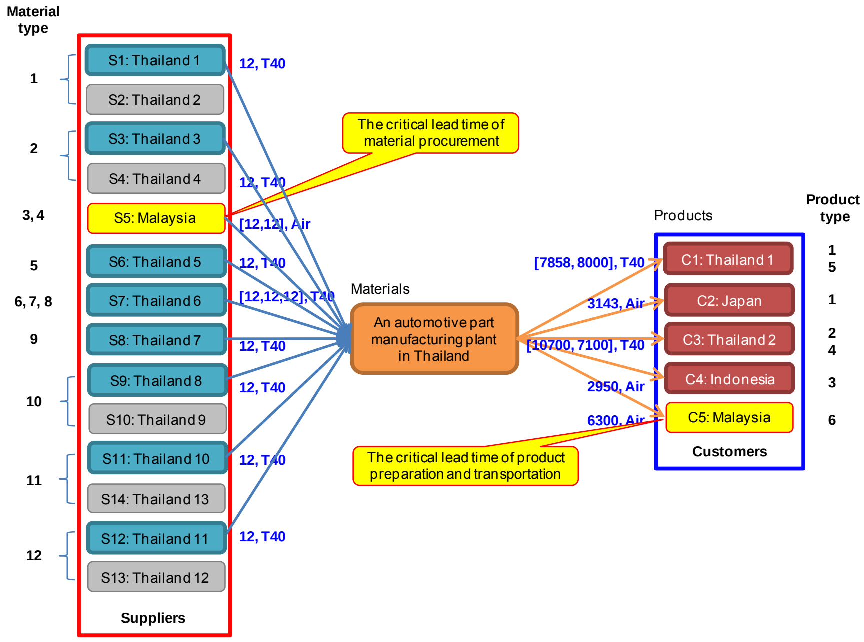


Figure 4-2-4 Supply chain networks based on lead time minimisation for the ten years of planning period

3) Environmental impact minimisation

The individual DSS based on environmental impact minimisation suggests a single configuration over the ten years of planning period as shown in Figure 4-2-5. The suggested configuration selects suppliers closer to the automotive part manufacturing plant, and utilises greener transport (i.e. 40-ton trucks and sea mode) with maximal lot-sizes. Suppliers in Thailand 1 are selected to supply the 1-st material type by utilising 40-ton trucks with a lot-size of 24 tons. 40-ton trucks are also utilised for delivering product models 1 and 5 to customers in Thailand 1 with lot-sizes of 15,715 and 17,000 items respectively. These suggestions contribute to the lowest environmental impact at 0.671 points per item on average, whereas its relative cost and lead time respectively are valued at 575.50 THB per item and 7.36 weeks on average.

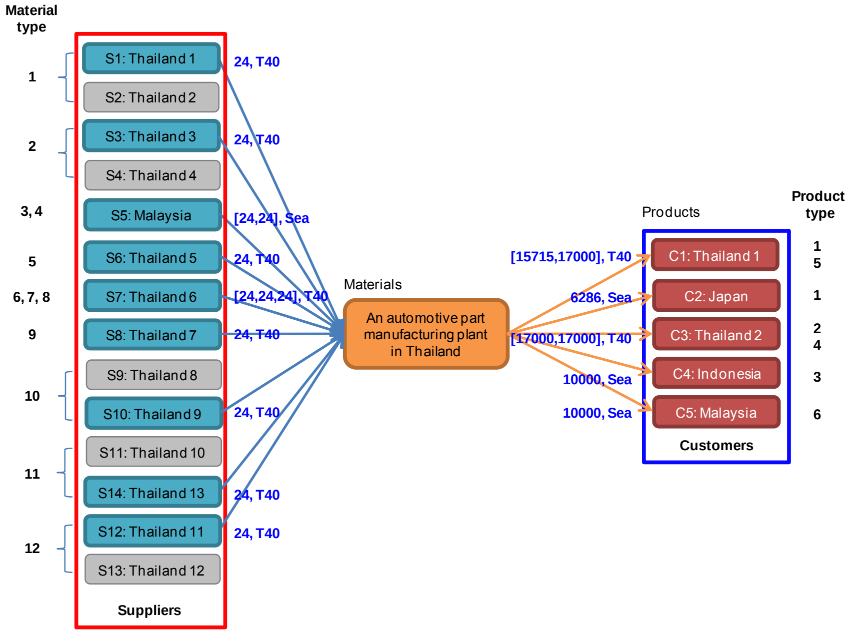


Figure 4-2-5 Supply chain networks based on environmental impact minimisation for the ten years of planning period

It is noticeable that the three single-objective decisions suggest different configurations. The optimal configuration based on an objective contributes to the optimum value of that objective, whereas it is in conflict with the other two objectives. The conflicts of three objectives are traded off by using the multi-objective decision. It is restricted with specific upper and lower bounds of the three objectives as shown in Table 4-2-1 (step 6)and optimised with 16,245 iterations (step 8) and relative weights of cost, lead time, and environmental impact at 0.4, 0.3, and 0.3 respectively (i.e. *W* [0.4, 0.3, 0.3]) (step 7). The much attention to cost objective is paid in order to achieve mass production, followed by environmental impact to comply ISO14001:2004 (i.e. environmental management). According to ISO14001:2004, the company has action plans to conserve energy and resources, reduce waste and recycling, curtail environmental impact of its products, and mitigate their impact on the environment. The outcomes of steps 6 to 8 are conducted to optimise the multi-objective decision in the next step (referred to Figure 4-1).

Table 4-2-1 Upper and lower bounds of three objectives

Objective	Cost minimisation	Lead time minimisation	Environmental impact minimisation	Upper bound	Lower bound
Cost (x100 THB per item)	5.608	6.259	5.755	**6.259**	**5.612**
Lead time (weeks)	5.465	4.011	7.363	**7.363**	**4.011**
Environmental impact (x0.1 points per item)	6.721	8.620	6.713	**8.620**	**6.713**

Step 9: Optimisation of multi-objective decision

The individual DSS based on the multi-objective decision suggests four configurations over the ten years of planning period as shown in Figures 4-2-6a to 4-2-6d. The four configurations utilise cheaper and greener transport (i.e. 40-ton trucks and sea mode) with smaller lot-sizes for product distribution, whereas material procurement selects different suppliers, transportation modes and lot-sizes. In the first four years, suppliers offering lower-price materials are selected. In addition, cheaper and greener transportation modes are utilised with maximal lot-sizes (i.e. 24 tons) (Figure 4-2-6a). These support lower-cost materials, manufacturing and transportation, and better environmental impact. However, two years later, the growth rate of product demand influences more fluctuation of material demand which has effects on increases in safety stocks and inventory holding cost. They are reduced by selecting suppliers in Thailand 5, 11 and 13 having shorter-distance and utilising minimal lot-sizes (i.e.12 tons) (Figure 4-2-6b). In year 2017, transportation lot-sizes are increased to 24 tons to reduce the influence of the growth rates of energy price, fuel price, wage rate, and currency depreciation along the supply chain (Figure 4-2-6c). After that, suppliers in Malaysia utilise air (the fastest) mode primarily aiming to reduce safety stocks and inventory holding cost, whereas the critical lead time is shortened (Figure 4-2-6d).

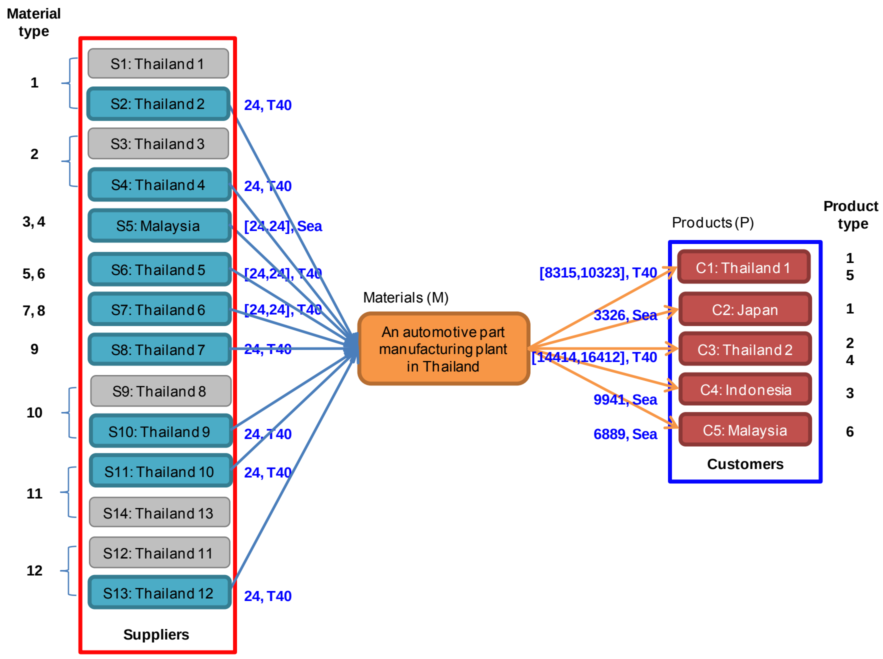


Figure 4-2-6a Supply chain networks based on *W* [0.4, 0.3, 0.3] in years 2011 to 2014 (the 1-st configuration)

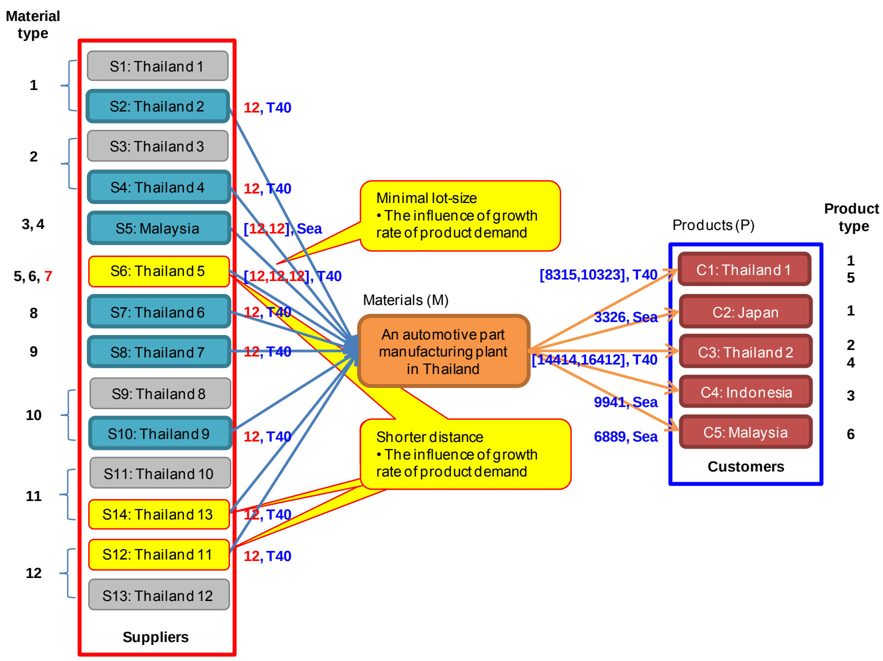


Figure 4-2-6b Supply chain networks based on *W* [0.4, 0.3, 0.3] in years 2015 and 2016 (the 2-nd configuration)

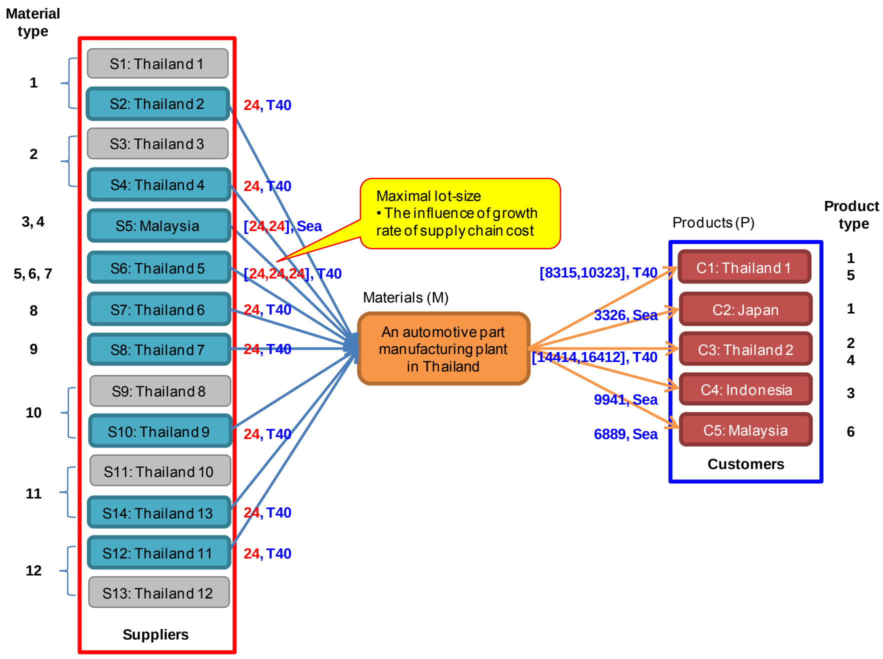


Figure 4-2-6c Supply chain networks based on *W* [0.4, 0.3, 0.3] in year 2017 (the 3-rd configuration)

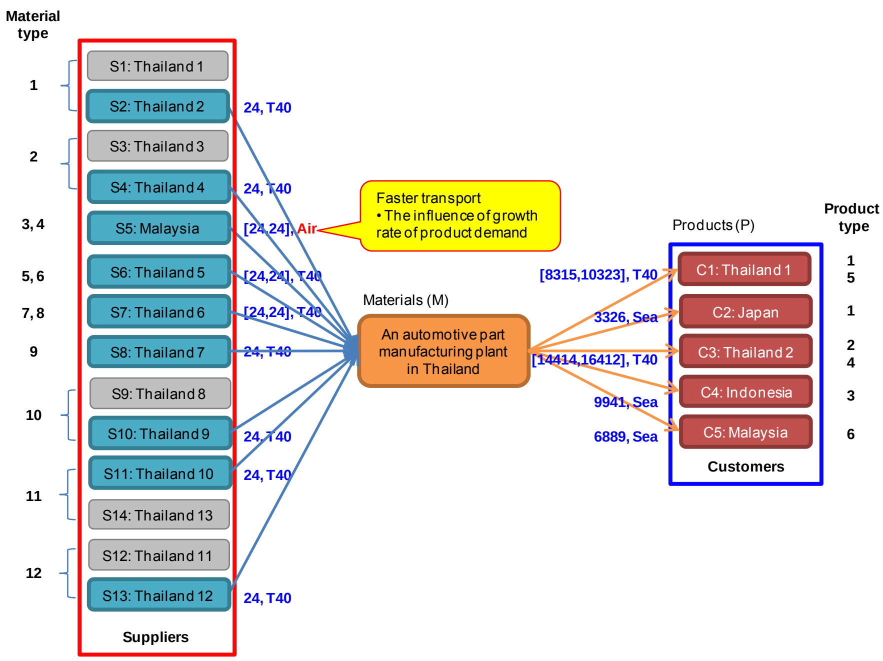


Figure 4-2-6d Supply chain networks based on *W* [0.4, 0.3, 0.3] in years 2018 to 2020 (the 4-th configuration)

The four configurations generate the Pareto-optimal outputs as shown in Table 4-2-2. Its last row reveals that supply chain networks of the automotive part manufacturing company are long-term designed with the 1-st configuration (Figure 4-2-6a) which generates the greatest overall utility (i.e. 0.9017). The 1-st configuration contributes to the Pareto-optimal cost at 562 THB per item, lead time at 5.04 weeks, and environmental impact at 0.672 points per item on average.

Table 4-2-2 Overall utility of candidate Pareto-optimal configurations

Output	Configuration			
	1	2	3	4
Cost (x100 THB per item)	5.620	5.625	5.621	5.699
Lead time (weeks)	5.041	5.041	5.041	4.759
Environmental impact (x0.1 points per item)	6.722	6.734	6.722	6.936
Overall utility	**0.9017**	**0.8963**	**0.9012**	**0.8442**

In summary, the individual DSS for environmentally sustainable SCND of the automotive part manufacturing company is capable of making several decisions such as baseline, single-objective, and multi-objective decisions. They require a number of subjective and uncertain parameters. Their sensitivity to the Pareto-optimal result is investigated and analysed in the tenth step of the first industrial case (i.e. the cryogenic storage tank manufacturing company). It is found that the generic DSS is sufficiently robust for the system validation in the next step (referred to Figure 4-1).

Step 11: Result comparisons and discussions

The results (i.e. outputs and their relative decision variables) of baseline, three single-objective, and multi-objective decisions are compared and discussed in order to demonstrate the potential of the individual DSS for industry implementation. This step provides three comparisons along with their discussions as follows.

1) Comparison of baseline and actual product cost in the base year

To demonstrate the first successful validation of the individual DSS, its product cost based on the baseline decision is compared to the actual product cost in the base year (year 2011). Figure 4-2-7 reveals that the individual DSS returns the baseline product cost at 425.91 THB per item. It is differed by 5.53% when compared to the actual product cost (i.e. 450.86 THB per item). The very small difference of product cost is considered a successful validation of the individual DSS.

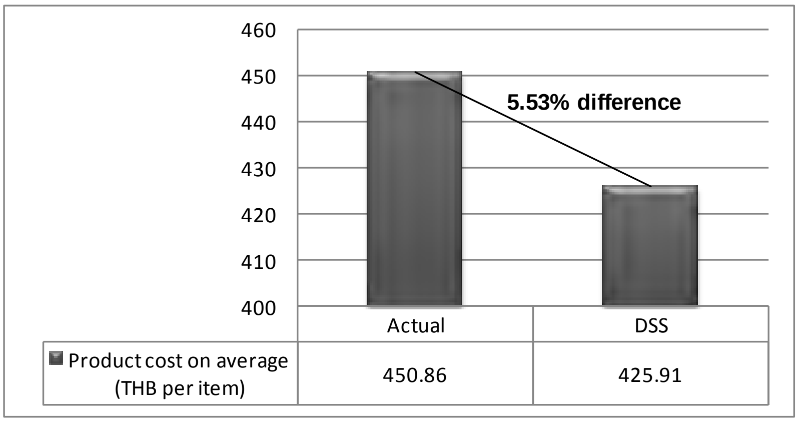


Figure 4-2-7 Product cost comparison in year 2011

2) Comparison of baseline and Pareto-optimal results

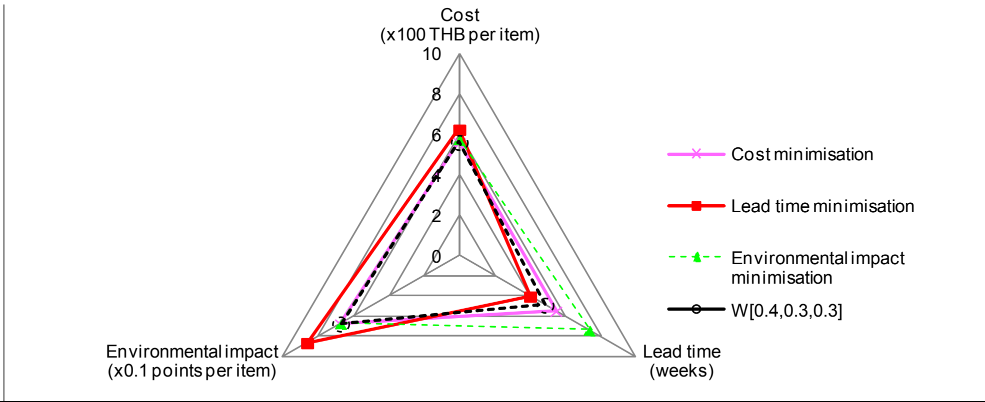
To demonstrate the second successful validation of the individual DSS, its outputs (on average) and decision variables based on the multi-objective decision with *W* [0.4, 0.3, 0.3] are compared to those based on the baseline decision. Table 4-2-3 reveals that the multi-objective decision generates the Pareto-optimal cost at 562.70 THB per item, lead time at 4.86 weeks, and environmental impact at 0.672 points per item. The multi-objective decision is capable of little improvement to the baseline cost (i.e. 578.20 THB per item) by 2.68% and environmental impact (i.e. 0.674 points per kilogram) by 0.26%, whereas the baseline lead time (i.e. 4.58 weeks) is lengthened by 6.19%. The improvements in cost and environmental impact are caused by utilising larger lot-sizes of the multi-objective decision with *W* [0.4, 0.3, 0.3] (Figure 4-2-6). On the other hand, the baseline decision (Figure 4-2-2) utilises minimal lot-sizes, so the baseline lead time is shorter than the Pareto-optimal lead time. Even if the Pareto-optimal outputs are conflicted with each other, they generate the better overall performance by 8.71% as shown in Table 4-2-3. The improvement in overall performance is, however, not much significant, so decision makers should select any decision which is appropriate for the automotive part manufacturing plant.

Table 4-2-3 Comparisons of baseline and Pareto-optimal outputs

Output	Baseline decision	*W* [0.4, 0.3, 0.3]	% Improvement
Cost (x100 THB per item)	5.782	5.627	**2.68%**
Lead time (weeks)	4.577	4.860	-6.19%
Environmental impact (x0.1 points per item)	6.740	6.723	**0.26%**
Overall utility	**0.9017**	**0.8402**	**7.32%**

3) Comparison of single-objective and Pareto-optimal results

To demonstrate the third successful validation of the individual DSS, its outputs (on average) and decision variables based on the multi-objective decision with *W* [0.4, 0.3, 0.3] are compared to those based on the three single-objective decisions. Figure 4-2-8 reveals that the three single objective decisions generate extreme values of individual objectives. For example, the single objective decision with cost minimisation generates the lowest cost without consideration of lead time and environmental impact as depicted in the cross-solid line. The individual DSS based on cost minimisation suggests suppliers offering lower-price materials, and cheaper transport (i.e. 40-ton trucks and sea mode) with smaller lot-sizes. The cheaper transportation modes have lower freight rates and consume lesser fuel (greener), whereas the smaller lot-sizes support lower-cost inventory holding and shorter lead time. The outputs of cost minimisation consequently approach to the shortest lead time and the lowest environmental impact. The shortest lead time worsens environmental impact as depicted in the square-red. The worsened environmental impact is caused by the utilisation of minimal lot-sizes due to infrequent roundtrips. On the other hand, the lowest environmental impact lengthens lead time as depicted in the triangle-dash line. The lengthened lead time is caused by the utilisation of slower modes (i.e. 40-ton trucks and sea mode). These conflicts cause the need for multi-objective decision with *W* [0.6, 0.1, 0.3]. The three outputs of multi-objective decision with *W* [0.4, 0.3, 0.3] approach the lowest cost by 97.70% and the lowest environmental impact by 99.50% since they fairly support each other as depicted in the circle-solid line of Figure 4-2-8. Their significant closeness is caused by two influences. The first influence is the utilisation of 40-ton trucks and sea mode as cheaper and greener transport. The cost and environmental impact are also improved by utilising maximal lot-sizes for all material types as the second influence. On the other hand, smaller lot-sizes are utilised for some product models to shorten production time. The shorten production time contributes to the greater degree of closeness of the Pareto-optimal lead time. It is, however, less than the closeness degrees of the Pareto optimal cost and environmental impact. These degrees of closeness correspond to the relative weights of cost, lead time, and environmental impact. The correspondence is considered another successful validation of the individual DSS.



Output	Single-objective decision			*W* [0.4, 0.3, 0.3]	Degree of closeness
	Cost	Lead time	Environmental impact		
Cost (AUD per kilogram)	5.612	6.259	5.755	5.627	0.977
Lead time (weeks)	5.467	4.011	7.363	4.860	0.747
Environmental impact (x 0.1 points per kilogram)	6.734	8.620	6.713	6.723	0.995

Figure 4-2-8 Comparisons of single-objective and Pareto-optimal outputs

In summary, the individual DSS for environmentally sustainable SCND is successfully validated by the industrial case of automotive part manufacturing company. The successful validation of the individual DSS is demonstrated with three comparisons along with their discussions. Firstly, there is a very small difference between baseline and actual product cost of 5.35% in the base year. Secondly, the individual DSS provides some suggestions that the baseline overall performance can be improved by 8.71% when the multi-objective decision with *W* [0.4, 0.5, 0.1] is implemented. The improvement in overall performance is, however, not much significant, so decision makers should select any decision which is appropriate for the company. Thirdly, there is a correspondence between the degrees of closeness and relative weights of the Pareto-optimal cost, lead time, and environmental impact. These comparisons and discussions can imply that the individual DSS is successfully validated.

4.3 Roof sheet manufacturing company

The roof sheet manufacturing company in Australia is the third industrial case. It is used to demonstrate step-by-step the system verification and validation by following the eleven steps as shown in Figure 4-1.

Step 1: Problem statement

The roof sheet company has one location of manufacturing plant (product MP) in Australia. It manufactured 1,000 tons of roof sheets in year 2011. It requires ten material types which are procured from four local suppliers and six global suppliers in five Asian countries, and the United States as presented in Figure 4-3-1.

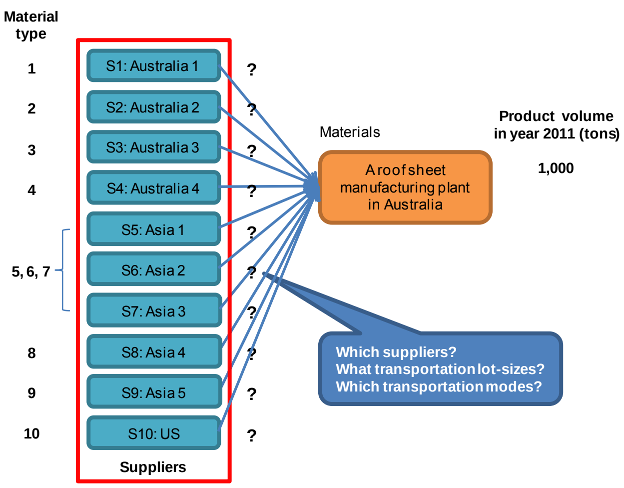


Figure 4-3-1 Supply chain networks of roof sheet manufacturing company

The supply chain networks of roof sheet manufacturing company (Figure 4-3-1) involve strategic decisions for Supply Network Design (SND). It determines which suppliers are the best-fitted. Suppliers offering lower-price materials may be farther from the roof sheet manufacturing plant. Alternatively, suppliers who are closer to the roof sheet manufacturing plant may offer higher-price materials. For example, suppliers in Asia 3 offer lower-price materials, whereas suppliers in Asia 1 have shorter-distance transportation (Appendix E). However, the material prices are dependent on suppliers‟ economic competitiveness, especially currency exchange rates. For example, the Australian Dollar (AUD) (-0.60% of annual depreciation rate) is more depreciated than the currency of Asia1 (-2.39% of annual depreciation rate) but less depreciated than other four currencies (Appendix E). These conflicts cause the need for trade-offs between currency depreciation rates, material prices and transportation distances to select the most economic, responsive, and green suppliers.

In addition, the SND determine which transportation modes and what lot-sizes are optimal. Firstly, cheaper and greener transportation modes have slower speeds; otherwise, faster transport consumes more fuel. Greater fuel consumption causes higher freight rates and more environmental impact. Secondly, larger lot-sizes contribute to reduction in transportation cost and environmental impact due to infrequent roundtrips, but produce a longer lead time. These conflicts cause the need for trade-offs between cost, lead time, and environmental impact to determine appropriate transportation modes and lot-sizes.

In summary, the SCND problems of the roof sheet manufacturing company involve the strategic decision (domain) of SND. It includes several conflicts of three objectives (i.e. cost, lead time, and environmental impact). These conflicts are however solved under numerous assumptions which are defined in the next step (referred to Figure 4-1).

Step 2: Assumption defining

The assumptions are defined as the second step in aiming to reduce complication of the SCND problems, which were stated in the first step. Certain assumptions concerning the roof sheet manufacturing company are made based on the discussions with the company officials as follows.

- Candidate transportation modes include air inter-continental, truck 16 ton B250, train B250, and sea ship B250 (BUWAL250, 1996).
- There are no costs of terminating and initiating a contract for a supplier.

These assumptions support the individual DSS to specify its relative parameters. They are input into generic moduleswhich are determined based on the SCND problems of the roof sheet manufacturing company in the next step (referred to Figure 4-1).

Step 3: Generic module determination

The generic modules are determined based on the SCND problems and assumptions, which were stated in the first two steps. The SCND problems of the roof sheet manufacturing company involve the strategic decision (domain) of SND. It has individual supply chain entities which are indexed as follows.

- Product manufacturing plant (*m* = 1) is located in Australia,
- Suppliers (*i* = 1,...,12) are in Australia 1 to 4, Asia 1 to 5, and the United States,
- Product (*r* = 1) is roof sheet,
- Materials (*p* = 1,...,10) include material types 1 to 3 (polymer), 4 (chemical substance), 5 to 7 (glass), 8 (polymer), 9 (chemical substance), and 10 (polymer), and
- Transportation modes (*s* = 1,...,5) include air, 16-ton truck (T16), rail, and sea.

These five supply chain entities involve three generic modules of the individual DSS. They are (1) material demand, (2) material procurement and warehousing, and (3) material distribution (Figure 3-2). These three generic modules are input with numerous parameters as shown in Appendix E. They contribute to the optimum values of three decision variablesincluding (1) supplier selection, (2) transportation mode selection, and (3) transportation lot-sizes utilised for delivering materials from the selected suppliers to the product MP.

The three generic modules, which were above determined for environmentally sustainable SCND of the roof sheet manufacturing company, are applied to simulate the baseline decision in the next step (referred to Figure 4-1).

Step 4: Simulation of baseline decision

The baseline decision selects suppliers having shorter-distance transportation in order to improve transportation cost, time, and environmental impact. The cost and environmental impact is also reduced by locally utilising cheaper and greener transport (i.e. sea mode). On the other hand, faster transport (i.e. 16-ton trucks) is globally utilised to shorten lead time. It is also shortened by utilising minimal lot-sizes (i.e. 12 tons) for the material procurement. As shown in Figure 4-3-2, suppliers in Asia 1 are selected to supply material types 5 to 7 by utilising sea mode with lot-sizes of 12 tons. Based on the baseline configuration, the individual DSS returns the baseline cost at 4.10 AUD per kilogram, lead time at 3.02 weeks, and environmental impact at 0.343 points per kilogram on average.

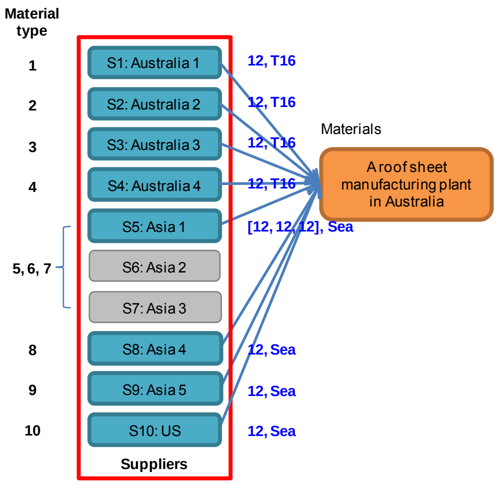


Figure 4-3-2 Baseline supply chain networks

It is noticeable that the individual DSS for environmentally sustainable SCND of the roof sheet manufacturing company is capable of explaining behaviour of the baseline supply chain networks and their relative outputs. They are used for comparing to the results of three single-objective and multi-objective decisions in the eleventh step.

Step 5: Optimisation of single-objective decisions

The single-objective decisions aim to optimise an objective without consideration of other objectives. This step presents the optimisation of three single-objective decisions including minimisation of cost, lead time, and environmental impact as follows.

1) Cost minimisation

The individual DSS based on cost minimisation suggests two configurations over the ten years of planning period as shown in Figures 4-3-3a and 4-3-3b. The two configurations utilise cheaper transport (i.e. rail and sea modes) with maximal lot-sizes (i.e. 60 tons), but suppliers are different. In the first year, suppliers in Asia 1 having offering shorter-distance transportation are selected (Figure 4-3-3a) which supports lower-cost transportation. After that, material types 5 to 7 are procured from suppliers in Asia 2 offering lower-price materials incurred by the greater appreciation of the currency of Asia 2 (Figure 4-3-3b). It overcomes a growth rate of transportation cost incurred by the growth rate of fuel.

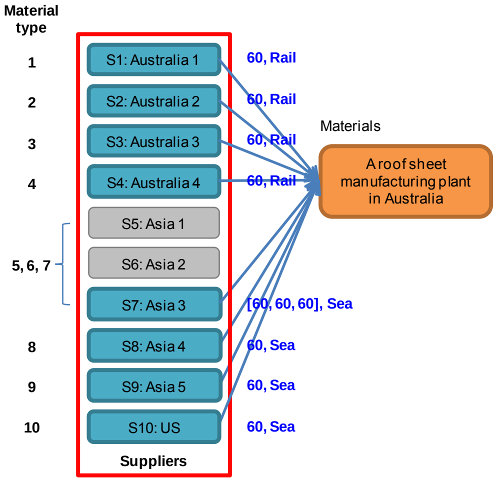


Figure 4-3-3a Supply chain networks based on cost minimisation in year 2011 (the 1-st configuration)

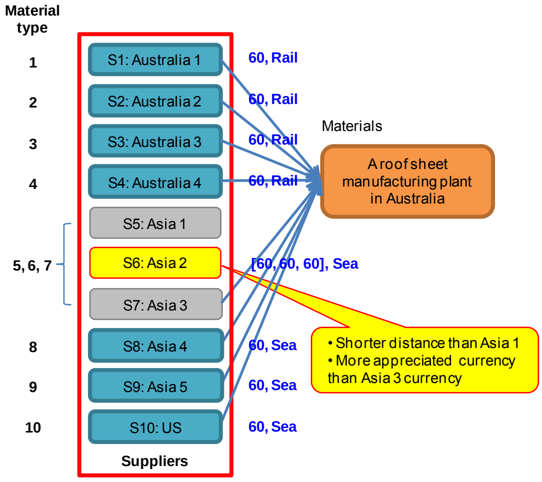


Figure 4-3-3b Supply chain networks based on cost minimisation in years 2012 to 2020 (the 2-nd configuration)

The two configurations generate the lowest cost in different time durations due to the influence of economic competitiveness as shown in Table 4-3-1. Its last row reveals that supply chain networks of the roof sheet manufacturing company are long-term designed with the 2-nd configuration (Figure 4-3-3b) which generates the lowest product cost on average at 2.52 AUD per kilogram on average. Its relative lead time and environmental impact respectively are valued at 3.12 weeks and 0.246 points per kilogram on average.

Table 4-3-1 Product cost of candidate economic configurations

Planning year	Product cost (AUD per kilogram)	
	Configuration 1	Configuration 2
2011	**2.48**	2.49
2012	2.51	**2.49**
2013	2.54	**2.49**
2014	2.57	**2.49**
2015	2.61	**2.50**
2016	2.66	**2.51**
2017	2.71	**2.53**
2018	2.76	**2.54**
2019	2.83	**2.57**
2020	2.91	**2.60**
Average	**2.66**	**2.52**

2) Lead time minimisation

The individual DSS based on lead time minimisation suggests a single configuration over the ten years of planning period as shown in Figure 4-3-4. The critical lead time is incurred by procuring the 1-st material type from suppliers in Australia 1. It is shortened by utilising 16-ton trucks with a minimal lot-size (i.e. 12 tons). To avoid lengthening the critical lead time, faster transport (i.e. air mode and 16-ton trucks) with minimal lot-sizes (i.e. 12 tons) are utilised for other suppliers. These suggestions contribute to the shortest lead time at 0.16 weeks, whereas its relative cost and environmental impact respectively are valued at 23.62 AUD per kilogram and 1.659 points per kilogram on average.

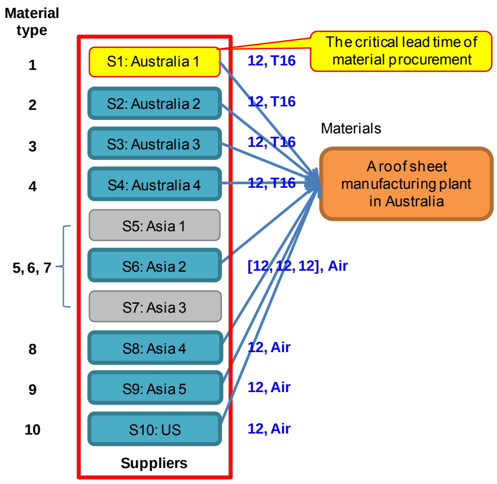


Figure 4-3-4 Supply chain networks based on lead time minimisation for the ten years of planning period

3) Environmental impact minimisation

The individual DSS based on environmental impact minimisation suggests a single configuration over the ten years of planning period as shown in Figure 4-3-5. The suggested configuration selects suppliers closer to the roof sheet manufacturing plant, and utilises greener transport (i.e. rail and sea modes) with maximal lot-sizes (i.e. 60 tons). Accordingly, material types 1 to 4 are procured from local suppliers by utilising rail mode with lot-sizes of 60 tons. Sea mode with lot-sizes of 60 tons are utilised for the rest of material types procured from global suppliers given that suppliers in Asia 1 are selected to supply material types 5 to 7. These suggestions contribute the lowest environmental impact at 0.246 points per kilogram, whereas its relative cost and lead time respectively are valued at 2.566 AUD per kilogram and 3.12 weeks on average.

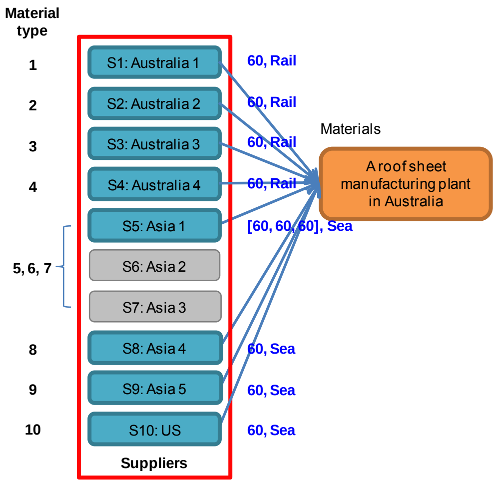


Figure 4-3-5 Supply chain networks based on environmental impact minimisation for the ten years of planning period

It is noticeable that the three single-objective decisions suggest different configurations. The optimal configuration based on an objective contributes to the optimum value of that objective, whereas it is in conflict with the other two objectives. The conflicts of three objectives are traded off by using the multi-objective decision. It is restricted with specific upper and lower bounds of the three objectives as shown in Table 4-3-2 (step 6), and optimised with 409 iterations (step 8) and relative weights of cost, lead time, and environmental impact at 0.6, 0.1, and 0.3 respectively (i.e. *W* [0.6, 0.1, 0.3]) (step 7). The much attention to cost objective is paid in order to achieve mass production, and followed by environmental impact since environmental regulations and consciousness are growing. The outcomes of steps 6 to 8 are conducted to optimise the multi-objective decision in the next step (referred to Figure 4-1).

Table 4-3-2 Upper and lower bounds of three objectives

Objective	Cost minimisation	Lead time minimisation	Environmental impact minimisation	Upper bound	Lower bound
Cost (AUD per kilogram)	2.52	23.62	2.57	**23.62**	**2.52**
Lead time (weeks)	3.12	0.16	3.12	**3.12**	**0.16**
Environmental impact (x 0.1 points per kilogram)	2.46	16.59	2.46	**16.59**	**2.46**

Step 9: Optimisation of multi-objective decision

The individual DSS based on the multi-objective decision suggests two configurations over the ten years of planning period as shown in Figures 4-3-6a and 4-3-6b. The two configurations select suppliers in Asia 1 offering lower-price materials and having more appreciated currency, and locally utilised cheaper and greener transport (i.e. rail mode) with smaller lot-sizes, whereas global suppliers utilise different transportation modes. In the first five years, air mode is utilised to shorten lead time (Figure 4-3-6a). After that, sea mode as a cheaper transport is utilised due to the influence of the growth rate of supply chain cost incurred by the growth rates of currency depreciation and fuel price (Figure 4-3-6b).

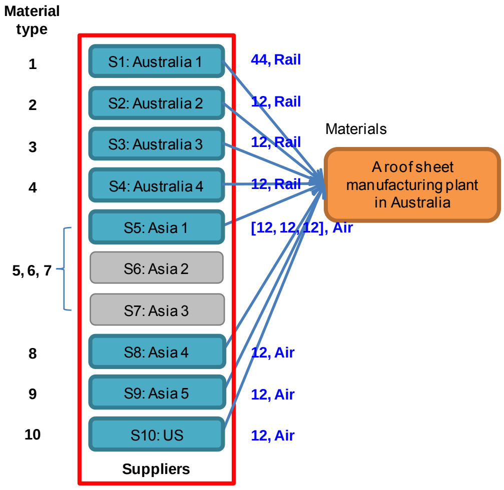


Figure 4-3-6a Supply chain networks based on *W* [0.6, 0.1, 0.3] in years 2011 to 2015 (the 1-st configuration)

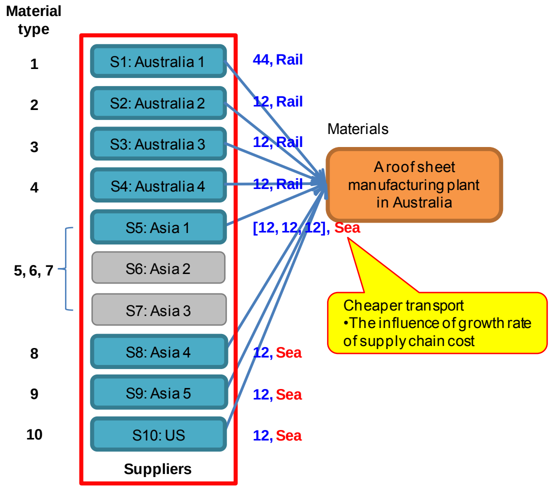


Figure 4-3-6b Supply chain networks based on *W* [0.6, 0.1, 0.3] from years 2016 to 2020 (the 2-nd configuration)

The two configurations generate the Pareto-optimal outputs as shown in Table 4-3-3. Its last row reveals that supply chain networks of the roof sheet manufacturing company are long-term designed with the 2-nd configuration (Figure 4-3-6b) which generates the greatest overall utility (i.e. 0.90). The 2-nd configuration contributes to the Pareto-optimal cost at 2.57 AUD per kilogram, lead time at 3.02 weeks, and environmental impact at 2.57 points per kilogram on average.

Table 4-3-3 Overall utility of candidate Pareto-optimal configurations

Output	Configuration	
	1	2
Cost (AUD per kilogram)	21.33	**2.57**
Lead time (weeks)	0.34	**3.02**
Environmental impact (x 0.1 points per kilogram)	15.18	**2.57**
Overall utility	**0.19**	**0.90**

In summary, the individual DSS for environmentally sustainable SCND of the roof sheet manufacturing company is capable of making several decisions such as baseline, single-objective, and multi-objective decisions. They require a number of subjective and uncertain parameters. Their sensitivity to the Pareto-optimal result is investigated and analysed in the tenth step of the first industrial case (i.e. the cryogenic storage tank manufacturing company). It is found that the generic DSS is sufficiently robust for the system validation in the next step (referred to Figure 4-1).

Step 11: Result comparisons and discussions

The results (i.e. outputs and their relative decision variables) of baseline, three single-objective, and multi-objective decisions are compared and discussed in order to demonstrate the potential of the individual DSS for industry implementation. This step provides two comparisons along with their discussions as follows, but the successful validation in comparison of baseline and actual product cost in the base year is not demonstrated since the actual product cost is not provided.

1) Comparison of baseline and Pareto-optimal results

To demonstrate the first successful validation of the individual DSS, its outputs (on average) and decision variables based on the multi-objective decision with *W* [0.6, 0.1, 0.3] are compared to those based on the baseline decision. Table 4-3-4 reveals that the multi-objective decision generates the Pareto-optimal cost at 2.57 AUD per kilogram, lead time at 3.02 weeks, and environmental impact at 0.263 points per kilogram. The multi-objective decision is capable of significant improvement to the baseline cost (i.e. 4.10 AUD per kilogram) by 37.46% and environmental impact (i.e. 0.343 points per kilogram) by 24.97%, whereas there is no difference in lead time (i.e. 3.02 weeks).

Table 4-3-4 Comparisons of baseline and Pareto-optimal outputs

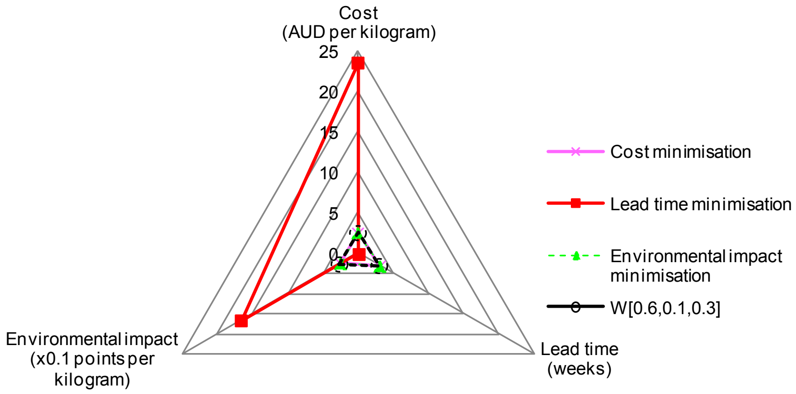
Output	Baseline decision	*W* [0.6, 0.1, 0.3]	% Improvement
Cost (AUD per kilogram)	4.10	2.57	**37.46%**
Lead time (weeks)	3.02	3.02	0.00%
Environmental impact (x 0.1 points per kilogram)	3.43	2.57	**24.97%**
Overall utility	**0.84**	**0.90**	**7.39%**

The improvements in cost and environmental impact are caused by locally utilising rail (cheaper and greener) mode of the multi-objective decision with *W* [0.6, 0.1, 0.3] (Figure 4-3-6b). The utilised rail mode does not have any effect on the critical lead time, so there is no difference in lead time. On the other hand, the baseline decision (Figure 4-3-2) locally utilises in-house transport (i.e. 16-ton trucks) because it is simply manageable. The 16-ton trucks, however, contribute to the higher cost and environmental impact, so a trade-off between the improvements in cost and environmental impact and the simple management in transportation is required for selecting the best decision.

2) Comparison of single-objective and Pareto-optimal results

To demonstrate the second successful validation of the individual DSS, its outputs (on average) and decision variables based on the multi-objective decision with *W* [0.6, 0.1, 0.3] are compared to those based on the three single-objective decisions. Figure 4-3-7 reveals that the three single objective decisions generate extreme values of individual objectives. For example, the single objective decision with environmental impact minimisation generates the lowest environmental impact without consideration of cost and lead time as depicted in the triangle-dash line. The environmental impact minimisation (Figure 4-3-5) supports the cost minimisation (Figure 4-3-3b) since the individual DSS suggests suppliers having shorter-distance transportation and greener transport (i.e. rail and sea modes) with maximal lot-sizes. The greener transportation modes consume lesser fuel and have a lower freight rate, although having slower speed. The maximal lot-sizes reduce transportation cost and environmental impact due to infrequent roundtrips. The three outputs of environmental impact minimisation consequently approach those of cost minimisation, but are conflicting with those of lead time minimisation as depicted in the cross-solid line. The lead time minimisation (Figure 4-3-4) suggests utilising faster transportation modes with minimal lot-sizes especially the critical lead time. The faster transportation modes consume more fuel, however, having higher freight rates and more environmental impact. The minimal lot-sizes shorten lead time, but increasing transportation cost and more environmental impact due to frequent roundtrips. These conflicts cause the need for multi-objective decision with *W* [0.6, 0.1, 0.3].

The three outputs of multi-objective decision with *W* [0.6, 0.1, 0.3] much approach to the lowest cost by 99.80% and the lowest environmental impact by 99.20% since they fairly support each other as depicted in the circle-solid line of Figure 4-3-7. Their much closeness is caused by two influences (Figure 4-3-6b). The first influence is the selection of suppliers having shorter-distance transportation which contributes to reduction in transportation cost and environmental impact. They are also improved by utilising cheaper and greener transport (i.e. rail and sea modes) as the second influences. On the other hand, minimal lot-sizes are utilised to shorten preparation time. The shorten production time contributes to the greater degree of closeness of the Pareto-optimal lead time. It is, however, less than the closeness degrees of the Pareto optimal cost and environmental impact. These degrees of closeness correspond to the relative weights of cost, lead time, and environmental impact. The correspondence is considered another successful validation of the individual DSS.



Output	Single-objective decision			*W* [0.6, 0.1, 0.3]	Degree of closeness
	Cost	Lead time	Environmental impact		
Cost (AUD per kilogram)	2.52	23.62	2.57	2.57	0.998
Lead time (weeks)	3.12	0.16	3.12	3.02	0.033
Environmental impact (x 0.1 points per kilogram)	2.46	16.59	2.46	2.57	0.992

Figure 4-3-7 Comparisons of single-objective and Pareto-optimal outputs

In summary, the individual DSS for environmentally sustainable SCND is successfully validated by the industrial case of roof sheet manufacturing company. The successful validation of the individual DSS is demonstrated with two comparisons along with their discussions. Firstly, the individual DSS provides some suggestions that the baseline cost environmental impact respectively can be improved by 37.46% and 24.97% when the multi-objective decision with *W* [0.6, 0.1, 0.3] is implemented. The improvements in cost and environmental impact trade off the simple management in transportation. This trade-off supports decision makers to select the best decision. Secondly, there is a correspondence between the degrees of closeness and relative weights of the Pareto-optimal cost, lead time, and environmental impact. These comparisons and discussions can imply that the individual DSS is successfully validated.

4.4 Power boat manufacturing company

The power boat manufacturing company in Australia is the fourth industrial case. It is used to demonstrate step-by-step the system verification and validation by following the eleven steps as shown in Figure 4-1.

Step 1: Problem statement

The power boat company has one location of manufacturing plant (product MP) in Australia. It manufactured 500 units of power boats in year 2011. It requires twelve materials which are procured from five Australian and two Asian suppliers as presented in Figure 4-4-1.

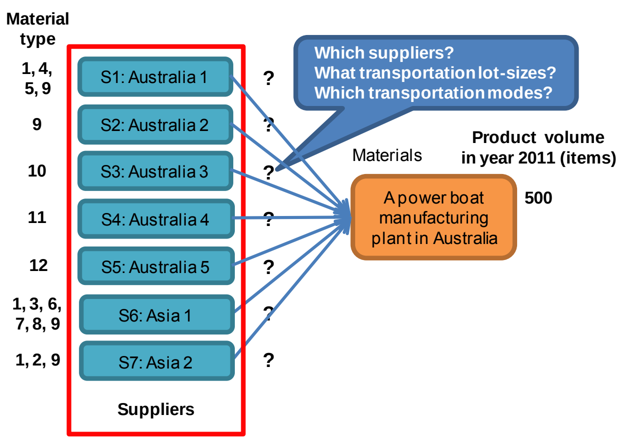


Figure 4-4-1 Supply chain networks of power boat manufacturing company

The supply chain networks of power boat manufacturing company (Figure 4-4-1) involve strategic decisions for Supply Network Design (SND). It determines which suppliers are the best-fitted. Suppliers offering lower-price materials may be farther from the power boat manufacturing plant. Alternatively, suppliers who are closer to the power boat manufacturing plant may offer higher-price materials. For example, suppliers in Asia 2 offer lower-price materials, whereas local suppliers have shorter-distance transportation, consequently higher prices (Appendix F). However, the material prices are dependent on suppliers‟ economic competitiveness, especially currency exchange rates. For example, the Australian Dollar (AUD) (-0.60% of annual depreciation rate) is more depreciated than the currency of Asia1 (-2.39% of annual depreciation rate) but is less depreciated than the currency of Asia2 (1.62% of annual depreciation rate). The less depreciation of the currency of Asia1 causes lower-price materials in the long-term. These conflicts cause the need for trade-offs between currency depreciation rates, material prices and transportation distances to select the most economic, responsive, and green suppliers.

In addition, the SND determine which transportation modes and what lot-sizes are optimal. Firstly, cheaper and greener transportation modes have slower speeds; otherwise, faster transport consumes more fuel. Greater fuel consumption causes higher freight rates and more environmental impact. Secondly, larger lot-sizes contribute to reduction in transportation cost and environmental impact due to infrequent roundtrips, but produce a longer lead time. These conflicts cause the need for trade-offs between cost, lead time, and environmental impact to determine appropriate transportation modes and lot-sizes.

In summary, the SCND problems of the power boat manufacturing company involve the strategic decision (domain) of SND. It includes several conflicts of three objectives (i.e. cost, lead time, and environmental impact). These conflicts are however solved under numerous assumptions which are defined in the next step (referred to Figure 4-1).

Step 2: Assumption defining

The assumptions are defined as the second step in aiming to reduce complication of the SCND problems, which were stated in the first step. Certain assumptions concerning the power boat manufacturing company are made based on the discussions with the company officials as follows.

- Candidate transportation modes include air inter-continental, truck 16 ton B250, train B250, and sea ship B250 (BUWAL250, 1996).
- There are no costs of terminating and initiating a contract for a supplier.

These assumptions support the individual DSS to specify its relative parameters. They are input into generic modules which are determined based on the SCND problems of the power boat manufacturing company in the next step (referred to Figure 4-1).

Step 3: Generic module determination

The generic modules are determined based on the SCND problems and assumptions, which were stated in the first two steps. The SCND problems of the power boat manufacturing company involve the strategic decision (domain) of SND. It has specific supply chain entitieswhich are indexed as follows.

- Product manufacturing plant (m = 1) is located in Australia,
- Suppliers (i = 1,...,7) are in Australia 1 to 5,and Asia 1 to 2,
- Product (r = 1) is power boat,
- Materials (p = 1,...,12) include polymer (material types 1, 2, 5, and 11), steel (3, 6, and 7), wood (10 and 12), and chemical substance (4 and 8), and
- Transportation modes (s = 1,...,5) include air, 16-ton truck (T16), rail, and sea.

These five entities involve three generic modules of the individual DSS. They are (1) material demand, (2) material procurement and warehousing, and (3) material distribution (Figure 3-2). These three generic modules are input with numerous parameters as shown in Appendix E. They contribute to the optimum values of three decision variables including (1) supplier selection, (2) transportation mode selection, and (3) transportation lot-sizes utilised for delivering materials from the selected suppliers to the product MP.

The three generic modules, which were above determined for environmentally sustainable SCND of the power boat manufacturing company, are applied to simulate the baseline decision in the next step (referred to Figure 4-1).

Step 4: Simulation of baseline decision

The baseline decision selects suppliers having shorter-distance transportation in order to improve transportation cost, time, and environmental impact. The cost and environmental impact is also reduced by locally utilising cheaper and greener transport (i.e. sea mode). On the other hand, faster transport (i.e. 16-ton trucks) is globally utilised to shorten lead time. It is also shortened by utilising minimal lot-sizes (i.e. 12 tons) for the material procurement. As shown in Figure 4-4-2, local suppliers are selected to supply material types 1 and 9 by utilising 16-ton trucks with lot-sizes of 12 tons. Based on the baseline configuration, the individual DSS returns the baseline cost at 42,617 AUD per item, lead time at 1.65 weeks, and environmental impact at 1,244 points per item on average.

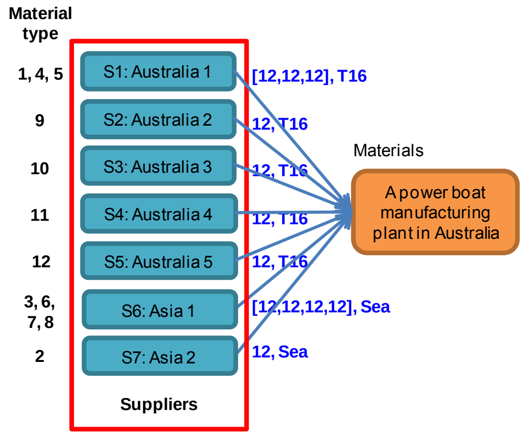


Figure 4-4-2 Baseline supply chain networks

It is noticeable that the individual DSS for environmentally sustainable SCND of the power boat manufacturing company is capable of explaining behaviour of the baseline supply chain networks and their relative outputs. They are used for comparing to the results of three single-objective and multi-objective decisions in the eleventh step.

Step 5: Optimisation of single-objective decisions

The single-objective decisions aim to optimise an objective without consideration of other objectives. This step presents the optimisation of three single-objective decisions including minimisation of cost, lead time, and environmental impact as follows.

1) Cost minimisation

The individual DSS based on cost minimisation suggests three configurations over the ten years of planning period as shown in Figures 4-4-3a to 4-4-3c. The three configurations utilise cheaper transport (i.e. rail and sea modes) with maximal lot-sizes (i.e. 60 tons), but suppliers are different. In the first four years, suppliers in Asia 2 offering lower-price materials are selected to supply material types 1 and 9 (Figure 4-4-3a). In year 2015, the 1-st material type is offered with lower-price by suppliers in Asia 1 having more appreciated currency (Figure 4-4-3b). After that, material type 1 and 9 are hence procured from suppliers in Asia 1 (Figure 4-4-3c).

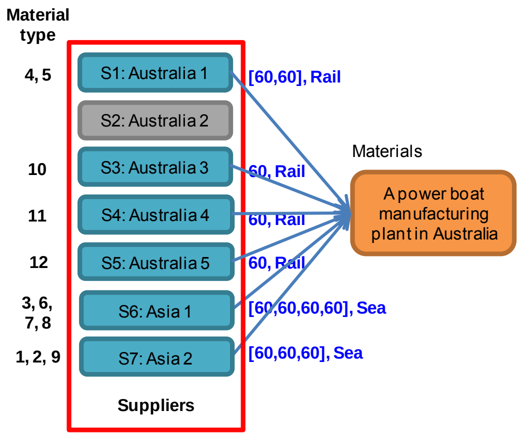


Figure 4-4-3a Supply chain networks based on cost minimisation in years 2011 to 2014 (the 1-st configuration)

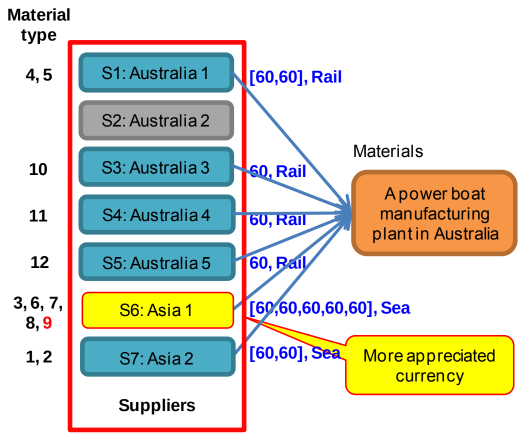


Figure 4-4-3b Supply chain networks based on cost minimisation in year 2015 (the 2-nd configuration)

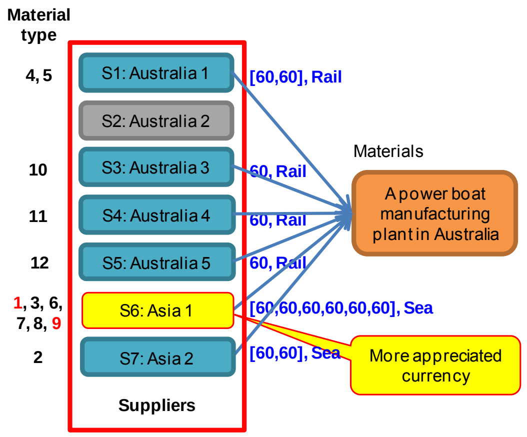


Figure 4-4-3c Supply chain networks based on cost minimisation in years 2016 to 2020 (the 3-rd configuration)

The three configurations generate the lowest cost in different time durations due to the influence of economic competitiveness as shown in Table 4-4-1. Its last row reveals that supply chain networks of the power boat manufacturing company are long-term designed with the 2-nd configuration (Figure 4-4-3b) which generates the lowest product cost at 39,839 AUD per item on average. Its lead time and environmental impact respectively are valued at 1.93 weeks and 1,066 points per item on average.

Table 4-4-1 Product cost of candidate economic configurations

Planning year	Product cost (AUD per kilogram)		
	Configuration 1	**Configuration 2**	**Configuration 3**
2011	**40,968**	40,986	41,098
2012	**40,709**	40,721	40,809
2013	**40,453**	40,460	40,523
2014	**40,200**	40,203	40,242
2015	39,952	**39,949**	39,965
2016	39,707	39,699	**39,691**
2017	39,466	39,453	**39,421**
2018	39,228	39,210	**39,156**
2019	38,993	38,970	**38,893**
2020	38,763	38,735	**38,635**
Average	**39,844**	**39,839**	**39,843**

2) Lead time minimisation

The individual DSS based on lead time minimisation suggests a single configuration over the ten years of planning period as shown in Figure 4-4-4. The critical lead time is incurred by procuring materials from suppliers in Asia 1. It is shortened by utilising air (the fastest) mode with a minimal lot-size (i.e. 12 tons). To avoid lengthening the critical lead time, faster transport (i.e. air mode and 16-ton trucks) with minimal lot-sizes (i.e. 12 tons) are utilised for other suppliers. These suggestions contribute the shortest lead time at 0.16 weeks, whereas its relative cost and environmental impact respectively are valued at 66,202 AUD per item and 2,784 points per item on average.

2.3) Environmental impact minimisation

The individual DSS based on environmental impact minimisation suggests a single configuration over the ten years of planning period as shown in Figure 4-4-5. The suggested configuration selects suppliers closer to the power boat manufacturing company, and utilises greener transport (i.e. rail and sea modes) with maximal lot-sizes (i.e. 60 tons). Accordingly, most of material types are procured from suppliers in Asia 1 by utilising sea mode with a lot-size of 48 tons. These suggestions contribute the lowest environmental impact at 1,066 points per kilogram, whereas its relative cost and lead time respectively are valued at 39,843 AUD per item and 1.79 weeks on average.

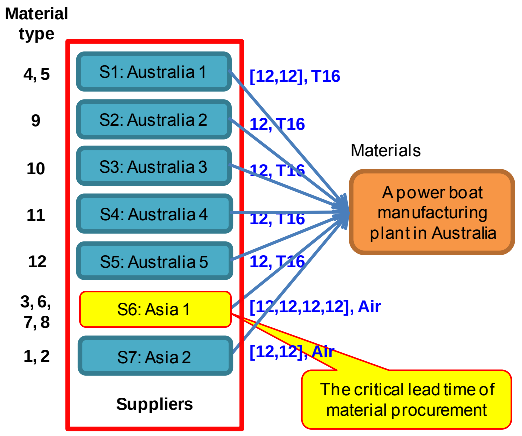


Figure 4-4-4 Supply chain networks based on lead time minimisation for the ten years of planning period

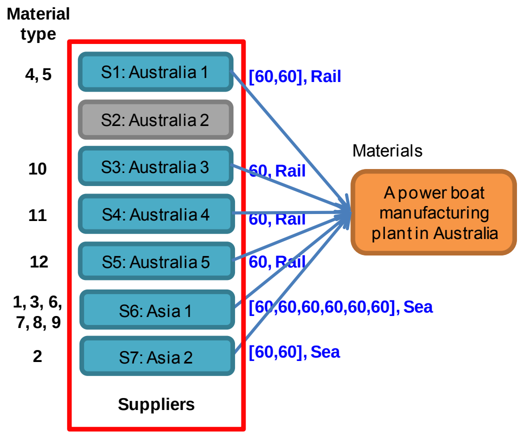


Figure 4-4-5 Supply chain networks based on environmental impact minimisation for the ten years of planning period

It is noticeable that the three single-objective decisions suggest different configurations. The optimal configuration based on an objective contributes to the optimum value of that objective, whereas it is in conflict with the other two objectives. The conflicts of three objectives are traded off by using the multi-objective decision. It is restricted with specific upper and lower bounds of the three objectives as shown in Table 4-4-2 (step 6), and optimised with 400 iterations (step 8) and relative weights of cost, lead time, and environmental impact at 1/3, 1/3, and 1/3 respectively (i.e. *W* [1/3, 1/3, 1/3]) (step 7). The outcomes of steps 6 to 8 are conducted to optimise the multi-objective decision in the next step.

Table 4-4-2 Upper and lower bounds of three objectives

Objective	Cost minimisation	Lead time minimisation	Environmental impact minimisation	Upper bound	Lower bound
Cost (AUD per item)	39,839	66,202	39,843	**66,202**	**39,839**
Lead time (weeks)	1.93	0.16	1.79	**1.93**	**0.16**
Environmental impact (points per item)	1,066	2,784	1,066	**2,784**	**1,066**

Step 9: Optimisation of multi-objective decision

The individual DSS based on the multi-objective decision suggests a single configuration over the ten years of planning period as shown in Figure 4-4-6. The suggested configuration procures material types 1 and 9 from local suppliers having slower growth rates of fuel price, more appreciated currency, and shorter-distance transportation. The shorter distance supports better transportation cost, time, and environmental impact. The cost and environmental impact are also improved by utilising cheaper and greener transport (i.e. sea and rail modes), whereas the minimal lot-sizes (i.e. 12 tons) is utilised to shorten lead time. These suggestions contribute to the Pareto-optimal cost at 42,793 AUD per item, lead time at 0.89 weeks, and environmental impact at 1,104 points per item.

In summary, the individual DSS for environmentally sustainable SCND of the power boat manufacturing company is capable of making several decisions such as baseline, single-objective, and multi-objective decisions. They require a number of subjective and uncertain parameters. Their sensitivity to the Pareto-optimal result is investigated and analysed in the tenth step of the first industrial case (i.e. the cryogenic storage tank manufacturing company). It is found that the generic DSS is sufficiently robust for the system validation in the next step (referred to Figure 4-1).

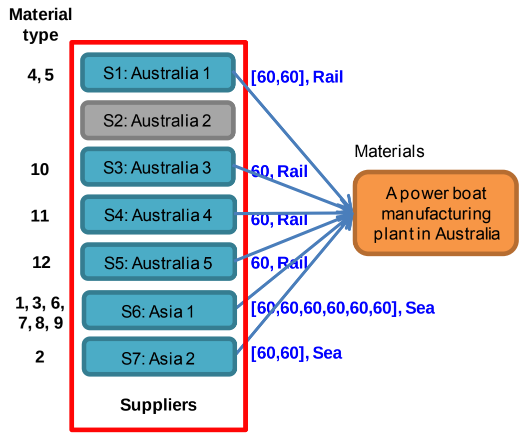


Figure 4-4-6 Supply chain networks based on *W* [1/3, 1/3, 1/3] for the ten years of planning period

Step 11: Result comparisons and discussions

The results (i.e. outputs and their relative decision variables) of baseline, three single-objective, and multi-objective decisions are compared and discussed in order to demonstrate the potential of the individual DSS for industry implementation. This step provides two comparisons along with their discussions as follows, but the successful validation in comparison of baseline and actual product cost in the base year is not demonstrated since the actual product cost is not provided.

1) Comparison of baseline and Pareto-optimal results

To demonstrate the first successful validation of the individual DSS, its outputs (on average) and decision variables based on the multi-objective decision with *W* [1/3, 1/3, 1/3] are compared to those based on the baseline decision. Table 4-4-3 reveals that the multi-objective decision generates the Pareto-optimal cost at 40,145 AUD per item, lead time at 1.65 weeks, and environmental impact at 1,089 points per item. The multi-objective decision is capable of little improvement to the baseline cost (i.e. 42,617 AUD per item) by 5.80% and environmental impact (i.e. 1,089 points per item) by 10.96%, whereas there is no difference in lead time (i.e. 1.65 weeks).

Table 4-4-3 Comparisons of baseline and Pareto-optimal outputs

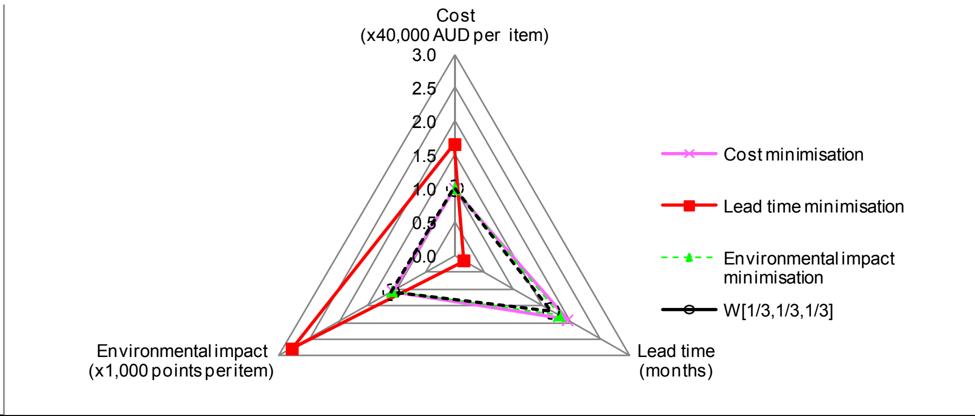
Output	Baseline decision	*W* [1/3, 1/3, 1/3]	% Improvement
Cost (AUD per item)	42,617	40,145	**5.80%**
Lead time (weeks)	1.65	1.65	0.00%
Environmental impact (points per item)	1,224	1,089	**10.96%**

The improvements in cost and environmental impact are caused by locally utilising rail (cheaper and greener) mode of the multi-objective decision with *W* [1/3, 1/3, 1/3] (Figure 4-4-6). The utilised rail mode does not have any effect on the critical lead time, so there is no difference in lead time. On the other hand, the baseline decision (Figure 4-4-2) locally utilises in-house transport (i.e. 16-ton trucks) because it is simply manageable. The 16-ton trucks, however, contribute to the higher cost and environmental impact, so a trade-off between the improvements in cost and environmental impact and the simple management in transportation is required for selecting the best decision.

2) Comparison of single-objective and Pareto-optimal results

To demonstrate the second successful validation of the individual DSS, its outputs (on average) and decision variables based on the multi-objective decision with *W* [1/3, 1/3, 1/3] are compared to those based on the three single-objective decisions. Figure 4-4-7 reveals that the three single objective decisions generate extreme values of individual objectives. For example, the single objective decision with environmental impact minimisation generates the lowest environmental impact without consideration of cost and lead time as depicted in the triangle-dash line. The environmental impact minimisation (Figure 4-4-5) supports the cost minimisation (Figure 4-4-3b) since the individual DSS suggests suppliers having shorter-distance transportation and greener transport (i.e. rail and sea modes) with maximal lot-sizes. The greener transportation modes consume lesser fuel and have a lower freight rate, although having slower speed. The maximal lot-sizes reduce transportation cost and environmental impact due to infrequent roundtrips. The three outputs of environmental impact minimisation consequently approach those of cost minimisation, but are conflicting with those of lead time minimisation as depicted in the cross-solid line. The lead time minimisation (Figure 4-4-4) suggests utilising faster transportation modes with minimal lot-sizes especially the critical lead time. The faster transportation modes consume more fuel, however, having higher freight rates and more environmental impact. The minimal lot-sizes shorten lead time, but increasing transportation cost and environmental impact due to frequent roundtrips. These conflicts cause the need for multi-objective decision with *W* [1/3, 1/3, 1/3].

The three outputs of multi-objective decision with *W* [1/3, 1/3, 1/3] much approach to the lowest cost by 98.70% and the lowest environmental impact by 98.60% since they fairly support each other as depicted in the circle-solid line of Figure 4-4-7. Their much closeness is caused by two influences (Figure 4-4-6). The first influence is the selection of suppliers having a slower growth rate of fuel price and more appreciated currency. They supports lower-cost materials and transportation cost in the long-term. In addition, the selected suppliers have shorter-distance transportation which contributes to reduction in transportation cost and environmental impact. They are also improved by utilising cheaper and greener transport (i.e. rail and sea modes) as the second influences. On the other hand, minimal lot-sizes are utilised to shorten preparation time. The shortened preparation time contributes to the greater degree of closeness of the Pareto-optimal lead time. It is, however, less than the Pareto-optimal cost and environmental impact. These degrees of closeness correspond to the relative weights of cost, lead time, and environmental impact. The correspondence is considered another successful validation of the individual DSS.



Output	Single-objective decision			*W* [1/3, 1/3, 1/3]	Degree of closeness
	Cost	Lead time	Environmental impact		
Cost (AUD per item)	39,839	66,202	39,843	40,145	0.987
Lead time (weeks)	1.93	0.16	1.79	1.65	0.158
Environmental impact (points per item)	1,066	2,784	1,066	1,089	0.986

Figure 4-4-7 Comparisons of single-objective and Pareto-optimal outputs

In summary, the individual DSS for environmentally sustainable SCND is successfully validated by the industrial case of power boat manufacturing company. The successful validation of the individual DSS is demonstrated with two comparisons along with their discussions. Firstly, the individual DSS provides some suggestions that the baseline cost environmental impact respectively can be improved by 5.80% and 10.96% when the multi-objective decision with *W* [1/3, 1/3, 1/3] is implemented. The improvements in cost and environmental impact trade off the simple management in transportation. This trade-off supports decision makers to select the best decision. Secondly, there is correspondence between the degrees of closeness and relative weights of the Pareto-optimal cost, lead time, and environmental impact. These comparisons and discussions can imply that the individual DSS is successfully validated.

4.5 Concluding remarks

This chapter demonstrates the successful verification and validation of the generic DSS for environmentally sustainable Supply Chain Network Design (SCND). It undergoes the eleven steps and four industrial cases. The individual industrial cases have specific characteristics (i.e. supply chain structures, product characteristics, and supply chain strategies). They lead to different emphases on cost, lead time, and environmental impact as shown in Table 4-5.

Table 4-5 Characteristics of four industrial cases

Industrial case	Supply chain structure	Product characteristic	Relative weights		
			Cost	Lead time	Environmental impact
Cryogenic storage tank	multi- product, 5-stage supply chain	Innovative	0.4	0.5	0.1
Automotive part	multi- product, 3-stage supply chain	Functional	0.4	0.3	0.3
Roof sheet	single-product, 2-stage supply chain	Functional	0.6	0.1	0.3
Power boat	single-product, 2-stage supply chain	Innovative	1/3	1/3	1/3

As a result, the generic DSS is capable of overcoming various characteristics. This capability is validated with three comparisons along with their discussions.

- The generic DSS returns the baseline product cost which is not significantly different from the actual product cost in the base year,
- The generic DSS provides some suggestions based on the Pareto-optimal result for improving the baseline outputs, and
- The generic DSS returns the Pareto-optimal outputs which correspond to their relative weights.

Through the development of a generic DSS for an environmentally sustainable SCND, it is found that the generic DSS is completely developed and ready for industrial implementation.

CHAPTER 5
CONCLUSION

This chapter aims to provide the conclusion of this research. It summarises the research needs corresponding to the research aim, methodology, and outcomes. They subsequently dictate several contributions to this research field, which is the development of decision support systems in Supply Chain Management, with suggestions for further studies.

5.1 Concluding remarks

The development of a generic Decision Support System (DSS) for Supply Chain Network Design (SCND) is one of the most challenging research areas in Supply Chain Management (SCM). It generally consists of multiple stages and multiple layers within each stage for multiple commodities under a dynamic behaviour. They are optimally determined by planning decisions including sources of supply, facility locations, order quantity allocations, transportation modes and lot-sizes. These planning decisions support the achievement of cost, lead time and environmental impact. In the long-term, the planning decisions and performances are influenced by time-dependent parameters. They include product volume, energy consumption and price, labour cost, and currency exchange rate. Accordingly the DSS for SCND is characterised as a multivariable, multi-objective, complex and dynamic problem. This is addressed by using the integration of Fuzzy Goal Programming (FGP) with a weighted max-min operator and system dynamics optimisation with Powell algorithm.

The development of research methodology framework undergoes six steps to develop a generic DSS for an environmentally sustainable SCND. Firstly, the generic DSS is developed through its architecture based on the integrated design of supply and facility networks. The architecture includes eight entities and nine generic modules. They are conceptualised into causal loop diagrams in the second step. The causal loop diagrams support the planning decisions of sources of supply, facility locations, order quantity allocations, transportation modes and lot-size. They are based on minimisation of cost, lead time, and environmental impact. The causal loop diagrams are mathematically formulated into multi-objective, fuzzy membership, and Pareto-optimal functions in the third step. These mathematical functions are configured into Vensim version 5.4d in the fourth step before being verified and validated with various industrial cases in the fifth and sixth steps.

The successful verification and validation of the generic DSS are demonstrated through eleven steps and four industrial cases. The individual industrial cases have specific characteristics (i.e. supply chain structures, product characteristics, and supply chain strategies). They lead to different emphases on cost, lead time, and environmental impact. As a result, the generic DSS is capable of overcoming various characteristics. This capability is validated with three result comparisons along with their discussions. Firstly, the baseline product cost is not significantly different from the actual product cost in the base year. Secondly, some suggestions are provided based on the Pareto-optimal result for improving the baseline outputs. Thirdly, the Pareto-optimal outputs correspond to their relative weights.

Through the development of a generic DSS for an environmentally sustainable SCND, it is found that there are several contributions to this research field. They are explained in the next section.

5.2 Research contribution

The primary contribution of this research is the development of a generic DSS for an environmentally sustainable SCND. It concerns realistic issues which are previously overlooked. They lead to additional four contributions to this research field as follows.

The first contribution is the optimisation of supply chain objectives and planning decisions (i.e. sources of supply, facility locations, transportation modes and lot-sizes) which are in conflict with each other. The conflicting objectives are comprised of cost, lead time, and environmental impact. The cost objective supports the objective of environmental impact due to transportation modes and lot-sizes. The cheaper forms of transport (i.e. rail and sea modes) are greener and the larger lot-sizes cause infrequent setups and round-trips. They contribute to lower cost and environmental impact. The cheaper and greener transport methods and larger lot-sizes, however, lengthen the objective of lead time. The cost objective conflicts with the objective of environmental impact when the cheaper suppliers and facility locations have longer-distance transportation which worsen environmental impact and lead time. It is evident that the conflicting objectives are achieved when the conflicting planning decisions are optimally determined by applying the generic DSS.

The second contribution is the inclusion of time-dependent parameters such as product volume, energy consumption, currency exchange rate, energy and fuel price, and wage rate. These parameters are evolved over time and may cause frequent reconfigurations of supply chain networks which are impractical. The Pareto-optimal configuration in the long-term is suggested by applying the generic DSS.

The third contribution is the inclusion of relative objective weights which are emphasised in correspondence with product characteristics and supply chain strategies. The generic DSS can hence be applied for various product characteristics and supply chain strategies. For example, the cryogenic storage tank manufacturing company strongly emphasises the objective of lead time, followed by the cost objective in order to achieve mass customisation.

The fourth contribution is the broader features on supply chain networks from-cradle-to-gate. The supply chain features are comprised of multiple stages, multiple layers, multiple commodities, multiple periods of time, and various transportation modes. These features are numbered, so the generic DSS can be applied for various supply chain structures.

These contributions, which are enabled by the development of a generic DSS for an environmentally sustainable SCND, can be however enhanced. The enhancement in contributions is directed for further studies in the next section.

5.3 Directions of further studies

The further studies for the development of a generic Decision Support System (DSS) for an environmentally sustainable Supply Chain Network Design (SCND) are directed as follows.

Firstly, the development of a generic DSS undergoes an important step which is the system validation. It needs to be demonstrated through various industrial cases in order to convince the generalisation of developed DSS. A further study is hence directed by inclusion of additional industrial cases. They have different supply chain structures, product characteristics, and supply chain strategies.

Secondly, the development of a generic DSS includes numerous parameters (e.g. energy unit consumption, production unit time, and wage rate) which cannot be precisely determined. The uncertainty of parameters needs to be addressed by applying stochastic theory as a direction of further study.

Thirdly, the development of a generic DSS covers cradle-to-gate stages which cannot reflect on the entire product life cycle. It includes material extraction, manufacturing process, transportation, usage, and disposal (cradle-to-grave) stages. These should be addressed as a direction of further studies.

Fourthly, the development of a generic DSS concerns the objective of environmental impact which is measured as single scores based on Eco-Indicator 99 H/A. However, the impact of environmental policies such as carbon tax and Emission Trading Scheme (ETS) are omitted. These policies significantly influence reduction in carbon emissions along the supply chain which may save money in the medium to long-term. The carbon tax and ETS, therefore, should be integrated into the development of a generic DSS as a direction of further studies.

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APPENDIX A
MATHEMATICAL EQUATIONS

The nine generic modules, which was conceptualised in section 3.2, are formulated into mathematical equations related to the three objectives (supply chain cost, lead time, and environmental impact) from Table A-1-1 to Table A-9-5. The three objectives of nine generic modules are subsequently formulated as multi-objective function, fuzzy membership function, and Pareto-optimal function in Table A-10. The Pareto-optimal function is optimised through optimisation setup of Vensim version 5.4d in Table A-11. Throughout Appendix A, the mathematical equations use some functions in Vensim version 5.4d as follows.

Functions:

IF THEN ELSE (cond, tval, fval)	If condition (cond) is true, first value (tval) is returned. Otherwise, second value (fval) is returned.
INTEG (rate, initial value)	INTEGral of the rate with initial value at starting point
INTEGER (x)	INTEGER part of x
SUM (x [i !])	SUMmation over subscript range
ZIDZ (A,B)	Zero If Divided by Zero (otherwise A/B)
VMAX (x [i !])	Vector MAXimum
VMIN (x [i !])	Vector MINimum

1 Product demand module

Product demand module covers three sub-modules. They are product MP $\rightarrow$ customer (Table A-1-1), product DC $\rightarrow$ customer (Table A-1-2), and product MP $\rightarrow$ product DC (Table A-1-3) as follows.

Table A-1-1 Product demand module: product MP $\rightarrow$ customer

Parameter	Unit	Mathematical equation
Increment of product volume [Customer,Product]	Items	Product volume[Customer,Product] *Growth rate of product volume[Product]
Product volume[Customer,Product]	Items	INTEG(Increment of product volume[Customer,Product] /TIME STEP,Baseline product volume[Customer,Product])
Integer product volume [Customer,Product]	Items	if then else (integer(Product volume[Customer,Product]) = Product volume[Customer,Product], Product volume [Customer,Product], integer(Product volume[Customer,Product])+1)

Product order allocation: customer=>product MP [Product MP, Customer,Product]	Items	Integer product volume[Customer,Product] *Locational selection of product MP[Product MP] *zidz(Distance: product MP=>customer[Product MP, Customer],Distance: product MP=>customer[Product MP, Customer])
Mode selection: product MP=>customer[Product MP, Customer,Product,Mode]	Dmnl	if then else(Product order allocation: customer=> product MP[Product MP,Customer,Product]>0, if then else(Distance: product MP=>customer [Product MP, Customer]>1000, Global mode selection of product MP[Product,Mode], Local mode selection of product MP[Product,Mode]) *zidz(Feasible mode of product MP[Product,Mode], Feasible mode of product MP[Product,Mode]),0)
Product order distribution: product MP=>customer [Product MP,Customer, Product,Mode]	Items	Product order allocation: customer=>product MP [Product MP,Customer,Product]*Mode selection: product MP=>customer[Product MP,Customer,Product,Mode] *Product MP=>Customer (1) or not (0)
Lotsize: product MP=>customer [Product MP,Customer, Product,Mode]	Items	if then else(Lotsize of product MP[Product MP,Product] >SUM(Product order allocation: customer=>product MP [Product MP,Customer!,Product]), SUM(Product order allocation: customer=>product MP [Product MP,Customer!,Product]), Lotsize of product MP[Product MP,Product]) *zidz(Product order allocation: customer=>product MP [Product MP,Customer,Product], SUM(Product order allocation: customer=>product MP [Product MP,Customer!,Product])) *Mode selection: product MP=>customer[Product MP,Customer,Product,Mode] *Product MP=>Customer (1) or not (0)
Integer lotsize: product MP=>customer[Product MP,Customer, Product]	Items	if then else(Lotsize: product MP=>customer[Product MP, Customer,Product,Mode] -integer(Lotsize: product MP=>customer[Product MP, Customer,Product,Mode])<0.01,Lotsize: product MP=>customer[Product MP,Customer,Product,Mode], integer(Lotsize: product MP=>customer[Product MP, Customer,Product,Mode])+1)
Number of roundtrip: product MP=>customer[Product MP, Customer,Product,Mode]	Dmnl	zidz(Product order distribution: product MP=>customer [Product MP,Customer,Product,Mode], Integer lotsize: product MP=>customer[Product MP, Customer,Product,Mode])
Integer number of roundtrip: product MP=>customer [Product MP,Customer, Product,Mode]	Dmnl	if then else(Number of roundtrip: product MP=>customer [Product MP,Customer,Product,Mode] -integer(Number of roundtrip: product MP=>customer [Product MP,Customer,Product,Mode])< 0.01, Number of roundtrip: product MP=>customer[Product MP, Customer,Product,Mode], integer(Number of roundtrip: product MP=>customer [Product MP,Customer,Product,Mode])+1)
Total product order distribution: product MP=>customer [Product MP,Customer, Product,Mode]	Items	Integer lotsize: product MP=>customer[Product MP, Customer,Product,Mode] *Integer number of roundtrip: product MP=>customer [Product MP,Customer,Product,Mode]
Service level: product MP=>customer[Product]	%	if then else(zidz(SUM(Total product order distribution: product MP=>customer[Product MP!,Customer!, Product,Mode!]),SUM(Integer product volume[Customer!,Product])) > 1,1, zidz(SUM(Total product order distribution: product MP=>customer[Product MP!,Customer!,Product,Mode!]), SUM(Integer product volume[Customer!,Product]))) +(1-Product MP=>Customer (1) or not (0))
Startup of product MP (customer) [Product MP]	Dmnl	if then else(SUM(Product order distribution: product MP=>customer[Product MP,Customer!,Product!,Mode!])>0 :AND::NOT:Binary variable for locational selection of product MP (customer)[Product MP],1,0)
Shutdown of product MP (customer)[Product MP]	Dmnl	if then else(SUM(Product order distribution: product MP=>customer[Product MP,Customer!,Product!,Mode!])=0 :AND:Binary variable for locational selection of product MP (customer)[Product MP],1,0)

Binary variable for locational selection of product MP (customer) [Product MP]	Dmnl	INTEG((Startup of product MP (customer)[Product MP] -Shutdown of product MP (customer)[Product MP]) /TIME STEP,Baseline locational selection of product MP [Product MP])
Locational selection cost of product MP (customer) [Product MP]	THB	((Shutdown of product MP (customer)[Product MP] *Shutdown cost of product MP[Product MP]) +(Startup of product MP (customer)[Product MP] *SUM(Startup cost of product MP[Product MP,Product!]))) *Currency depreciation of product MP[Product MP]

Table A-1-2 Product demand module: product DC $\rightarrow$ customer

Parameter	Unit	Mathematical equation
Product order allocation: customer=>product DC[Product DC, Customer,Product]	Items	Integer product volume[Customer,Product] *Locational selection of product DC[Product DC] *zidz(Distance: product DC=>customer[Product DC, Customer], Distance: product DC=>customer[Product DC,Customer])
Mode selection: product DC=>customer[Product DC,Customer, Product,Mode]	Dmnl	if then else(Product order allocation: customer=> product DC[Product DC,Customer,Product]>0, if then else(Distance: product DC=>customer [Product DC,Customer]>0, Global mode selection of product DC[Product,Mode], Local mode selection of product DC[Product,Mode]) *zidz(Feasible mode of product DC[Product,Mode], Feasible mode of product DC[Product,Mode]),0)
Product order distribution: product DC=>customer [Product DC,Customer, Product,Mode]	Items	Product order allocation: customer=>product DC [Product DC,Customer,Product] *Mode selection: product DC=>customer[Product DC, Customer,Product,Mode] *Product DC=>Customer (1) or not (0)
Lotsize: product DC=>customer [Product DC,Customer, Product,Mode]	Items	if then else(Lotsize of product DC[Product DC,Product] >SUM(Product order allocation: customer=>product DC [Product DC,Customer!,Product]), SUM(Product order allocation: customer=>product DC [Product DC,Customer!,Product]), Lotsize of product DC[Product DC,Product]) *zidz(Product order allocation: customer=>product DC [Product DC,Customer,Product], SUM(Product order allocation: customer=>product DC [Product DC,Customer!,Product])) *Mode selection: product DC=>customer[Product DC, Customer,Product,Mode] *Product DC=>Customer (1) or not (0)
Integer lotsize: product DC=>customer[Product DC,Customer, Product,Mode]	Items	if then else(Lotsize: product DC=>customer[Product DC, Customer,Product,Mode] -integer(Lotsize: product DC=>customer[Product DC, Customer,Product,Mode])<0.01, Lotsize: product DC=>customer[Product DC, Customer,Product,Mode], integer(Lotsize: product DC=>customer[Product DC, Customer,Product,Mode])+1)
Number of roundtrip: product DC=>customer [Product DC, Customer,Product,Mode]	Dmnl	zidz(Product order distribution: product DC=>customer [Product DC,Customer,Product,Mode], Integer lotsize: product DC=>customer[Product DC, Customer,Product,Mode])
Integer number of roundtrip: product MP=>customer [Product MP,Customer, Product,Mode]	Dmnl	if then else(Number of roundtrip: product MP=>customer [Product MP,Customer,Product,Mode] -integer(Number of roundtrip: product MP=>customer [Product MP,Customer,Product,Mode]) < 0.01, Number of roundtrip: product MP=>customer[Product MP, Customer,Product,Mode], integer(Number of roundtrip: product MP=>customer [Product MP,Customer,Product,Mode])+1)
Total product order distribution: product DC=>customer [Product DC,Customer, Product,Mode]	Items	Integer lotsize: product DC=>customer[Product DC, Customer,Product,Mode] *Integer number of roundtrip: product DC=>customer [Product DC,Customer,Product,Mode]

Service level of product DC[Product]	%	if then else(zidz(SUM(Total product order distribution: product DC=>customer[Product DC!,Customer!, Product,Mode!]), SUM(Integer product volume[Customer!,Product])) > 1,1, zidz(SUM(Total product order distribution: product DC=>customer[Product DC!,Customer!,Product,Mode!]), SUM(Integer product volume[Customer!,Product]))) +(1-Product DC=>Customer (1) or not (0))
Startup of product DC[Product DC]	Dmnl	if then else(SUM(Product order distribution: product DC=>customer[Product DC,Customer!,Product!,Mode!])>0 :AND::NOT:Binary variable for locational selection of product DC[Product DC],1,0)
Shutdown of product DC [Product DC]	Dmnl	if then else(SUM(Product order distribution: product DC=>customer[Product DC,Customer!,Product!,Mode!])=0 :AND:Binary variable for locational selection of product DC[Product DC],1,0)
Binary variable for locational selection of product DC[Product DC]	Dmnl	INTEG((Startup of product DC[Product DC]-Shutdown of product DC[Product DC])/TIME STEP,Baseline locational selection of product DC[Product DC])
Locational selection cost of product DC[Product DC]	THB	((Shutdown of product DC[Product DC] *Shutdown cost of product DC[Product DC]) +(Startup of product DC[Product DC] *Startup cost of product DC[Product DC])) *Currency depreciation of product DC[Product DC]

Table A-1-3 Product demand module: product MP $\rightarrow$ product DC

Parameter	**Unit**	**Mathematical equation**
Product order allocation: product DC=>product MP [Product MP,Product DC,Product]	Items	SUM(Product order allocation: customer=>product MP [Product MP,Customer!,Product]) *Locational selection of product MP[Product MP] *zidz(Distance: product MP=>product DC[Product MP, Product DC], Distance: product MP=>product DC[Product MP, Product DC])
Mode selection: product MP=>product DC[Product MP, Product DC,Product,Mode]	Dmnl	if then else(Product order allocation: product DC=> product MP[Product MP,Product DC,Product]>0, if then else(Distance: product MP=>product DC [Product MP, Product DC]>0, Global mode selection of product MP[Product,Mode], Local mode selection of product MP[Product,Mode]) *zidz(Feasible mode of product MP[Product,Mode],Feasible mode of product MP[Product,Mode]),0)
Product order distribution: product MP=>product DC [Product MP,Product DC, Product,Mode]	Items	Product order allocation: product DC=>product MP [Product MP,Product DC,Product] *Mode selection: product MP=>product DC[Product MP, Product DC,Product,Mode] *Product MP=>Product DC (1) or not (0)
Lotsize: product MP=>product DC [Product MP,Product DC, Product,Mode]	Items	if then else(Lotsize of product MP[Product MP,Product] >SUM(Product order allocation: product DC=>product MP [Product MP,Product DC!,Product]), SUM(Product order allocation: product DC=>product MP [Product MP,Product DC!,Product]), Lotsize of product MP[Product MP,Product]) *zidz(Product order allocation: product DC=>product MP [Product MP,Product DC,Product], SUM(Product order allocation: product DC=>product MP [Product MP,Product DC!,Product])) *Mode selection: product MP=>product DC [Product MP, Product DC,Product,Mode] *Product MP=>Product DC (1) or not (0)
Integer lotsize: product MP=>product DC[Product MP, Product DC,Product,Mode]	Items	if then else(Lotsize: product MP=>product DC [Product MP,Product DC,Product,Mode] -integer(Lotsize: product MP=>product DC[Product MP, Product DC,Product,Mode])<0.01, Lotsize: product MP=>product DC[Product MP, Product DC,Product,Mode], integer(Lotsize: product MP=>product DC[Product MP, Product DC,Product,Mode])+1)

Number of roundtrip: product MP=>product DC [Product MP, Product DC,Product,Mode]	Dmnl	zidz(Product order distribution: product MP=>product DC [Product MP,Product DC,Product,Mode], Integer lotsize: product MP=>product DC[Product MP, Product DC,Product,Mode])
Integer number of roundtrip: product MP=>product DC [Product MP,Product DC, Product,Mode]	Dmnl	if then else(Number of roundtrip: product MP=> product DC[Product MP,Product DC,Product,Mode] -integer(Number of roundtrip: product MP=>product DC [Product MP,Product DC,Product,Mode]) < 0.01, Number of roundtrip: product MP=>product DC [Product MP,Product DC,Product,Mode], integer(Number of roundtrip: product MP=>product DC [Product MP,Product DC,Product,Mode])+1)
Total product order distribution: product MP=>product DC [Product MP,Product DC, Product,Mode]	Items	Integer lotsize: product MP=>product DC[Product MP, Product DC,Product,Mode] *Integer number of roundtrip: product MP=>product DC [Product MP,Product DC,Product,Mode]
Service level: product MP=>product DC[Product]	%	if then else(zidz(SUM(Total product order distribution: product MP=>product DC[Product MP!,Product DC!, Product,Mode!]), SUM(Product order allocation: customer=>product MP [Product MP!,Customer!,Product])) > 1,1, zidz(SUM(Total product order distribution: product MP=>product DC[Product MP!,Product DC!,Product,Mode!]), SUM(Product order allocation: customer=>product MP [Product MP!,Customer!,Product]))) +(1-Product MP=>Product DC (1) or not (0))
Startup of product MP (customer) [Product MP]	Dmnl	if then else(SUM(Product order distribution: product MP=>product DC[Product MP,Product DC!,Product!,Mode!])>0 :AND::NOT:Binary variable for locational selection of product MP(product DC)[Product MP],1,0)
Shutdown of product MP (product DC)[Product MP]	Dmnl	if then else(SUM(Product order distribution: product MP=>product DC[Product MP,Product DC!,Product!,Mode!])=0 :AND:Binary variable for locational selection of product MP (product DC)[Product MP],1,0)
Binary variable for locational selection of product MP (product DC)[Product MP]	Dmnl	INTEG((Startup of product MP (product DC)[Product MP] -Shutdown of product MP (product DC)[Product MP]) /TIME STEP,Baseline locational selection of product MP [Product MP])
Locational selection cost of product MP (product DC) [Product MP]	THB	((Shutdown of product MP (product DC)[Product MP] *Shutdown cost of product MP[Product MP]) +(Startup of product MP (product DC)[Product MP] *SUM(Startup cost of product MP[Product MP,Product!]))) *Currency depreciation of product MP[Product MP]

2 Product manufacturing and warehousing module

Product manufacturing and warehousing module covers three sub-modules. They are product MP$\rightarrow$customer (Table A-2-1), product DC$\rightarrow$customer (Table A-2-2), and product MP$\rightarrow$product DC (Table A-2-3) as follows.

Table A-2-1 Product manufacturing module: product MP$\rightarrow$customer

Parameter	Unit	Mathematical equation
Decrement of energy unit consumption of product MP [Product MP,Product]	MJ / item	Energy unit consumption of product MP[Product MP, Product] *Improvement rate of energy consumption of product MP [Product MP]
Energy unit consumption of product MP[Product MP,Product]	MJ / item	INTEG(Decrement of energy unit consumption of product MP[Product MP,Product]/TIME STEP, Baseline energy unit consumption of product MP [Product MP,Product])

Energy consumption: product MP =>customer [Product MP, Customer,Product,Mode]	MJ	Energy unit consumption of product MP[Product MP, Product] *Product order distribution: product MP=>customer [Product MP,Customer,Product,Mode]
Selected energy EI: product MP =>customer[Product MP,Customer, Product,Mode,Energy]	Points	Energy consumption: product MP=>customer[Product MP, Customer,Product,Mode] *Energy EI driver[Energy] *Energy type selection of product MP[Product MP,Energy]
Energy EI: product MP=>customer [Product MP,Customer, Product, Mode]	Points	SUM(Selected energy EI: product MP=>customer [Product MP,Customer,Product,Mode,Energy!])
Increment of energy unit price of product MP[Product MP]	THB/MJ	Energy unit price of product MP[Product MP] *Growth rate of energy price of product MP[Product MP]
Energy unit price of product MP [Product MP]	THB/MJ	INTEG(Increment of energy unit price of product MP [Product MP]/TIME STEP,Baseline energy unit cost of product MP[Product MP])
Increment of currency depreciation of product MP [Product MP]	Dmnl	Currency depreciation of product MP[Product MP] *Growth rate of currency depreciation of product MP [Product MP]
Currency depreciation of product MP [Product MP]	Dmnl	INTEG(Increment of currency depreciation of product MP [Product MP]/TIME STEP,1)
Energy price: product MP=> customer[Product MP,Product]	THB	Energy unit price of product MP[Product MP] *SUM(Energy consumption: product MP=>customer [Product MP,Customer!,Product,Mode!]) *Currency depreciation of product MP[Product MP]
Production time: product MP=>customer[Product MP,Product]	Hours	Production unit time of product MP[Product MP,Product] *SUM(Integer lotsize: product MP=>customer [Product MP,Customer!,Product,Mode!])
Preparation time: product MP=>customer[Product MP, Customer,Product,Mode]	Hours	if then else(Integer lotsize: product MP=>customer [Product MP,Customer,Product,Mode]>0, Setup time of product MP[Product MP,Product] +Production time: product MP=>customer[Product MP, Product],0)
Setup unit time: product MP=>customer[Product MP,Product]	Hours / item	zidz(Setup time of product MP[Product MP,Product], SUM(Integer lotsize: product MP=>customer [Product MP, Customer!,Product,Mode!]))
Preparation unit time: product MP =>customer[Product MP,Product]	Hours / item	Setup unit time: product MP=>customer[Product MP, Product] +if then else(Setup unit time: product MP=>customer [Product MP,Product]>0, Production unit time of product MP[Product MP,Product],0)
Total preparation time: product MP =>customer[Product MP, Customer,Product,Mode]	Hours	Preparation unit time: product MP=>customer [Product MP,Product] *Product order distribution: product MP=>customer [Product MP,Customer,Product,Mode]
Increment of wage rate of product MP[Product MP,Product]	THB/hour	Wage rate of product MP[Product MP,Product] *Growth rate of wage rate of product MP[Product MP]
Wage rate of product MP [Product MP,Product]	THB / hour	INTEG(Increment of wage rate of product MP [Product MP,Product]/TIME STEP,Baseline wage rate of product MP[Product MP,Product])
Labour cost: product MP=>customer [Product MP,Product]	THB	Wage rate of product MP[Product MP,Product] *SUM(Total preparation time: product MP=>customer [Product MP,Customer!,Product,Mode!]) *Currency depreciation of product MP[Product MP]
Product safety stock: product MP=> customer [Product MP, Product,Mode]	Items	Service factor *Standard deviation of product volume[Product] *zidz(SUM(Product order distribution: product MP=>customer[Product MP,Customer!,Product,Mode]), SUM(Product order distribution: product MP=>customer [Product MP!,Customer!,Product,Mode])) *SQRT(Lead time (product MP): supplier=>customer [Product MP])
Product holding cost: product MP =>customer[Product MP,Product]	THB	SUM(Product safety stock: product MP=>customer [Product MP,Product,Mode!]) *Product unit price[Product] *% inventory holding cost of product MP[Product MP]/100 *Currency depreciation of product MP[Product MP]

Table A-2-2 Product warehousing module: product DC$\rightarrow$customer

Parameter	Unit	Mathematical equation
Decrement of energy unit consumption of product DC [Product DC,Product]	MJ / item	Energy unit consumption of product DC[Product DC,Product] *Improvement rate of energy consumption of product DC [Product DC]
Energy unit consumption of product DC[Product DC,Product]	MJ / item	INTEG(Decrement of energy unit consumption of product DC [Product DC,Product]/TIME STEP,Baseline energy unit consumption of product DC [Product DC,Product])
Energy consumption: product DC=>customer [Product DC, Customer,Product,Mode]	MJ	Energy unit consumption of product DC[Product DC,Product] *Product order distribution: product DC=>customer [Product DC,Customer,Product,Mode]
Selected energy EI: product DC=>customer[Product DC, Customer,Product,Mode,Energy]	Points	Energy consumption: product DC=>customer[Product DC,Customer,Product,Mode] *Energy EI driver[Energy] *Energy type selection of product DC[Product DC,Energy]
Energy EI: product DC=>customer [Product DC, Customer,Product,Mode]	Points	SUM(Selected energy EI: product MP=>customer [Product MP,Customer,Product,Mode,Energy!])
Increment of energy unit price of product DC[Product DC]	THB/MJ	Energy unit price of product DC[Product DC] *Growth rate of energy cost of product DC[Product DC]
Energy unit price of product DC [Product DC]	THB/MJ	INTEG(Increment of energy unit price of product DC [Product DC]/TIME STEP,Baseline energy unit price of product DC[Product DC])
Increment of currency depreciation of product DC[Product DC]	Dmnl	Currency depreciation of product DC[Product DC] *Growth rate of currency depreciation of product DC [Product DC]
Currency depreciation of product DC [Product DC]	Dmnl	INTEG(Increment of currency depreciation of product DC [Product DC]/TIME STEP,1)
Energy price of product DC [Product DC,Product]	THB	Energy unit price of product DC[Product DC] *SUM(Energy consumption: product DC=>customer [Product DC,Customer!,Product,Mode!]) *Currency depreciation of product DC[Product DC]
Preparation time: product MP=>customer[Product MP, Customer,Product,Mode]	Hours	if then else(Integer lotsize: product DC=>customer [Product DC,Customer,Product,Mode]>0, Warehousing unit time of product DC[Product DC,Product] *SUM(Integer lotsize: product DC=>customer[Product DC,Customer!,Product,Mode!]),0)
Total preparation time: product DC=>customer [Product DC, Customer,Product,Mode]	Hours	Warehousing unit time of product DC[Product DC,Product] *Product order distribution: product DC=>customer [Product DC,Customer,Product,Mode]
Increment of wage rate of product DC[Product DC,Product]	THB/hour	Wage rate of product DC[Product DC,Product] *Growth rate of wage rate of product DC[Product DC]
Wage rate of product MP [Product MP,Product]	THB / hour	INTEG(Increment of wage rate of product DC [Product DC,Product]/TIME STEP,Baseline wage rate of product DC[Product DC,Product])
Wage rate of product DC [Product DC,Product]	THB	Wage rate of product MP[Product MP,Product] *SUM(Total preparation time: product MP=>customer [Product MP,Customer!,Product,Mode!]) *Currency depreciation of product MP[Product MP]
Lead time (product DC): product MP=>customer [Product DC]	Hours	SUM(Lead time: product DC=>customer[Product DC, Customer!]) +VMAX(Lead time: product MP=>product DC [Product MP!,Product DC])
Product safety stock of product DC [Product DC,Product,Mode]	Items	Service factor *Standard deviation of product volume[Product] *zidz(SUM(Product order distribution: product DC =>customer[Product DC,Customer!,Product,Mode]), SUM(Product order distribution: product DC=>customer [Product DC!,Customer!,Product,Mode])) *SQRT(Lead time (product DC): product MP=>customer [Product DC])
Product holding cost of product DC [Product DC,Product]	THB	SUM(Product safety stock of product DC[Product DC, Product,Mode!]) *Product unit price[Product] *% inventory holding cost of product DC[Product DC] /100 *Currency depreciation of product DC[Product DC]

Table A-2-3 Product manufacturing module: product MP $\rightarrow$ product DC

Parameter	Unit	Mathematical equation
Energy consumption: product MP =>product DC [Product MP, Product DC,Product,Mode]	MJ	Energy unit consumption of product MP[Product MP,Product] *Product order distribution: product MP=>product DC [Product MP,Product DC,Product,Mode]
Selected energy EI: product MP =>product DC [Product MP, Product DC,Product,Mode,Energy]	Points	Energy consumption: product MP=>product DC [Product MP,Product DC,Product,Mode] *Energy EI driver[Energy] *Energy type selection of product MP[Product MP,Energy]
Energy EI: product MP=> product DC[Product MP, Product DC,Product,Mode]	Points	SUM(Selected energy EI: product MP=>product DC [Product MP,Product DC,Product,Mode,Energy!])
Energy price: product MP=> product DC[Product MP,Product]	THB	Energy unit price of product MP[Product MP] *SUM(Energy consumption: product MP=>product DC [Product MP,Product DC!,Product,Mode!]) *Currency depreciation of product MP[Product MP]
Production time: product MP =>product DC[Product MP,Product]	Hours	Production unit time of product MP[Product MP,Product] *SUM(Integer lotsize: product MP=>product DC [Product MP,Product DC!,Product,Mode!])
Preparation time: product MP =>product DC[Product MP, Product DC,Product,Mode]	Hours	if then else(Integer lotsize: product MP=>product DC [Product MP,Product DC,Product,Mode]>0, Setup time of product MP[Product MP,Product] +Production time: product MP=>product DC [Product MP, Product],0)
Setup unit time: product MP =>product DC[Product MP,Product]	Hours / item	zidz(Setup time of product MP[Product MP,Product], SUM(Integer lotsize: product MP=>product DC [Product MP,Product DC!,Product,Mode!]))
Preparation unit time: product MP =>product DC [Product MP, Product]	Hours / item	Setup unit time: product MP=>product DC [Product MP,Product] +if then else(Setup unit time: product MP=>product DC [Product MP,Product]>0, Production unit time of product MP[Product MP,Product],0)
Total preparation time: product MP =>product DC [Product MP, Product DC,Product,Mode]	Hours	Preparation unit time: product MP=>product DC [Product MP,Product] *Product order distribution: product MP=>product DC [Product MP,Product DC,Product,Mode]
Labour cost: product MP=> product DC[Product MP,Product]	THB	Wage rate of product MP[Product MP,Product] *SUM(Total preparation time: product MP=>product DC [Product MP,Product DC!,Product,Mode!]) *Currency depreciation of product MP[Product MP]
Product safety stock: product MP =>product DC [Product MP, Product,Mode]	Items	Service factor *Standard deviation of product volume[Product] *zidz(SUM(Product order distribution: product MP=> product DC[Product MP,Product DC!,Product,Mode]), SUM(Product order distribution: product MP=>product DC [Product MP!,Product DC!,Product,Mode])) *SQRT(Lead time (product MP): supplier=>customer [Product MP])
Product holding cost: product MP =>product DC [Product MP, Product]	THB	SUM(Product safety stock: product MP=>product DC [Product MP,Product,Mode!]) *Product unit price[Product] *% inventory holding cost of product MP[Product MP]/100 *Currency depreciation of product MP[Product MP]

3 Product distribution module

Product distribution module covers three sub-modules. They are product MP $\rightarrow$ customer (Table A-3-1), product DC $\rightarrow$ customer (Table A-3-2), and product MP $\rightarrow$ product DC (Table A-3-3) as follows.

Table A-3-1 Product distribution module: product MP $\rightarrow$ customer

Parameter	Unit	Mathematical equation
Transportation time: product MP =>customer[Product MP, Customer,Mode]	Hours	if then else(SUM(Integer number of roundtrip: product MP =>customer[Product MP,Customer,Product!,Mode])>0, zidz(Distance: product MP=>customer[Product MP, Customer],Speed of product MP[Mode]),0)
Production capacity: product MP =>customer [Product MP, Customer,Product,Mode]	Items	if then else(Production capacity of product MP[Product MP, Product]>SUM(Product order distribution: product MP =>customer[Product MP,Customer!,Product,Mode!]), SUM(Product order distribution: product MP=>customer [Product MP,Customer!,Product,Mode!]), Production capacity of product MP[Product MP,Product]) *zidz(Product order distribution: product MP=>customer [Product MP,Customer,Product,Mode], SUM(Product order distribution: product MP=>customer [Product MP,Customer!,Product,Mode!]))
Full container load: product MP=> customer [Product MP,Customer, Product,Mode]	Items	zidz(Production capacity: product MP=>customer [Product MP,Customer,Product,Mode], Integer lotsize: product MP=>customer[Product MP, Customer,Product,Mode]) *Product order distribution: product MP=>customer [Product MP,Customer,Product,Mode]
Mode EI: product MP=>customer [Product MP,Customer, Product,Mode]	Points	Full container load: product MP=>customer[Product MP, Customer,Product,Mode] *SUM(BOM[Product,Material!]) *Distance: product MP=>customer[Product MP,Customer] *Mode EI driver[Mode]
Increment of transportation unit cost: product MP=>customer [Product MP,Customer,Mode]	THB /(kilogram *kilometre)	Transportation unit cost: product MP=>customer [Product MP,Customer,Mode] *Proportion of fuel unit price to transportation unit cost of product MP[Product MP,Mode] *Growth rate of fuel price of product MP[Product MP]
Transportation unit cost: product MP=>customer [Product MP,Customer,Mode]	THB /(kilogram *kilometre)	INTEG(Increment of transportation unit cost: product MP =>customer[Product MP,Customer,Mode]/TIME STEP,Baseline transportation unit cost: product MP =>customer[Product MP,Customer,Mode])
Transportation variable cost: product MP=>customer [Product MP,Customer,Mode]	THB /kilogram	Transportation unit cost: product MP=>customer [Product MP,Customer,Mode] *Distance: product MP=>customer[Product MP,Customer]
Transportation unit fixed cost: product MP=>customer [Product MP,Customer,Mode]	THB /kilogram	zidz(Transportation fixed cost: product MP=>customer [Product MP,Customer,Mode], SUM(Integer lotsize (weight): product MP=>customer [Product MP,Customer,Product!,Mode]))
Transportation cost: product MP =>customer [Product MP, Customer,Product,Mode]	THB	(Transportation unit fixed cost: product MP=>customer [Product MP,Customer,Mode] +Transportation variable cost: product MP=>customer [Product MP,Customer,Mode]) *Product order distribution: product MP=>customer [Product MP,Customer,Product,Mode] *SUM(BOM[Product,Material!]) *Currency depreciation of product MP[Product MP]

Table A-3-2 Product distribution module: product DC $\rightarrow$ customer

Parameter	Unit	Mathematical equation
Transportation time: product DC =>customer [Product DC, Customer,Mode]	Hours	if then else(SUM(Integer number of roundtrip: product DC =>customer[Product DC,Customer,Product!,Mode])>0, zidz(Distance: product DC=>customer[Product DC, Customer],Speed of product DC[Mode]),0)
Warehousing capacity: product DC =>customer [Product DC, Customer,Product,Mode]	Items	if then else(Warehousing capacity of product DC [Product DC,Product]>SUM(Product order distribution: product DC=>customer[Product DC,Customer!,Product, Mode!]),SUM(Product order distribution: product DC=> customer[Product DC,Customer!,Product,Mode!]), Warehousing capacity of product DC[Product DC,Product]) *zidz(Product order distribution: product DC=>customer [Product DC,Customer,Product,Mode],

		SUM(Product order distribution: product DC=>customer [Product DC,Customer!,Product,Mode!]))
Full container load: product DC=> customer[Product DC,Customer, Product,Mode]	Items	zidz(Warehousing capacity: product DC=>customer [Product DC,Customer,Product,Mode], Integer lotsize: product DC=>customer[Product DC, Customer,Product,Mode]) *Product order distribution: product DC=>Customer [Product DC,Customer,Product,Mode]
Mode EI: product DC=>customer [Product DC,Customer, Product,Mode]	Points	Full container load: product DC=>customer[Product DC, Customer,Product,Mode] *SUM(BOM[Product,Material!]) *Distance: product DC=>customer[Product DC,Customer] *Mode EI driver[Mode]
Increment of transportation unit cost: product DC=>customer [Product DC,Customer,Mode]	THB /(kilogram *kilometre)	Transportation unit cost: product DC=>customer [Product DC,Customer,Mode] *Proportion of fuel unit price to transportation unit cost of product DC[Product DC,Mode] *Growth rate of fuel price of product DC[Product DC]
Transportation unit cost: product DC=>customer [Product DC,Customer,Mode]	THB /(kilogram *kilometre)	INTEG(Increment of transportation unit cost: product DC=>customer[Product DC,Customer,Mode] /TIME STEP,Baseline transportation unit cost: product MP=>customer[Product MP,Customer,Mode])
Transportation variable cost: product DC=>customer [Product DC,Customer,Mode]	THB /kilogram	Transportation unit cost: product DC=>customer [Product DC,Customer,Mode] *Distance: product DC=>customer[Product DC,Customer]
Transportation unit fixed cost: product DC=>customer [Product DC,Customer,Mode]	THB /kilogram	zidz(Transportation fixed cost: product DC=>customer [Product DC,Customer,Mode], SUM(Integer lotsize (weight): product DC=>customer [Product DC,Customer,Product!,Mode]))
Transportation cost: product DC =>customer [Product DC, Customer,Product,Mode]	THB	(Transportation unit fixed cost: product DC=>customer [Product DC,Customer,Mode] +Transportation variable cost: product DC=>customer [Product DC,Customer,Mode]) *Product order distribution: product DC=>customer [Product DC,Customer,Product,Mode] *SUM(BOM[Product,Material!]) *Currency depreciation of product DC[Product DC]

Table A-3-3 Product distribution module: product MP $\rightarrow$ product DC

Parameter	Unit	Mathematical equation
Transportation time: product MP =>product DC [Product MP, Product DC,Mode]	Hours	if then else(SUM(Integer number of roundtrip: product MP =>product DC[Product MP,Product DC,Product!,Mode])>0, zidz(Distance: product MP=>product DC[Product MP, Product DC],Speed of product DC[Mode]),0)
Production capacity: product MP =>product DC [Product MP, Product DC,Product,Mode]	Items	if then else(Production capacity of product MP[Product MP, Product]>SUM(Product order distribution: product MP =>product DC[Product MP,Product DC!,Product,Mode!]), SUM(Product order distribution: product MP=>product DC [Product MP,Product DC!,Product,Mode!]), Production capacity of product MP[Product MP,Product]) *zidz(Product order distribution: product MP=>product DC [Product MP,Product DC,Product,Mode], SUM(Product order distribution: product MP=>product DC [Product MP,Product DC!,Product,Mode!]))
Full container load: product MP=> product DC[Product MP,Product DC, Product,Mode]	Items	zidz(Production capacity: product MP=>product DC [Product MP,Product DC,Product,Mode], Integer lotsize: product MP=>product DC[Product MP, Product DC,Product,Mode]) *Product order distribution: product MP=>product DC [Product MP,Product DC,Product,Mode]
Mode EI: product MP=>product DC [Product MP,Product DC, Product,Mode]	Points	Full container load: product MP=>product DC [Product MP, Product DC,Product,Mode] *SUM(BOM[Product,Material!]) *Distance: product MP=>product DC[Product MP, Product DC]*Mode EI driver[Mode]

Increment of transportation unit cost: product MP=>product DC [Product MP,Product DC,Mode]	THB /(kilogram *kilometre)	Transportation unit cost: product MP=>product DC [Product MP,Product DC,Mode] *Proportion of fuel unit price to transportation unit cost of product MP[Product MP,Mode] *Growth rate of fuel price of product MP[Product MP]
Transportation unit cost: product MP =>product DC [Product MP, Product DC,Mode]	THB /(kilogram *kilometre)	INTEG(Increment of transportation unit cost: product MP =>product DC[Product MP,Product DC,Mode]/TIME STEP,Baseline transportation unit cost: product MP =>product DC[Product MP,Product DC,Mode])
Transportation variable cost: product MP=>product DC [Product MP,Product DC,Mode]	THB /kilogram	Transportation unit cost: product MP=>product DC [Product MP,Product DC,Mode] *Distance: product MP=>product DC[Product MP, Product DC]
Transportation unit fixed cost: product MP=>product DC [Product MP,Product DC,Mode]	THB /kilogram	zidz(Transportation fixed cost: product MP=>product DC [Product MP,Product DC,Mode], SUM(Integer lotsize (weight): product MP=>product DC [Product MP,Product DC,Product!,Mode]))
Transportation cost: product MP =>product DC [Product MP, Product DC,Product,Mode]	THB	(Transportation unit fixed cost: product MP=>product DC [Product MP,Product DC,Mode] +Transportation variable cost: product MP=>product DC [Product MP,Product DC,Mode]) *Product order distribution: product MP=>product DC [Product MP,Product DC,Product,Mode] *SUM(BOM[Product,Material!]) *Currency depreciation of product MP[Product MP]

The generic modules of product demand, product manufacturing and warehousing, and product distribution generate cost (Table A-3-4), lead time (Table A-3-5), and environmental impact (Table A-3-6) as follows.

Table A-3-4 Cost of product MP and product DC

Parameter	**Unit**	**Mathematical equation**
Energy cost of product MP [Product MP,Product]	THB	Energy price: product MP=>customer[Product MP,Product] +Energy price: product MP=>product DC[Product MP, Product]
Labour cost of product MP [Product MP,Product]	THB	Labour cost: product MP=>customer[Product MP,Product] +Labour cost: product MP=>product DC[Product MP, Product]
Product holding cost of product MP [Product MP,Product]	THB	Product holding cost: product MP=>customer [Product MP,Product] +Product holding cost: product MP=>product DC [Product MP,Product]
Transportation cost of product MP [Product MP,Product]	THB	SUM(Transportation cost: product MP=>customer [Product MP,Customer!,Product,Mode!]) +SUM(Transportation cost: product MP=>product DC [Product MP,Product DC!,Product,Mode!])
Locational selection cost of product MP[Product MP]	THB	Locational selection cost of product MP (customer) [Product MP] +Locational selection cost of product MP (product DC) [Product MP]
Total cost of product MP [Product MP]	THB	SUM(Energy cost of product MP[Product MP,Product!]) +SUM(Importation cost: product MP=>product DC [Product MP,Product DC!,Product!,Mode!]) +SUM(Labour cost of product MP[Product MP,Product!]) +SUM(Product holding cost of product MP[Product MP, Product!]) +SUM(Transportation cost of product MP[Product MP, Product!]) +Locational selection cost of product MP[Product MP]
Total cost of product DC [Product DC]	THB	SUM(Energy price of product DC[Product DC,Product!]) +SUM(Labour cost of product DC[Product DC,Product!]) +SUM(Product holding cost of product DC[Product DC, Product!])+SUM(Transportation cost: product DC=>customer [Product DC,Customer!,Product!,Mode!]) +Locational selection cost of product DC[Product DC]

Table A-3-5 Lead time of product MP and product DC

Parameter	Unit	Mathematical equation
Lead time by product: product MP =>customer[Product MP, Customer,Mode]	Hours	SUM(Preparation time: product MP=>customer [Product MP,Customer,Product!,Mode]) +Transportation time: product MP=>customer [Product MP,Customer,Mode]
Lead time: product MP =>customer[Product MP,Customer]	Hours	SUM(Lead time by product: product MP=>customer [Product MP,Customer,Mode!])
Lead time by product: product MP =>product DC[Product MP, Product DC,Mode]	Hours	SUM(Preparation time: product MP=>product DC [Product MP,Product DC,Product!,Mode]) +Transportation time: product MP=>product DC [Product MP,Product DC,Mode]
Lead time: product MP=> product DC[Product MP,Product DC]	Hours	SUM(Lead time by product: product MP=>product DC [Product MP,Product DC,Mode!])
Lead time by product: product DC =>customer[Product DC, Customer,Mode]	Hours	SUM(Preparation time: product DC=>customer [Product DC,Customer,Product!,Mode]) +Transportation time: product DC=>customer [Product DC,Customer,Mode]
Lead time: product DC =>customer[Product DC,Customer]	Hours	SUM(Lead time by product: product DC=>customer [Product DC,Customer,Mode!])
Lead time (product MP): product MP=>customer [Product MP,Product DC]	Hours	Lead time: product MP=>product DC[Product MP, Product DC] +if then else(Lead time: product MP=>product DC [Product MP,Product DC]>0,SUM(Lead time: product DC=>customer[Product DC,Customer!]) +SUM(Lead time: product MP=>customer[Product MP, Customer!]),0) +if then else(SUM(Lead time: product MP=>product DC [Product MP!,Product DC!])=0,SUM(Lead time: product DC =>customer[Product DC,Customer!]) +SUM(Lead time: product MP=>customer[Product MP, Customer!]),0)
Lead time (product MP): supplier=>customer[Product MP]	Hours	VMAX(Lead time: supplier=>product MP[Supplier!, Product MP]) +VMAX(Lead time: component DC=>product MP [Component DC!,Product MP]) +VMAX(Lead time: component MP=>product MP [Component MP!,Product MP]) +SUM(Lead time (product MP): product MP=>customer [Product MP,Product DC!])

Table A-3-6 Environmental impact of product MP and product DC

Parameter	Unit	Mathematical equation
Total EI: product MP=>customer [Product MP,Customer, Product,Mode]	Points	Energy EI: product MP=>customer[Product MP, Customer,Product,Mode] +Mode EI: product MP=>customer[Product MP, Customer,Product,Mode]
Total EI: product MP=>product DC [Product MP,Product DC, Product,Mode]	Points	Energy EI: product MP=>product DC[Product MP, Product DC,Product,Mode] +Mode EI: product MP=>product DC[Product MP, Product DC,Product,Mode]
Total EI of product MP[Product MP]	Points	SUM(Total EI: product MP=>customer[Product MP, Customer!,Product!,Mode!]) +SUM(Total EI: product MP=>product DC[Product MP, Product DC!,Product!,Mode!])
Total EI: product DC=>customer [Product DC,Customer, Product,Mode]	Points	Energy EI: product DC=>customer[Product DC, Customer,Product,Mode] +Mode EI: product DC=>customer[Product DC, Customer,Product,Mode]
Total EI of product DC[Product DC]	Points	SUM(Total EI: product DC=>customer[Product DC, Customer!,Product!,Mode!])

4 Component demand module

Component demand module covers three sub-modules. They are component MP $\rightarrow$ product MP (Table A-4-1), component DC $\rightarrow$ product MP (Table A-4-2), and component MP $\rightarrow$ component DC (Table A-4-3) as follows.

Table A-4-1 Component demand module: component MP $\rightarrow$ product MP

Parameter	Unit	Mathematical equation
Component volume of product MP [Product MP,Product,Component]	Items	SUM(Product order allocation: customer=>product MP [Product MP,Customer!,Product]) *BOC[Product,Component]
Component order allocation: product MP=>component MP [Component MP,Product MP, Component]	Items	SUM(Component volume of product MP[Product MP, Product!,Component]) *Locational selection of component MP[Component MP] *zidz(Distance: component MP=>product MP [Component MP,Product MP], Distance: component MP=>product MP[Component MP, Product MP])
Mode selection: component MP =>product MP[Component MP, Product MP,Component,Mode]	Dmnl	if then else(Component order allocation: product MP =>component MP[Component MP,Product MP, Component]>0, if then else(Distance: component MP=>product MP [Component MP,Product MP]>0, Global mode selection of component MP[Component,Mode], Local mode selection of component MP[Component,Mode]) *zidz(Feasible mode of component MP [Component,Mode],Feasible mode of component MP [Component,Mode]),0)
Component order distribution: component MP=>product MP [Component MP,Product MP, Component,Mode]	Items	Component order allocation: product MP=>component MP [Component MP,Product MP,Component] *Mode selection: component MP=>product MP [Component MP,Product MP,Component,Mode] *Component MP=>Product MP (1) or not (0)
Lotsize: component MP =>product MP[Component MP, Product MP,Component,Mode]	Items	if then else(Lotsize of component MP[Component MP, Component] >SUM(Component order allocation: product MP =>component MP[Component MP,Product MP!, Component]), SUM(Component order allocation: product MP=> component MP[Component MP,Product MP!,Component]), Lotsize of component MP[Component MP,Component]) *zidz(Component order allocation: product MP=> component MP[Component MP,Product MP,Component], SUM(Component order allocation: product MP=> component MP[Component MP,Product MP!,Component])) *Mode selection: component MP=>product MP [Component MP,Product MP,Component,Mode] *Component MP=>Product MP (1) or not (0)
Integer lotsize: component MP =>product MP[Component MP, Product MP,Component,Mode]	Items	if then else(Lotsize: component MP=>product MP [Component MP,Product MP,Component,Mode] -integer(Lotsize: component MP=>product MP [Component MP,Product MP,Component,Mode]) <0.01, Lotsize: component MP=>product MP[Component MP, Product MP,Component,Mode], integer(Lotsize: component MP=>product MP [Component MP,Product MP,Component,Mode])+1)
Number of roundtrip: component MP=>product MP [Component MP,Product MP, Component,Mode]	Dmnl	zidz(Component order distribution: component MP=> product MP[Component MP,Product MP,Component,Mode], Integer lotsize: component MP=>product MP [Component MP,Product MP,Component,Mode])
Integer number of roundtrip: component MP=>product MP [Component MP,Product MP, Component,Mode]	Dmnl	if then else(Number of roundtrip: component MP=> product MP[Component MP,Product MP,Component,Mode] -integer(Number of roundtrip: component MP=> product MP[Component MP,Product MP,Component,Mode])

		< 0.01, Number of roundtrip: component MP=>product MP [Component MP,Product MP,Component,Mode], integer(Number of roundtrip: component MP=>product MP [Component MP,Product MP,Component,Mode])+1)
Total component order distribution: component MP=>product MP [Component MP,Product MP, Component,Mode]	Items	Integer lotsize: component MP=>product MP [Component MP,Product MP,Component,Mode] *Integer number of roundtrip: component MP=> product MP[Component MP,Product MP,Component,Mode]
Service level: component MP =>product MP[Component]	%	if then else(zidz(SUM(Total component order distribution: component MP=>product MP[Component MP!, Product MP!,Component,Mode!]), SUM(Component volume of product MP[Product MP!, Product!,Component])) > 1,1, zidz(SUM(Total component order distribution: component MP=>product MP[Component MP!, Product MP!,Component,Mode!]), SUM(Component volume of product MP[Product MP!, Product!,Component]))) +(1-Component MP=>Product MP (1) or not (0))
Startup of component MP (product MP)[Component MP]	Dmnl	if then else(SUM(Component order distribution: component MP=>product MP[Component MP, Product MP!,Component!,Mode!])>0 :AND::NOT:Binary variable for locational selection of component MP (product MP)[Component MP],1,0)
Shutdown of component MP (product MP)[Component MP]	Dmnl	if then else(SUM(Component order distribution: component MP=>product MP[Component MP, Product MP!,Component!,Mode!])=0 :AND:Binary variable for locational selection of component MP (product MP)[Component MP],1,0)
Binary variable for locational selection of component MP (product MP)[Component MP]	Dmnl	INTEG((Startup of component MP (product MP) [Component MP]-Shutdown of component MP (product MP)[Component MP])/TIME STEP,Baseline binary variable for locational selection of component MP [Component MP])
Locational selection cost of component MP (product MP) [Component MP]	THB	((Shutdown of component MP (product MP) [Component MP] *Shutdown cost of component MP[Component MP]) +(Startup of component MP (product MP) [Component MP] *Startup cost of component MP[Component MP])) *Currency depreciation of component MP[Component MP]

Table A-4-2 Component demand module: component DC→product MP

Parameter	Unit	Mathematical equation
Component order allocation: product MP=>component DC [Component DC,Product MP, Component]	Items	SUM(Component volume of product MP[Product MP, Product!,Component]) *Locational selection of component DC[Component DC] *zidz(Distance: component DC=>product MP [Component DC,Product MP], Distance: component DC=>product MP [Component DC, Product MP])
Mode selection: component DC =>product MP[Component DC, Product MP,Component,Mode]	Dmnl	if then else(Component order allocation: product MP =>component DC[Component DC,Product MP, Component]>0, if then else(Distance: component DC=>Product MP [Component DC,Product MP]>0, Global mode selection of component DC[Component,Mode], Local mode selection of component DC[Component,Mode]) *zidz(Feasible mode of component DC [Component,Mode],Feasible mode of component DC [Component,Mode]),0)
Component order distribution: component DC=>product MP [Component DC,Product MP, Component,Mode]	Items	Component order allocation: product MP=>component DC [Component DC,Product MP,Component] *Mode selection: component DC=>product MP [Component DC,Product MP,Component,Mode] *Component DC=>Product MP (1) or not (0)
Lotsize: component DC=> product MP[Component DC, Product MP,Component,Mode]	Items	if then else(Lotsize of component DC[Component DC, Component] >SUM(Component order allocation: product MP

		=>component DC[Component DC,Product MP!,Component]), SUM(Component order allocation: product MP=> component DC[Component DC,Product MP!,Component]), Lotsize of component DC[Component DC,Component]) *zidz(Component order allocation: product MP=> component DC[Component DC,Product MP,Component], SUM(Component order allocation: product MP=> component DC[Component DC,Product MP!,Component])) *Mode selection: component DC=>product MP [Component DC,Product MP,Component,Mode] *Component DC=>Product MP (1) or not (0)
Integer lotsize: component DC =>product MP[Component DC, Product MP,Component,Mode]	Items	if then else(Lotsize: component DC=>product MP [Component DC,Product MP,Component,Mode] -integer(Lotsize: component DC=>product MP [Component DC,Product MP,Component,Mode])<0.01, Lotsize: component DC=>product MP[Component DC, Product MP,Component,Mode], integer(Lotsize: component DC=>product MP [Component DC,Product MP,Component,Mode])+1)
Number of roundtrip: component DC=>product MP [Component DC,Product MP, Component,Mode]	Dmnl	zidz(Component order distribution: component DC=> product MP[Component DC,Product MP,Component,Mode], Integer lotsize: component DC=>product MP [Component DC,Product MP,Component,Mode])
Integer number of roundtrip: component DC=>product MP [Component DC,Product MP, Component,Mode]	Dmnl	if then else(Number of roundtrip: component DC=> product MP[Component DC,Product MP,Component,Mode] -integer(Number of roundtrip: component DC=> product MP[Component DC,Product MP,Component,Mode]) < 0.01, Number of roundtrip: component DC=>product MP [Component DC,Product MP,Component,Mode], integer(Number of roundtrip: component DC=> product MP[Component DC,Product MP, Component,Mode])+1)
Total component order distribution: component DC=>product MP [Component DC,Product MP, Component,Mode]	Items	Integer lotsize: component DC=>product MP [Component DC,Product MP,Component,Mode] *Integer number of roundtrip: component DC=> product MP[Component DC,Product MP,Component,Mode]
Service level of component DC [Component]	%	if then else(zidz(SUM(Total component order distribution: component DC=>product MP[Component DC!, Product MP!,Component,Mode!]), SUM(Component volume of product MP[Product MP!, Product!,Component])) > 1,1, zidz(SUM(Total component order distribution: component DC=>product MP[Component DC!, Product MP!,Component,Mode!]), SUM(Component volume of product MP[Product MP!, Product!,Component]))) +(1-Component DC=>Product MP (1) or not (0))
Startup of component DC [Component DC]	Dmnl	if then else(SUM(Component order distribution: component DC=>product MP[Component DC, Product MP!,Component!,Mode!])>0 :AND::NOT:Binary variable for locational selection of component DC[Component DC],1,0)
Shutdown of component DC [Component DC]	Dmnl	if then else(SUM(Component order distribution =: component DC=>product MP[Component DC,Product MP!, Component!,Mode!])=0 :AND:Binary variable for locational selection of component DC[Component DC],1,0)
Binary variable for locational selection of component DC [Component DC]	Dmnl	INTEG((Startup of component DC[Component DC] -Shutdown of component DC[Component DC])/TIME STEP,Baseline binary variable for locational selection of component DC[Component DC])
Locational selection cost of component DC[Component DC]	THB	((Shutdown of component DC[Component DC] *Shutdown cost of component DC[Component DC]) +(Startup of component DC[Component DC] *Startup cost of component DC[Component DC])) *Currency depreciation of component DC[Component DC]

Table A-4-3 Component demand module: component MP $\rightarrow$ component DC

Parameter	Unit	Mathematical equation
Component order allocation: component DC=>component MP [Component MP,Component DC,Component]	Items	SUM(Component order allocation: product MP=>component DC[Component DC,Product MP!,Component]) *Locational selection of component MP[Component MP] *zidz(Distance: component MP=>component DC [Component MP,Component DC], Distance: component MP=>component DC [Component MP,Component DC])
Mode selection: component MP=>component DC[Component MP,Component DC,Component,Mode]	Dmnl	if then else(Component order allocation: component DC=>component MP[Component MP,Component DC,Component]>0, if then else(Distance: component MP=>component DC [Component MP,Component DC]>0, Global mode selection of component MP[Component,Mode], Local mode selection of component MP[Component,Mode]) *zidz(Feasible mode of component MP[Component,Mode],Feasible mode of component MP[Component,Mode]),0)
Component order distribution: component MP=>component DC [Component MP,Component DC,Component,Mode]	Items	Component order allocation: component DC=> component MP[Component MP,Component DC,Component] *Mode selection: component MP=>component DC [Component MP,Component DC,Component,Mode] *Component MP=>Component DC (1) or not (0)
Lotsize: component MP=>component DC[Component MP,Component DC,Component,Mode]	Items	if then else(Lotsize of component MP[Component MP,Component]>SUM(Component order allocation: component DC=>component MP[Component MP,Component DC!,Component]), SUM(Component order allocation: component DC=>component MP[Component MP,Component DC!,Component]), Lotsize of component MP[Component MP,Component]) *zidz(Component order allocation: component DC=>component MP[Component MP,Component DC,Component], SUM(Component order allocation: component DC=>component MP[Component MP,Component DC!,Component])) *Mode selection: component MP=>component DC[Component MP,Component DC,Component,Mode] *Component MP=>Component DC (1) or not (0)
Integer lotsize: component MP=>component DC[Component MP,Component DC,Component,Mode]	Items	if then else(Lotsize: component MP=>component DC [Component MP,Component DC,Component,Mode] -integer(Lotsize: component MP=>component DC [Component MP,Component DC,Component,Mode])<0.01, Lotsize: component MP=>component DC [Component MP,Component DC,Component,Mode], integer(Lotsize: component MP=>component DC [Component MP,Component DC,Component,Mode])+1)
Number of roundtrip: component MP=>component DC [Component MP,Component DC,Component,Mode]	Dmnl	zidz(Component order distribution: component MP=>component DC[Component MP,Component DC,Component,Mode], Integer lotsize: component MP=>component DC [Component MP,Component DC,Component,Mode])
Integer number of roundtrip: component MP=>component DC [Component MP,Component DC,Component,Mode]	Dmnl	if then else(Number of roundtrip: component MP=>component DC[Component MP,Component DC,Component,Mode]-integer(Number of roundtrip: component MP=>component DC[Component MP, Component DC,Component,Mode]) < 0.01, Number of roundtrip: component MP=>component DC [Component MP,Component DC,Component,Mode], integer(Number of roundtrip: component MP=> component DC[Component MP,Component DC,Component,Mode])+1)
Total component order distribution: component MP=>component DC [Component MP,Component DC,Component,Mode]	Items	Integer lotsize: component MP=>component DC [Component MP,Component DC,Component,Mode] *Integer number of roundtrip: component MP=> component DC[Component MP,Component DC,Component,Mode]

Service level: component MP=>component DC[Component]	%	if then else(zidz(SUM(Total component order distribution: component MP=>component DC[Component MP!,Component DC!,Component,Mode!]), SUM(Component order allocation: component DC=>component MP[Component MP!,Component DC!,Component])) > 1,1, zidz(SUM(Total component order distribution: component MP=>component DC[Component MP!,Component DC!,Component,Mode!]), SUM(Component order allocation: component DC=>component MP[Component MP!,Component DC!,Component]))) +(1-Component MP=>Component DC (1) or not (0))
Startup of component MP (component DC)[Component MP]	Dmnl	if then else(SUM(Component order distribution: component MP=>component DC[Component MP,Component DC!,Component!,Mode!])>0 :AND::NOT:Binary variable for locational selection of component MP (component DC)[Component MP],1,0)
Shutdown of component MP (component DC)[Component MP]	Dmnl	if then else(SUM(Component order distribution: component MP=>component DC[Component MP,Component DC!,Component!,Mode!])=0 :AND:Binary variable for locational selection of component MP (component DC)[Component MP],1,0)
Binary variable for locational selection of component MP (component DC)[Component MP]	Dmnl	INTEG((Startup of component MP (component DC) [Component MP]-Shutdown of component MP (component DC)[Component MP])/TIME STEP,Baseline binary variable for locational selection of component MP [Component MP])
Locational selection cost of component MP (component DC) [Component MP]	THB	((Shutdown of component MP (component DC) [Component MP] *Shutdown cost of component MP[Component MP]) +(Startup of component MP (component DC) [Component MP] *Startup cost of component MP[Component MP])) *Currency depreciation of component MP[Component MP]

5 Component manufacturing and warehousing module

Component manufacturing and warehousing module covers three sub-modules. They are component MP $\rightarrow$ product MP (Table A-5-1), component DC $\rightarrow$ product MP (Table A-5-2), and component MP $\rightarrow$ component DC (Table A-5-3) as follows.

Table A-5-1 Component manufacturing module: component MP $\rightarrow$ product MP

Parameter	Unit	Mathematical equation
Decrement of energy unit consumption of component MP [Component MP,Component]	MJ / item	Energy unit consumption of component MP[Component MP, Component] *Improvement rate of energy consumption of component MP [Component MP]
Energy unit consumption of component MP[Component MP, Component]	MJ / item	INTEG(Decrement of energy unit consumption of component MP[Component MP,Component]/TIME STEP, Baseline energy unit consumption of component MP [Component MP,Component])
Energy consumption: component MP=>product MP [Component MP,Product MP, Component,Mode]	MJ	Energy unit consumption of component MP[Component MP, Component] *Component order distribution: component MP=> product MP[Component MP,Product MP,Component,Mode]
Selected energy EI: component MP =>product MP[Component MP, Product MP, Component,Mode,Energy]	MJ	Energy consumption: component MP=>product MP [Component MP,Product MP,Component,Mode] *Energy EI driver[Energy] *Energy type selection of component MP[Component MP, Energy]

Energy EI: component MP =>product MP[Component MP, Product MP,Component,Mode]	Points	SUM(Selected energy EI: component MP=>product MP [Component MP,Product MP,Component,Mode,Energy!])
Increment of energy unit price of component MP[Component MP]	THB/MJ	Energy unit price of component MP[Component MP] *Growth rate of energy price of component MP [Component MP]
Energy unit price of component MP [Component MP]	THB/MJ	INTEG(Increment of energy unit price of component MP [Component MP]/TIME STEP,Baseline energy unit cost of component MP[Component MP])
Increment of currency depreciation of component MP [Component MP]	Dmnl	Currency depreciation of component MP[Component MP] *Growth rate of currency depreciation of component MP [Component MP]
Currency depreciation of component MP [Component MP]	Dmnl	INTEG(Increment of currency depreciation of component MP [Component MP]/TIME STEP,1)
Energy price: component MP =>product MP[Component MP, Component]	THB	Energy unit price of component MP[Component MP] *SUM(Energy consumption: component MP=> product MP[Component MP,Product MP!, Component,Mode!]) *Currency depreciation of component MP[Component MP]
Production time: component MP =>product MP[Component MP, Component]	Hours	Production unit time of component MP[Component MP, Component] *SUM(Integer lotsize: component MP=>product MP [Component MP,Product MP!,Component,Mode!])
Preparation time: component MP =>product MP[Component MP, Product MP,Component,Mode]	Hours	if then else(Integer lotsize: component MP=>product MP [Component MP,Product MP,Component,Mode]>0, Production time: component MP=>product MP [Component MP,Component] +Setup time of component MP[Component MP,Component], 0)
Setup unit time: component MP =>product MP[Component MP, Component]	Hours / item	zidz(Setup time of component MP[Component MP, Component], SUM(Integer lotsize: component MP=>product MP [Component MP,Product MP!,Component,Mode!]))
Preparation unit time: component MP=>product MP [Component MP,Component]	Hours / item	Setup unit time: component MP=>product MP [Component MP,Component] +if then else(Setup unit time: component MP=> product MP[Component MP,Component]>0, Production unit time of component MP[Component MP, Component],0)
Total preparation time: component MP=>product MP [Component MP,Product MP, Component,Mode]	Hours	Preparation unit time: component MP=>product MP [Component MP,Component] *Component order distribution: component MP=> product MP[Component MP,Product MP,Component,Mode]
Increment of wage rate of component MP[Component MP, Component]	THB/hour	Wage rate of component MP[Component MP,Component] *Growth rate of wage rate of component MP [Component MP]
Wage rate of component MP [Component MP,Component]	THB / hour	INTEG(Increment of wage rate of component MP [Component MP,Component]/TIME STEP,Baseline wage rate of component MP[Component MP,Component])
Labour cost: component MP =>product MP[Component MP, Component]	THB	Wage rate of component MP[Component MP,Component] *SUM(Total preparation time: component MP=> product MP[Component MP,Product MP!, Component,Mode!]) *Currency depreciation of component MP[Component MP]
Component safety stock: component MP=>product MP [Component MP,Component,Mode]	Items	Service factor *SUM(Standard deviation of component volume[Product!,Component]) *zidz(SUM(Component order distribution: component MP =>product MP[Component MP,Product MP!, Component,Mode]),SUM(Component order distribution: component MP=>product MP[Component MP!,Product MP!, Component,Mode])) *SQRT(Lead time (component MP): supplier=>customer [Component MP])
Compoonent holding cost: component MP=>product MP [Component MP,Component]	THB	SUM(Component safety stock: component MP=> product MP[Component MP,Component,Mode!]) *Component unit price[Component] *% inventory holding cost of component MP [Component MP]/100 *Currency depreciation of component MP[Component MP]

Table A-5-2 Component warehousing module: component DC$\rightarrow$product MP

Parameter	Unit	Mathematical equation
Decrement of energy unit consumption of component DC [Component DC,Component]	MJ / item	Energy unit consumption of component DC[Component DC, Component] *Improvement rate of energy consumption of component DC [Component DC]
Energy unit consumption of component DC[Component DC, Component]	MJ / item	INTEG(Decrement of energy unit consumption of component DC[Component DC,Component]/TIME STEP, Baseline energy unit consumption of component DC [Component DC,Component])
Energy consumption: component DC=>product MP [Component DC,Product MP, Component,Mode]	MJ	Energy unit consumption of component DC [Component DC, Component] *Component order distribution: component DC=> product MP[Component DC,Product MP,Component,Mode]
Selected energy EI: component DC =>product MP[Component DC, Product MP,Component, Mode,Energy]	MJ	Energy consumption: component DC=>product MP [Component DC,Product MP,Component,Mode] *Energy EI driver[Energy] *Energy type selection of component DC[Component DC, Energy]
Energy EI: component DC =>product MP[Component DC, Product MP,Component,Mode]	Points	SUM(Selected energy EI: component DC=>product MP [Component DC,Product MP,Component,Mode,Energy!])
Increment of energy unit price of component DC[Component DC]	THB/MJ	Energy unit price of component DC[Component DC] *Growth rate of energy price of component DC [Component DC]
Energy unit price of component DC [Component DC]	THB/MJ	INTEG(Increment of energy unit price of component DC [Component DC]/TIME STEP,Baseline energy unit cost of component DC[Component DC])
Increment of currency depreciation of component DC[Component DC]	Dmnl	Currency depreciation of component DC[Component DC] *Growth rate of currency depreciation of component DC [Component DC]
Currency depreciation of component DC[Component DC]	Dmnl	INTEG(Increment of currency depreciation of component DC [Component DC]/TIME STEP,1)
Energy price of component DC [Component DC,Component]	THB	Energy unit price of component DC[Component DC] *SUM(Energy consumption: component DC=> product MP[Component DC,Product MP!, Component,Mode!]) *Currency depreciation of component DC[Component DC]
Preparation time: component DC =>product MP[Component DC, Product MP,Component,Mode]	Hours	if then else(Integer lotsize: component DC=>product MP [Component DC,Product MP,Component,Mode]>0, Warehousing unit time of component DC[Component DC, Component] *SUM(Integer lotsize: component DC=>product MP [Component DC,Product MP!,Component,Mode!]),0)
Total preparation time: component MP=>product MP [Component MP,Product MP, Component,Mode]	Hours	Warehousing unit time of component DC[Component DC, Component] *Component order distribution: component DC=> product MP[Component DC,Product MP,Component,Mode]
Increment of wage rate of component DC[Component DC, Component]	THB/hour	Wage rate of component DC[Component DC,Component] *Growth rate of wage rate of component DC [Component DC]
Wage rate of component DC [Component DC,Component]	THB / hour	INTEG(Increment of wage rate of component DC [Component DC,Component]/TIME STEP,Baseline wage rate of component DC[Component DC,Component])
Labour cost of component DC [Component DC,Component]	THB	Wage rate of component DC[Component DC,Component] *SUM(Total preparation time: component DC=> product MP[Component DC,Product MP!, Component,Mode!]) *Currency depreciation of component DC[Component DC]
Standard deviation of component volume[Product,Component]	Items	Standard deviation of product volume[Product] *BOC[Product,Component]
Component safety stock of component DC[Component DC, Component,Mode]	Items	Service factor *SUM(Standard deviation of component volume[Product!,Component]) *zidz(SUM(Component order distribution: component DC =>product MP[Component DC,Product MP!, Component,Mode]),SUM(Component order distribution: component DC=>product MP[Component DC!,Product MP!,

		Component,Mode])) *SQRT(Lead time (component DC): component MP =>customer[Component DC])
Component holding cost of component DC[Component DC, Component]	THB	SUM(Component safety stock of component DC [Component DC,Component,Mode!]) *Component unit price[Component] *% inventory holding cost of component DC [Component DC]/100 *Currency depreciation of component DC[Component DC]

Table A-5-3 Component manufacturing module: component MP $\rightarrow$ component DC

Parameter	**Unit**	**Mathematical equation**
Energy consumption: component MP=>component DC [Component MP,Component DC, Component,Mode]	MJ	Energy unit consumption of component MP[Component MP, Component] *Component order distribution: component MP=> component DC[Component MP,Component DC, Component,Mode]
Selected energy EI: component MP =>component DC[Component MP, Component DC,Component, Mode,Energy]	MJ	Energy consumption: component MP=>component DC [Component MP,Component DC,Component,Mode] *Energy EI driver[Energy] *Energy type selection of component MP[Component MP, Energy]
Energy EI: component MP =>component DC[Component MP, Component DC,Component,Mode]	Points	SUM(Selected energy EI: component MP=> component DC[Component MP,Component DC, Component,Mode,Energy!])
Energy price: component MP =>component DC[Component MP, Component]	THB	Energy unit price of component MP[Component MP] *SUM(Energy consumption: component MP=> component DC[Component MP,Component DC!, Component,Mode!]) *Currency depreciation of component MP[Component MP]
Production time: component MP =>component DC[Component MP, Component]	Hours	Production unit time of component MP[Component MP, Component] *SUM(Integer lotsize: component MP=>component DC [Component MP,Component DC!,Component,Mode!])
Preparation time: component MP =>component DC[Component MP, Component DC,Component,Mode]	Hours	if then else(Integer lotsize: component MP=> component DC[Component MP,Component DC, Component,Mode]>0, Production time: component MP=>component DC [Component MP,Component] +Setup time of component MP[Component MP,Component], 0)
Setup unit time: component MP =>component DC[Component MP, Component]	Hours / item	zidz(Setup time of component MP[Component MP, Component], SUM(Integer lotsize: component MP=>component DC [Component MP,Component DC!,Component,Mode!]))
Preparation unit time: component MP=>component DC [Component MP,Component]	Hours / item	Setup unit time: component MP=>component DC [Component MP,Component] +if then else (Setup unit time: component MP=>component DC [Component MP,Component]>0, Production unit time of component MP[Component MP, Component],0)
Total preparation time: component MP=>component DC [Component MP,Component DC, Component,Mode]	Hours	Preparation unit time: component MP=>component DC [Component MP,Component] *Component order distribution: component MP=> component DC[Component MP,Component DC, Component,Mode]
Labour cost: component MP =>component DC[Component MP, Component]	THB	Wage rate of component MP[Component MP,Component] *SUM(Total preparation time: component MP=> component DC[Component MP,Component DC!, Component,Mode!]) *Currency depreciation of component MP[Component MP]
Component safety stock: component MP=>component DC [Component MP,Component,Mode]	Items	Service factor *SUM(Standard deviation of component volume[Product!,Component]) *zidz(SUM(Component order distribution: component MP =>component DC[Component MP,Component DC!, Component,Mode]),SUM(Component order distribution:

		component MP=>component DC[Component MP!, Component DC!,Component,Mode])) *SQRT(Lead time (component MP): supplier=>customer [Component MP])
Compoonent holding cost: component MP=>component DC [Component MP,Component]	THB	SUM(Component safety stock: component MP=> component DC[Component MP,Component,Mode!]) *Component unit price[Component] *% inventory holding cost of component MP [Component MP]/100 *Currency depreciation of component MP[Component MP]

6 Component distribution module

Component distribution module covers three sub-modules. They are component MP $\rightarrow$ product MP (Table A-6-1), component DC $\rightarrow$ product MP (Table A-6-2), and component MP $\rightarrow$ component DC (Table A-6-3) as follows.

Table A-6-1 Component distribution module: component MP $\rightarrow$ product MP

Parameter	Unit	Mathematical equation
Transportation time: component MP=>product MP [Component MP,Product MP,Mode]	Hours	if then else(SUM(Integer number of roundtrip: component MP=>product MP[Component MP,Product MP, Component!,Mode])>0, zidz(Distance: component MP=>product MP [Component MP,Product MP],Speed of component MP [Mode]),0)
Production capacity: component MP=>product MP [Component MP,Product MP, Component,Mode]	Items	if then else(Production capacity of component MP [Component MP,Component]>SUM(Component order distribution: component MP=>product MP[Component MP, Product MP!,Component,Mode!]), SUM(Component order distribution: component MP =>product MP[Component MP,Product MP!, Component,Mode!]), Production capacity of component MP[Component MP, Component]) *zidz(Component order distribution: component MP =>product MP[Component MP,Product MP, Component,Mode], SUM(Component order distribution: component MP =>product MP[Component MP,Product MP!, Component,Mode!]))
Full container load: component MP =>product MP [Component MP,Product MP, Component,Mode]	Items	zidz(Production capacity: component MP=>product MP [Component MP,Product MP,Component,Mode], Integer lotsize: component MP=>product MP [Component MP,Product MP,Component,Mode]) *Component order distribution: component MP=> product MP[Component MP,Product MP,Component,Mode]
Mode EI: component MP=> product MP[Component MP, Product MP,Component,Mode]	Points	Full container load: component MP=>product MP [Component MP,Product MP,Component,Mode] *SUM(BOM of component[Product!,Component,Material!]) *Distance: component MP=>product MP[Component MP, Product MP] *Mode EI driver[Mode]
Increment of transportation unit cost: component MP=>product MP [Component MP,Product MP,Mode]	THB /(kilogram *kilometre)	Transportation unit cost: component MP=>product MP [Component MP,Product MP,Mode] *Proportion of fuel unit price to transportation unit cost of component MP[Component MP,Mode] *Growth rate of fuel price of component MP[Component MP]
Transportation unit cost: component MP=>product MP [Component MP,Product MP,Mode]	THB /(kilogram *kilometre)	INTEG(Increment of transportation unit cost: component MP=>product MP[Component MP,Product MP, Mode]/TIME STEP,Baseline transportation unit cost: component MP=>product MP[Component MP,Product MP, Mode])

Transportation variable cost: component MP=>product MP [Component MP,Product MP,Mode]	THB /kilogram	Transportation unit cost: component MP=>product MP [Component MP,Product MP,Mode] *Distance: component MP=>product MP[Component MP, Product MP]
Transportation unit fixed cost: component MP=>product MP [Component MP,Product MP,Mode]	THB /kilogram	zidz(Transportation fixed cost: component MP=> product MP[Component MP,Product MP,Mode], SUM(Integer lotsize (weight): component MP=> product MP[Component MP,Product MP, Component!,Mode]))
Transportation cost: component MP=>product MP [Component MP,Product MP, Component,Mode]	THB	(Transportation unit fixed cost: component MP=> product MP[Component MP,Product MP,Mode] +Transportation variable cost: component MP=> product MP[Component MP,Product MP,Mode]) *Component order distribution: component MP=> product MP[Component MP,Product MP,Component,Mode] *SUM(BOM of component[Product!,Component,Material!]) *Currency depreciation of component MP[Component MP]

Table A-6-2 Component distribution module: component DC $\rightarrow$ product MP

Parameter	Unit	Mathematical equation
Transportation time: component DC=>product MP [Component DC,Product MP,Mode]	Hours	if then else(SUM(Integer number of roundtrip: component DC=>product MP[Component DC,Product MP, Component!,Mode])>0, zidz(Distance: component DC=>product MP [Component DC,Product MP], Speed of component DC[Mode]),0)
Warehousing capacity: component DC=>product MP [Component DC,Product MP, Component,Mode]	Items	if then else (Warehousing capacity of component DC [Component DC,Component]>SUM(Component order distribution: component DC=>product MP[Component DC, Product MP!,Component,Mode!]), SUM(Component order distribution: component DC =>product MP[Component DC,Product MP!, Component,Mode!]), Warehousing apacity of component DC[Component DC, Component]) *zidz(Component order distribution: component DC =>product MP[Component DC,Product MP, Component,Mode], SUM(Component order distribution: component DC =>product MP[Component DC,Product MP!, Component,Mode!]))
Full container load: component DC =>product MP [Component DC, Product MP, Component,Mode]	Items	zidz(Warehousing capacity: component DC=>product MP [Component DC,Product MP,Component,Mode], Integer lotsize: component DC=>product MP [Component DC,Product MP,Component,Mode]) *Component order distribution: component DC=> product MP[Component DC,Product MP,Component,Mode]
Mode EI: component DC=> product MP[Component DC, Product MP,Component,Mode]	Points	Full container load: component DC=>product MP [Component DC,Product MP,Component,Mode] *SUM(BOM of component[Product!,Component,Material!]) *Distance: component DC=>product MP[Component DC, Product MP]*Mode EI driver[Mode]
Increment of transportation unit cost: component DC=>product MP [Component DC, Product MP,Mode]	THB /(kilogram *kilometre)	Transportation unit cost: component DC=>product MP [Component DC,Product MP,Mode] *Proportion of fuel unit price to transportation unit cost of component DC[Component DC,Mode] *Growth rate of fuel price of component DC[Component DC]
Transportation unit cost: component DC=>product MP [Component DC,Product MP,Mode]	THB /(kilogram *kilometre)	INTEG(Increment of transportation unit cost: component DC=>product MP[Component DC,Product MP, Mode]/TIME STEP,Baseline transportation unit cost: component DC=>product MP[Component DC,Product MP, Mode])
Transportation variable cost: component DC=>product MP [Component DC,Product MP,Mode]	THB /kilogram	Transportation unit cost: component DC=>product MP [Component DC,Product MP,Mode] *Distance: component DC=>product MP[Component DC, Product MP]

Transportation unit fixed cost: component DC=>product MP [Component DC,Product MP,Mode]	THB /kilogram	zidz(Transportation fixed cost: component DC=>product MP [Component DC,Product MP,Mode], SUM(Integer lotsize (weight): component DC=>product MP [Component DC,Product MP,Component!,Mode]))
Transportation cost: component DC =>product MP[Component DC, Product MP,Component,Mode]	THB	(Transportation unit fixed cost: component DC=> product MP[Component DC,Product MP,Mode] +Transportation variable cost: component DC=> product MP[Component DC,Product MP,Mode]) *Component order distribution: component DC=> product MP[Component DC,Product MP,Component,Mode] *SUM(BOM of component[Product!,Component,Material!]) *Currency depreciation of component DC[Component DC]

Table A-6-3 Component distribution module: component MP $\rightarrow$ component DC

Parameter	**Unit**	**Mathematical equation**
Transportation time: component MP=>component DC [Component MP,Component DC, Mode]	Hours	if then else(SUM(Integer number of roundtrip: component MP=>component DC[Component MP, Component DC,Component!,Mode])>0, zidz(Distance: component MP=>component DC [Component MP,Component DC], Speed of component MP[Mode]),0)
Production capacity: component MP=>component DC [Component MP,Component DC, Component,Mode]	Items	if then else(Production capacity of component MP [Component MP,Component] >SUM(Component order distribution: component MP =>component DC[Component MP,Component DC!, Component,Mode!]), SUM(Component order distribution: component MP =>component DC[Component MP,Component DC!, Component,Mode!]), Production capacity of component MP[Component MP, Component]) *zidz(Component order distribution: component MP =>component DC[Component MP,Component DC, Component,Mode], SUM(Component order distribution: component MP =>component DC[Component MP,Component DC!, Component,Mode!]))
Full container load: component MP =>component DC [Component MP, Component DC,Component,Mode]	Items	zidz(Production capacity: component MP=> component DC[Component MP,Component DC, Component,Mode],Integer lotsize: component MP =>component DC[Component MP,Component DC, Component,Mode])*Component order distribution: component MP=>component DC[Component MP, Component DC, Component,Mode]
Mode EI: component MP =>component DC[Component MP, Component DC,Component,Mode]	Points	Full container load: component MP=>component DC [Component MP,Component DC, Component,Mode] *SUM(BOM of component[Product!,Component,Material!]) *Distance: component MP=>component DC [Component MP,Component DC]*Mode EI driver[Mode]
Increment of transportation unit cost: component MP=> component DC[Component MP, Component DC,Mode]	THB /(kilogram *kilometre)	Transportation unit cost: component MP=>component DC [Component MP,Component DC,Mode] *Proportion of fuel unit price to transportation unit cost of component MP[Component MP,Mode] *Growth rate of fuel price of component MP[Component MP]
Transportation unit cost: component MP=>component DC [Component MP,Component DC, Mode]	THB /(kilogram *kilometre)	INTEG(Increment of transportation unit cost: component MP =>component DC[Component MP,Component DC, Mode]/TIME STEP,Baseline transportation unit cost: component MP=>component DC[Component MP, Component DC,Mode])
Transportation variable cost: component MP=>component DC [Component MP,Component DC, Mode]	THB /kilogram	Transportation unit cost: component MP=> component DC[Component MP,Component DC,Mode] *Distance: component MP=>component DC [Component MP,Component DC]
Transportation unit fixed cost: component MP=>component DC [Component MP,Component DC, Mode]	THB /kilogram	zidz(Transportation fixed cost: component MP=> component DC[Component MP,Component DC,Mode], SUM(Integer lotsize (weight): component MP=> component DC[Component MP,Component DC, Component!,Mode]))

Transportation cost: component MP=>component DC [Component MP,Component DC, Component,Mode]	THB	(Transportation unit fixed cost: component MP=> component DC[Component MP,Component DC,Mode] +Transportation variable cost: component MP=> component DC[Component MP,Component DC,Mode]) *Component order distribution: component MP=> component DC[Component MP,Component DC, Component,Mode] *SUM(BOM of component[Product!,Component,Material!]) *Currency depreciation of component MP[Component MP]

The generic modules of component demand, component manufacturing and warehousing, and component distribution generate cost (Table A-6-4),lead time (Table A-6-5),and environmental impact (Table A-6-6) as follows.

Table A-6-4 Cost of component MP and component DC

Parameter	**Unit**	**Mathematical equation**
Energy cost of component MP [Component MP,Component]	THB	Energy price: component MP=>component DC [Component MP,Component] +Energy price: component MP=>product MP [Component MP,Component]
Labour cost of component MP [Component MP,Component]	THB	Labour cost: component MP=>component DC [Component MP,Component] +Labour cost: component MP=>product MP [Component MP,Component]
Component holding cost of component MP[Component MP, Component]	THB	Compoonent holding cost: component MP=>component DC [Component MP,Component] +Compoonent holding cost: component MP=>product MP [Component MP,Component]
Transportation cost of component MP[Component MP, Component]	THB	SUM(Transportation cost: component MP=>component DC [Component MP,Component DC!, Component,Mode!]) +SUM(Transportation cost: component MP=>product MP [Component MP,Product MP!,Component,Mode!])
Importation cost of component MP [Component MP,Component]	THB	SUM(Importation cost: component MP=>component DC [Component MP,Component DC!,Component,Mode!]) +SUM(Importation cost: component MP=>Product MP [Component MP,Product MP!,Component,Mode!])
Locational selection cost of component MP[Component MP]	THB	Locational selection cost of component MP (component DC)[Component MP] +Locational selection cost of component MP (product MP) [Component MP]
Total cost of component MP [Component MP]	THB	SUM(Component holding cost of component MP [Component MP,Component!]) +SUM(Energy cost of component MP[Component MP, Component!]) +SUM(Importation cost of component MP[Component MP, Component!]) +SUM(Labour cost of component MP[Component MP, Component!]) +SUM(Transportation cost of component MP [Component MP,Component!])+Locational selection cost of component MP[Component MP]
Total cost of component DC [Component DC,Component]	THB	SUM(Component holding cost of component DC [Component DC,Component!]) +SUM(Energy price of component DC[Component DC, Component!]) +SUM(Importation cost: component DC=>product MP [Component DC,Product MP!,Component!,Mode!]) +SUM(Labour cost of component DC[Component DC, Component!]) +SUM(Transportation cost: component DC=>product MP [Component DC,Product MP!,Component!,Mode!]) +Locational selection cost of component DC[Component DC]

Table A-6-5 Lead time of component MP and component DC

Parameter	Unit	Mathematical equation
Lead time by component: component MP=>product MP [Component MP,Product MP,Mode]	Hours	SUM(Preparation time: component MP=>product MP [Component MP,Product MP,Component!,Mode]) +Transportation time: component MP=>product MP [Component MP,Product MP,Mode]
Lead time: component MP =>product MP[Component MP, Product MP]	Hours	SUM(Lead time by component: component MP=> product MP[Component MP,Product MP,Mode!])
Lead time by component: component MP=>component DC [Component MP,Component DC, Mode]	Hours	SUM(Preparation time: component MP=>component DC [Component MP,Component DC,Component!,Mode]) +Transportation time: component MP=>component DC [Component MP,Component DC,Mode]
Lead time: component MP =>component DC[Component MP, Component DC]	Hours	SUM(Lead time by component: component MP=>component DC[Component MP,Component DC,Mode!])
Lead time (component MP): component MP=>customer [Component MP,Component DC]	Hours	Lead time: component MP=>component DC [Component MP,Component DC] +if then else(Lead time: component MP=>component DC [Component MP,Component DC]>0, SUM(Lead time (component DC): component DC =>customer[Component DC,Product MP!]),0) +if then else(SUM(Lead time: component MP=> component DC[Component MP!,Component DC!])=0, SUM(Lead time (component DC): component DC =>customer[Component DC,Product MP!]),0)
Lead time (component MP): supplier=>customer [Component MP]	Hours	SUM(Lead time (component MP): component MP =>customer[Component MP,Component DC!]) +VMAX(Lead time: supplier=>component MP [Supplier!,Component MP])
Lead time by component: component DC=>product MP [Component DC,Product MP,Mode]	Hours	SUM(Preparation time: component DC=>product MP [Component DC,Product MP,Component!,Mode]) +Transportation time: component DC=>product MP [Component DC,Product MP,Mode]
Lead time: component DC =>product MP[Component DC, Product MP]	Hours	SUM(Lead time by component: component DC=> product MP[Component DC,Product MP,Mode!])
Lead time (component DC): component DC=>customer [Component DC,Product MP]	Hours	Lead time: component DC=>product MP[Component DC,Product MP] +if then else(Lead time: component DC=>product MP [Component DC,Product MP]>0, SUM(Lead time (product MP): product MP=>customer [Product MP,Product DC!]),0) +if then else(SUM(Lead time: component DC=> product MP[Component DC!,Product MP!])=0, SUM(Lead time (product MP): product MP=>customer [Product MP,Product DC!]),0)
Lead time (component DC): component MP=>customer [Component DC]	Hours	SUM(Lead time (component DC): component DC =>customer[Component DC,Product MP!]) +VMAX(Lead time: component MP=>component DC [Component MP!,Component DC])

Table A-6-6 Environmental impact of component MP and component DC

Parameter	Unit	Mathematical equation
Total EI: component MP =>component DC[Component MP, Component DC,Component,Mode]	Points	Mode EI: component MP=>component DC [Component MP,Component DC,Component,Mode] +Energy EI: component MP=>component DC [Component MP,Component DC,Component,Mode]
Total EI: component MP=> product MP[Component MP, Product MP,Component,Mode]	Points	Mode EI: component MP=>product MP[Component MP, Product MP,Component,Mode] +Energy EI: component MP=>product MP [Component MP,Product MP,Component,Mode]
Total EI of component MP [Component MP]	Points	SUM(Total EI: component MP=>component DC [Component MP,Component DC!,Component!,Mode!]) +SUM(Total EI: component MP=>product MP [Component MP,Product MP!,Component!,Mode!])

Total EI: component DC=> product MP[Component DC, Product MP,Component,Mode]	Points	Energy EI: component DC=>product MP[Component DC, Product MP,Component,Mode] +Mode EI: component DC=>product MP[Component DC, Product MP,Component,Mode]
Total EI of component DC [Component DC]	Points	SUM(Total EI: component DC=>product MP [Component DC,Product MP!,Component!,Mode!])

7 Material demand module

Material demand module covers two sub-modules. They are supplier $\rightarrow$ product MP (Table A-7-1) and supplier $\rightarrow$ component MP (Table A-7-2) as follows.

Table A-7-1 Material demand module: supplier $\rightarrow$ product MP

Parameter	Unit	Mathematical equation
Material volume of product MP [Product MP,Product,Material]	Kilograms	SUM(Product order allocation: customer=>product MP [Product MP,Customer!,Product]) *BOM[Product,Material]
Material order allocation: product MP=>supplier[Supplier, Product MP,Material]	Kilograms	SUM(Material volume of product MP[Product MP, Product!,Material]) *Selection of supplier[Material,Supplier] *zidz(Distance: supplier=>product MP[Product MP,Supplier], Distance: supplier=>product MP[Product MP,Supplier])
Mode selection: supplier=> product MP[Supplier,Product MP, Material,Mode]	Dmnl	if then else(Material order allocation: product MP =>supplier[Supplier,Product MP,Material]>0, if then else(Distance: supplier=>product MP [Supplier,Product MP]>0, Global mode selection of supplier[Material,Mode], Local mode selection of supplier[Material,Mode]) *zidz(Feasible mode of supplier[Material,Mode],Feasible mode of supplier[Material,Mode]),0)
Material order distribution: supplier=>product MP[Supplier, Product MP,Material,Mode]	Kilograms	Material order allocation: product MP =>supplier[Supplier,Product MP,Material] *Mode selection: supplier=>product MP[Supplier, Product MP,Material,Mode] *Supplier=>Product MP (1) or not (0)
Lotsize: supplier=>product MP [Supplier,Product MP, Material,Mode]	Kilograms	if then else(Lotsize of supplier[Supplier,Material] >SUM(Material order allocation: product MP=>supplier [Supplier,Product MP!,Material]), SUM(Material order allocation: product MP=>supplier [Supplier,Product MP!,Material]), Lotsize of supplier[Supplier,Material]) *zidz(Material order allocation: product MP=>supplier [Supplier,Product MP,Material], SUM(Material order allocation: product MP=>supplier [Supplier,Product MP!,Material])) *Mode selection: supplier=>product MP[Supplier, Product MP,Material,Mode] *Supplier=>Product MP (1) or not (0)
Number of roundtrip: supplier=>product MP[Supplier, Product MP, Material,Mode]	Dmnl	zidz(Material order distribution: supplier=>product MP [Supplier,Product MP,Material,Mode], Lotsize: supplier=>product MP[Supplier,Product MP, Material,Mode])
Integer number of roundtrip: supplier=>product MP[Supplier, Product MP,Material,Mode]	Dmnl	if then else(Number of roundtrip: supplier=>product MP [Supplier,Product MP,Material,Mode] -integer(Number of roundtrip: supplier=>product MP [Supplier,Product MP,Material,Mode]) < 0.01, Number of roundtrip: supplier=>product MP [Supplier,Product MP,Material,Mode], integer(Number of roundtrip: supplier=>product MP [Supplier,Product MP,Material,Mode])+1)
Total material order distribution: supplier=>product MP [Supplier, Product MP,Material,Mode]	Kilograms	Integer number of roundtrip: supplier=>product MP[Supplier,Product MP,Material,Mode] *Lotsize: supplier=>product MP[Supplier,Product MP, Material,Mode]

Service level: supplier=> product MP[Material]	%	if then else(zidz(SUM(Total material order distribution: supplier=>product MP[Supplier!,Product MP!, Material,Mode!]),SUM(Material volume of product MP [Product MP!,Product!,Material])) > 1,1, zidz(SUM(Total material order distribution: supplier=> product MP[Supplier!,Product MP!,Material,Mode!]), SUM(Material volume of product MP[Product MP!, Product!,Material])))+(1-Supplier=>Product MP (1) or not (0))
Initiation of supplier's contract (product MP)[Product MP,Supplier]	Dmnl	if then else(SUM(Material order distribution: supplier=>product MP[Supplier,Product MP, Material!,Mode!])>0:AND::NOT:Binary variable for supplier selection (product MP)[Product MP,Supplier],1,0)
Termination of supplier's contract (product MP)[Product MP,Supplier]	Dmnl	if then else(SUM(Material order distribution: supplier=>product MP[Supplier,Product MP, Material!,Mode!])=0 :AND:Binary variable for supplier selection (product MP) [Product MP,Supplier],1,0)
Binary variable for supplier selection (product MP)[Product MP, Supplier]	Dmnl	INTEG((Initiation of supplier's contract (product MP) [Product MP,Supplier]-Termination of supplier's contract (product MP)[Product MP,Supplier])/TIME STEP,Baseline binary variable for locational selection of supplier (product MP)[Product MP,Supplier])
Supplier selection cost (product MP)[Supplier,Product MP]	THB	((Termination of supplier's contract (product MP) [Product MP,Supplier] *Termination cost of supplier's contract[Supplier]) +(Initiation of supplier's contract (product MP)[Product MP, Supplier]*Initiation cost of supplier's contract[Supplier])) *Currency depreciation of product MP[Product MP]

Table A-7-2 Material demand module: supplier $\rightarrow$ component MP

Parameter	Unit	Mathematical equation
Component volume of component MP[Component MP, Component]	Items	SUM(Component order allocation: component DC =>component MP[Component MP,Component DC!, Component]) +SUM(Component order allocation: product MP =>component MP[Component MP,Product MP!,Component])
Material volume of component MP [Component MP, Component,Material]	Kilograms	Component volume of component MP[Component MP, Component] *SUM(BOM of component[Product!,Component,Material])
Material order allocation: component MP=>supplier [Supplier,Component MP,Material]	Kilograms	SUM(Material volume of component MP[Component MP, Component!,Material]) *Selection of supplier[Material,Supplier] *zidz(Distance: supplier=>component MP [Component MP,Supplier],Distance: supplier=> component MP[Component MP,Supplier])
Mode selection: supplier=> component MP[Supplier, Component MP,Material,Mode]	Dmnl	if then else(Material order allocation: component MP=>supplier[Supplier,Component MP,Material]>0, if then else(Distance: supplier=>component MP [Supplier,Component MP]>0, Global mode selection of supplier[Material,Mode], Local mode selection of supplier[Material,Mode]) *zidz(Feasible mode of supplier[Material,Mode],Feasible mode of supplier[Material,Mode]),0)
Material order distribution: supplier=>component MP[Supplier, Component MP,Material,Mode]	Kilograms	Material order allocation: component MP=>supplier [Supplier,Component MP,Material] *Mode selection: supplier=>component MP [Supplier,Component MP,Material,Mode] *Supplier=>Component MP (1) or not (0)
Lotsize: supplier=>component MP [Supplier,Component MP, Material,Mode]	Kilograms	if then else(Lotsize of supplier[Supplier,Material] >SUM(Material order allocation: component MP =>supplier[Supplier,Component MP!,Material]), SUM(Material order allocation: component MP =>supplier[Supplier,Component MP!,Material]), Lotsize of supplier[Supplier,Material]) *zidz(Material order allocation: component MP =>supplier[Supplier,Component MP,Material], SUM(Material order allocation: component MP =>supplier[Supplier,Component MP!,Material]))

		*Mode selection: supplier=>component MP [Supplier,Component MP,Material,Mode] *Supplier=>Component MP (1) or not (0)
Number of roundtrip: supplier =>component MP[Supplier, Component MP,Material,Mode]	Dmnl	zidz(Material order distribution: supplier=>component MP [Supplier,Component MP,Material,Mode], Lotsize: supplier=>component MP[Supplier, Component MP,Material,Mode])
Integer number of roundtrip: supplier=>component MP [Supplier,Component MP, Material,Mode]	Dmnl	if then else(Number of roundtrip: supplier=> component MP[Supplier,Component MP,Material,Mode] -integer(Number of roundtrip: supplier=>component MP [Supplier,Component MP,Material,Mode]) < 0.01, Number of roundtrip: supplier=>component MP [Supplier,Component MP,Material,Mode], integer(Number of roundtrip: supplier=>component MP [Supplier,Component MP,Material,Mode])+1)
Total material order distribution: supplier=>component MP [Supplier,Component MP, Material,Mode]	Kilograms	Integer number of roundtrip: supplier=>component MP [Supplier,Component MP,Material,Mode] *Lotsize: supplier=>component MP[Supplier, Component MP,Material,Mode]
Service level: supplier=>component MP[Material]	%	if then else(zidz(SUM(Total material order distribution: supplier=>component MP[Supplier!,Component MP!, Material,Mode!]), SUM(Material volume of component MP[Component MP!, Component!,Material])) > 1,1, zidz(SUM(Total material order distribution: supplier=>component MP[Supplier!,Component MP!, Material,Mode!]), SUM(Material volume of component MP[Component MP!, Component!,Material]))) +(1-Supplier=>Component MP (1) or not (0))
Initiation of supplier's contract (component MP)[Component MP, Supplier]	Dmnl	if then else(SUM(Material order distribution: supplier=>component MP[Supplier,Component MP, Material!,Mode!])>0 :AND::NOT:Binary variable for supplier selection (component MP)[Component MP,Supplier],1,0)
Termination of supplier's contract (component MP)[Component MP, Supplier]	Dmnl	if then else(SUM(Material order distribution: supplier=>component MP[Supplier,Component MP, Material!,Mode!])=0 :AND:Binary variable for supplier selection (component MP) [Component MP,Supplier],1,0)
Binary variable for supplier selection (component MP) [Component MP,Supplier]	Dmnl	INTEG(((Initiation of supplier's contract (component MP) [Component MP,Supplier]-Termination of supplier's contract (component MP)[Component MP,Supplier])/TIME STEP,Baseline binary variable for locational selection of supplier (component MP)[Component MP,Supplier])
Supplier selection cost (component MP) [Supplier,Component MP]	THB	((Termination of supplier's contract (component MP) [Component MP,Supplier] *Termination cost of supplier's contract[Supplier]) +(Initiation of supplier's contract (component MP) [Component MP,Supplier] *Initiation cost of supplier's contract[Supplier])) *Currency depreciation of component MP[Component MP]

8 Material procurement module

Material procurement module covers two sub-modules. They are supplier $\rightarrow$ product MP (Table A-8-1) and supplier $\rightarrow$ component MP (Table A-8-2) as follows.

Table A-8-1 Material procurement module: supplier $\rightarrow$ product MP

Parameter	**Unit**	**Mathematical equation**
Preparation time: supplier=> product MP[Supplier,Product MP, Material,Mode]	Hours	if then else(Lotsize: supplier=>product MP[Supplier, Product MP,Material,Mode]>0, Preparation time of supplier[Supplier,Material] *SUM(Lotsize: supplier=>product MP[Supplier, Product MP!,Material,Mode!]),0)
Material EI: supplier=>product MP [Supplier,Product MP, Material,Mode]	Points	Material order distribution: supplier=>product MP [Supplier,Product MP,Material,Mode] *Material EI driver[Material]
Increment of currency depreciation of supplier[Supplier]	Dmnl	Currency depreciation of supplier[Supplier] *Growth rate of currency depreciation of supplier[Supplier]
Currency depreciation of supplier [Supplier]	Dmnl	INTEG(Increment of currency depreciation of supplier [Supplier]/TIME STEP,1)
Material cost of product MP [Supplier,Product MP, Material,Mode]	THB	Material unit price[Supplier,Material] *Material order distribution: supplier=>product MP [Supplier,Product MP,Material,Mode] *Currency depreciation of supplier[Supplier]

Table A-8-2 Material procurement module: supplier $\rightarrow$ component MP

Parameter	**Unit**	**Mathematical equation**
Preparation time: supplier=> component MP[Supplier, Component MP,Material,Mode]	Hours	if then else(Lotsize: supplier=>component MP [Supplier,Component MP,Material,Mode]>0, Preparation time of supplier[Supplier,Material] *SUM(Lotsize: supplier=>component MP [Supplier,Component MP!,Material,Mode!]),0)
Material EI: supplier=> component MP[Supplier, Component MP,Material,Mode]	Points	Material order distribution: supplier=>component MP [Supplier,Component MP,Material,Mode] *Material EI driver[Material]
Material cost of component MP [Supplier,Component MP, Material,Mode]	THB	Material unit price[Supplier,Material] *Material order distribution: supplier=>component MP [Supplier,Component MP,Material,Mode] *Currency depreciation of supplier[Supplier]

9 Material distribution module

Material distribution module covers two sub-modules. They are supplier $\rightarrow$ product MP (Table A-9-1) and supplier $\rightarrow$ component MP (Table A-9-2) as follows.

Table A-9-1 Material distribution module: supplier $\rightarrow$ product MP

Parameter	**Unit**	**Mathematical equation**
Transportation time: supplier=>product MP [Supplier,Product MP,Mode]	Hours	if then else(SUM(Integer number of roundtrip: supplier=>product MP[Supplier,Product MP, Material!,Mode])>0, zidz(Distance: supplier=>product MP[Product MP, Supplier],Speed of supplier[Mode]),0)
Production capacity: supplier=> product MP[Supplier,Product MP, Material,Mode]	Kilograms	if then else(Production capacity of supplier[Supplier,Material] >SUM(Material order distribution: supplier=>product MP [Supplier,Product MP!,Material,Mode!]), SUM(Material order distribution: supplier=>product MP [Supplier,Product MP!,Material,Mode!]), Production capacity of supplier[Supplier,Material]) *zidz(Material order distribution: supplier=>product MP [Supplier,Product MP,Material,Mode], SUM(Material order distribution: supplier=>product MP [Supplier,Product MP!,Material,Mode!]))

Full container load: supplier =>product MP[Supplier, Product MP,Material,Mode]	Kilograms	zidz(Production capacity: supplier=>product MP [Supplier,Product MP,Material,Mode], Lotsize: supplier=>product MP[Supplier,Product MP, Material,Mode]) *Material order distribution: supplier=>product MP [Supplier,Product MP,Material,Mode]
Mode EI: supplier=>product MP [Supplier,Product MP, Material,Mode]	Points	Full container load: supplier=>product MP [Supplier, Product MP,Material,Mode] *Distance: supplier=>product MP[Product MP,Supplier] *Mode EI driver[Mode]
Increment of transportation unit cost: supplier=>product MP [Supplier,Product MP,Mode]	THB /(kilogram *kilometre)	Transportation unit cost: supplier=>product MP [Supplier,Product MP,Mode] *Proportion of fuel unit price to transportation unit cost of supplier[Supplier,Mode] *Growth rate of fuel price of supplier[Supplier]
Transportation unit cost: supplier=>product MP[Supplier, Product MP,Mode]	THB /(kilogram *kilometre)	INTEG(Increment of transportation unit cost: supplier=>product MP[Supplier,Product MP,Mode]/TIME STEP,Baseline transportation unit cost: supplier=> product MP[Supplier,Product MP,Mode])
Transportation variable cost: supplier=>product MP [Supplier,Product MP,Mode]	THB /kilogram	Transportation unit cost: supplier=>product MP [Supplier,Product MP,Mode] *Distance: supplier=>product MP[Product MP,Supplier]
Transportation unit fixed cost: supplier=>product MP [Supplier,Product MP,Mode]	THB /kilogram	zidz(Transportation fixed cost: supplier=>product MP [Supplier,Product MP,Mode], SUM(Lotsize: supplier=>product MP[Supplier, Product MP,Material!,Mode]))
Transportation cost: supplier=> product MP[Supplier,Product MP, Material,Mode]	THB	(Transportation unit fixed cost: supplier=>product MP [Supplier,Product MP,Mode] +Transportation variable cost: supplier=>product MP [Supplier,Product MP,Mode]) *Material order distribution: supplier=>product MP [Supplier,Product MP,Material,Mode] *Currency depreciation of product MP[Product MP]

Table A-9-2 Material distribution module: supplier $\rightarrow$ component MP

Parameter	**Unit**	**Mathematical equation**
Transportation time: supplier=> component MP[Supplier, Component MP,Mode]	Hours	if then else(SUM(Integer number of roundtrip: supplier=>component MP[Supplier,Component MP, Material!,Mode]) >0, zidz(Distance: supplier=>component MP[Component MP, Supplier],Speed of supplier[Mode]),0)
Production capacity: supplier=> component MP[Supplier, Component MP,Material,Mode]	Kilograms	if then else(Production capacity of supplier[Supplier,Material] >SUM(Material order distribution: supplier=> component MP[Supplier,Component MP!,Material,Mode!]), SUM(Material order distribution: supplier=> component MP[Supplier,Component MP!,Material,Mode!]), Production capacity of supplier[Supplier,Material]) *zidz(Material order distribution: supplier=> component MP[Supplier,Component MP,Material,Mode], SUM(Material order distribution: supplier=> component MP[Supplier,Component MP!,Material,Mode!]))
Full container load: supplier =>component MP [Supplier, Component MP, Material,Mode]	Kilograms	zidz(Production capacity: supplier=>component MP [Supplier,Component MP,Material,Mode], Lotsize: supplier=>component MP[Supplier, Component MP,Material,Mode]) *Material order distribution: supplier=>component MP [Supplier,Component MP,Material,Mode]
Mode EI: supplier=> component MP[Supplier, Component MP,Material,Mode]	Points	Full container load: supplier=>component MP [Supplier,Component MP,Material,Mode] *Distance: supplier=>component MP[Component MP, Supplier]*Mode EI driver[Mode]
Increment of transportation unit cost: supplier=>component MP [Supplier,Component MP,Mode]	THB /(kilogram *kilometre)	Transportation unit cost: supplier=>component MP [Supplier,Component MP,Mode] *Proportion of fuel unit price to transportation unit cost of supplier[Supplier,Mode] *Growth rate of fuel price of supplier[Supplier]
Transportation unit cost: supplier =>component MP[Supplier,	THB /(kilogram	INTEG(Increment of transportation unit cost: supplier=>component MP[Supplier,Component MP,

Component MP,Mode]	*kilometre)	Mode]/TIME STEP,Baseline transportation unit cost: supplier=>component MP[Supplier,Component MP,Mode])
Transportation variable cost: supplier=>component MP [Supplier,Component MP,Mode]	THB /kilogram	Transportation unit cost: supplier=>component MP [Supplier,Component MP,Mode] *Distance: supplier=>component MP[Component MP, Supplier]
Transportation unit fixed cost: supplier=>component MP [Supplier,Component MP,Mode]	THB /kilogram	zidz(Transportation fixed cost: supplier=>component MP [Supplier,Component MP,Mode], SUM(Lotsize: supplier=>component MP [Supplier,Component MP,Material!,Mode]))
Transportation cost: supplier=> component MP[Supplier, Component MP,Material,Mode]	THB	(Transportation unit fixed cost: supplier=>component MP [Supplier,Component MP,Mode] +Transportation variable cost: supplier=>component MP [Supplier,Component MP,Mode]) *Material order distribution: supplier=>component MP [Supplier,Component MP,Material,Mode] *Currency depreciation of component MP[Component MP]

The generic modules of material demand, material procurement, and material distribution generate cost (Table A-9-4), lead time (Table A-9-5), and environmental impact (Table A-9-6) as follows.

Table A-9-4 Cost of material procurement

Parameter	Unit	Mathematical equation
Material cost[Supplier,Material]	THB	SUM(Material cost of component MP[Supplier, Component MP!,Material,Mode!]) +SUM(Material cost of product MP[Supplier,Product MP!,Material,Mode!])
Transportation of supplier [Supplier,Material]	THB	SUM(Transportation cost: supplier=>component MP [Supplier,Component MP!,Material,Mode!]) +SUM(Transportation cost: supplier=>product MP [Supplier,Product MP!,Material,Mode!])
Importation cost of material [Supplier,Material]	THB	SUM(Importation cost: supplier=>component MP [Supplier,Component MP!,Material,Mode!]) +SUM(Importation cost: supplier=>product MP [Supplier,Product MP!,Material,Mode!])
Supplier selection cost[Supplier]	THB	SUM(Supplier selection cost (component MP) [Supplier,Component MP!]) +SUM(Supplier selection cost (product MP)[Supplier, Product MP!])
Total cost of material procurement [Supplier]	THB	SUM(Importation cost of material[Supplier,Material!]) +SUM(Material cost[Supplier,Material!]) +Supplier selection cost[Supplier] +SUM(Transportation of supplier[Supplier,Material!])

Table A-9-5 Lead time of material procurement

Parameter	Unit	Mathematical equation
Lead time by component: supplier=>product MP[Supplier, Product MP,Mode]	Hours	SUM(Preparation time: supplier=>product MP [Supplier,Product MP,Material!,Mode]) +Transportation time: supplier=>product MP [Supplier,Product MP,Mode]
Lead time: supplier=> component MP[Supplier, Component MP]	Hours	SUM(Lead time by component: supplier=>component MP [Supplier,Component MP,Mode!])
Lead time by component: supplier=>component MP [Supplier,Component MP,Mode]	Hours	SUM(Preparation time: supplier=>component MP [Supplier,Component MP,Material!,Mode]) +Transportation time: supplier=>component MP [Supplier,Component MP,Mode]
Lead time: supplier=> component MP[Supplier, Component MP]	Hours	SUM(Lead time by component: supplier=>component MP [Supplier,Component MP,Mode!])

Table A-9-6 Environmental impact of material procurement

Parameter	Unit	Mathematical equation
Total EI: supplier=>product MP [Supplier,Product MP,Material,Mode]	Points	Mode EI: supplier=>product MP[Supplier,Product MP, Material,Mode] +Material EI: supplier=>product MP[Supplier,Product MP, Material,Mode]
Total EI: supplier=> component MP[Supplier, Component MP,Material,Mode]	Points	Mode EI: supplier=>component MP[Supplier, Component MP,Material,Mode] +Material EI: supplier=>component MP[Supplier,Component MP,Material,Mode]
Total EI of material procurement [Supplier]	Points	(SUM(Total EI: supplier=>component MP [Supplier,Component MP!,Material!,Mode!]) +SUM(Total EI: supplier=>product MP[Supplier, Product MP!,Material!,Mode!]))

10 Pareto-optimal function

The three objectives (cost, lead time, and environmental impact) of nine generic modules are formulated as multi-objective function, fuzzy membership function, and Pareto-optimal function as shown in Table A-10.

Table A-10 Pareto-optimal function

Parameter	Unit	Mathematical equation
Service level	Dmnl	VMIN(Service level of component DC[Component!]) *VMIN(Service level of component MP[Component!]) *VMIN(Service level of product MP[Product!]) *VMIN(Service level of supplier[Material!])
Supply chain cost	THB	(SUM(Total cost of product DC[Product DC!]) +SUM(Total cost of product MP[Product MP!]) +SUM(Total cost of component MP[Component MP!]) +SUM(Total cost of component DC[Component DC!]) +SUM(Total cost of material procurement[Supplier!])) /Service level
Supply chain cost per item	THB / item	Supply chain cost/SUM(Integer product volume[Customer!,Product!])
Supplier=>Product MP=>Customer (1) or not (0)	Dmnl	Product MP=>Customer (1) or not (0) *Supplier=>Product MP (1) or not (0)
Lead time: Supplier=>Product MP =>Customer[Product MP]	Hours	(VMAX(Lead time: product MP=>customer[Product MP ,Customer!]) +if then else(VMAX(Lead time: product MP=>customer [Product MP,Customer!])>0,VMAX(Lead time: supplier=>product MP[Supplier!,Product MP]),0)) * Supplier=>Product MP=>Customer (1) or not (0)
Supplier=>Product MP=>Product DC=>Customer (1) or not (0)	Dmnl	Product DC=>Customer (1) or not (0) *Product MP=>Product DC (1) or not (0) *Supplier=>Product MP (1) or not (0)
Lead time: Product MP=> Product DC=>Customer [Product MP,Product DC]	Hours	Lead time: product MP=>product DC[Product MP, Product DC] +if then else(Lead time: product MP=>product DC [Product MP,Product DC]>0,VMAX(Lead time: product DC=>customer[Product DC,Customer!]),0)
Lead time: Supplier=>Product MP =>Product DC=>Customer [Product MP,Product DC]	Hours	(Lead time: Product MP=>Product DC=>Customer [Product MP,Product DC]+if then else(Lead time: Product MP=>Product DC=> Customer[Product MP, Product DC]>0,VMAX(Lead time: supplier=>product MP [Supplier!,Product MP]),0))*Supplier=>Product MP=> Product DC=>Customer (1) or not (0)
Supplier=>Component MP=> Product MP=>Customer (1) or not (0)	Dmnl	Component MP=>Product MP (1) or not (0) *Product MP=>Customer (1) or not (0) *Supplier=>Component MP (1) or not (0)

Lead time: Component MP=> Product MP=>Product DC=> Customer[Component MP, Product MP]	Hours	Lead time: component MP=>product MP [Component MP,Product MP] +if then else(Lead time: component MP=>product MP [Component MP,Product MP]>0,VMAX(Lead time: Product MP=>Product DC=>Customer[Product MP, Product DC!]),0)
Lead time: Supplier=> Component MP=>Product MP=> Customer[Component MP, Product MP]	Hours	(Lead time: Component MP=>Product MP=>Customer [Component MP,Product MP] +if then else(Lead time: Component MP=>Product MP=> Customer[Component MP,Product MP]>0,VMAX(Lead time: supplier=>component MP[Supplier!,Component MP]),0)) *Supplier=>Component MP=>Product MP=>Customer (1) or not (0)
Supplier=>Component MP=> Product MP=>Product DC=> Customer (1) or not (0)	Dmnl	Component MP=>Product MP (1) or not (0) *Product DC=>Customer (1) or not (0) *Product MP=>Product DC (1) or not (0) *Supplier=>Component MP (1) or not (0)
Lead time: Component MP=> Product MP=>Product DC=> Customer[Component MP,Product MP]	Hours	Lead time: component MP=>product MP [Component MP,Product MP] +if then else(Lead time: component MP=>product MP [Component MP,Product MP]>0,VMAX(Lead time: Product MP=>Product DC=>Customer[Product MP, Product DC!]),0)
Lead time: Supplier=> Component MP=>Product MP=> Product DC=>Customer [Component MP,Product MP]	Hours	(Lead time: Component MP=> Product MP=>Product DC=> Customer[Component MP,Product MP] +if then else(Lead time: Component MP=> Product MP=> Product DC=> Customer [Component MP,Product MP]>0, VMAX(Lead time: supplier=>component MP[Supplier!, Component MP]),0))*Supplier=>Component MP=> Product MP=>Product DC=> Customer (1) or not (0)
Supplier=>Component MP=> Component DC=>Product MP=> Customer (1) or not (0)	Dmnl	Component DC=>Product MP (1) or not (0) *Component MP=>Component DC (1) or not (0) *Product MP=>Customer (1) or not (0) *Supplier=>Component MP (1) or not (0)
Lead time: Component DC=> Product MP=>Customer [Component DC,Product MP]	Hours	Lead time: component DC=>product MP[Component DC, Product MP] +if then else(Lead time: component DC=>product MP [Component DC,Product MP]>0,VMAX(Lead time: product MP=>customer[Product MP,Customer!]),0)
Lead time: Component MP=> Component DC=>Product MP=> Customer[Component MP,Component DC]	Hours	Lead time: component MP=>component DC [Component MP,Component DC] +if then else(Lead time: component MP=>component DC [Component MP,Component DC]>0,VMAX(Lead time: Component DC=> Product MP=>Customer[Component DC, Product MP!]),0)
Lead time: Supplier=> Component MP=>Component DC =>Product MP=>Customer [Component MP,Component DC]	Hours	(Lead time: Component MP=> Component DC=>Product MP =>Customer[Component MP, Component DC] +if then else(Lead time: Component MP=> Component DC =>Product MP=> Customer[Component MP,Component DC]>0,VMAX(Lead time: supplier=>component MP [Supplier!,Component MP]),0))*Component MP=> Component DC=>Product MP=> Customer (1) or not (0)
Supplier=>Component MP=> Component DC=>Product MP=> Product DC=>Customer (1) or not (0)	Dmnl	Component DC=>Product MP (1) or not (0) *Component MP=>Component DC (1) or not (0) *Product DC=>Customer (1) or not (0) *Product MP=>Product DC (1) or not (0) *Supplier=>Component MP (1) or not (0)
Lead time: Component DC=> Product MP=>Product DC=> Customer[Component DC, Product MP]	Hours	Lead time: component DC=>product MP[Component DC, Product MP]+if then else(Lead time: component DC=> product MP [Component DC,Product MP]>0,VMAX(Lead time: Product MP=>Product DC=>Customer[Product MP, Product DC!]),0)
Lead time: Component MP=> Component DC=>Product MP=> Product DC=>Customer [Component MP,Component DC]	Hours	Lead time: component MP=>component DC [Component MP,Component DC] +if then else(Lead time: component MP=>component DC [Component MP,Component DC]>0, VMAX(Lead time: Component DC=> Product MP=> Product DC=>Customer[Component DC,Product MP!]),0)

Lead time: Supplier=> Component MP=>Component DC =>Product MP=>Product DC=> Customer[Component MP, Component DC]	Hours	(Lead time: Component MP=> Component DC=>Product MP =>Product DC=>Customer[Component MP,Component DC] +if then else(Lead time: Component MP=> Component DC =>Product MP=> Product DC=>Customer[Component MP, Component DC]>0,VMAX(Lead time: supplier=> component MP[Supplier!,Component MP]),0)) *Supplier=>Component MP=>Component DC=> Product MP=>Product DC=>Customer (1) or not (0)
Supply chain LT	Hours	(VMAX(Lead time: Supplier=>Component MP=> Component DC=>Product MP=>Customer[Component MP!, Component DC!]) +VMAX(Lead time: Supplier=>Component MP=> Component DC=>Product MP=>Product DC=>Customer [Component MP!, Component DC!]) +VMAX(Lead time: Supplier=>Component MP=>Product MP =>Customer[Component MP!,Product MP!]) +VMAX(Lead time: Supplier=>Component MP=>Product MP =>Product DC=>Customer[Component MP!,Product MP!]) +VMAX(Lead time: Supplier=>Product MP=>Customer [Product MP!]) +VMAX(Lead time: Supplier=>Product MP=>Product DC=> Customer[Product MP!, Product DC!])) /Service level
Supply chain EI	Points	(SUM(Total EI of product DC[Product DC!]) +SUM(Total EI of product MP[Product MP!]) +SUM(Total EI of component DC[Component DC!]) +SUM(Total EI of component MP[Component MP!]) +SUM(Total EI of material procurement[Supplier!])) /Service level
Supply chain EI per item	Points / item	Supply chain EI/SUM(Integer product volume[Customer!,Product!])
Multi-objective function[Objective]	-	if then else(Objective=Cost,Supply chain cost per item, if then else(Objective=LT,Supply chain LT, if then else(Objective=EI,Supply chain EI per item,0)))
LB of multi-objective[Objective]	-	if then else(Objective=Cost,LB of cost, if then else(Objective=LT,LB of LT, if then else(Objective=EI,LB of EI,0)))
UB of multi-objective[Objective]	-	if then else(Objective=Cost,UB of cost, if then else(Objective=LT,UB of LT, if then else(Objective=EI,UB of EI,0)))
Fuzzy membership function[Objective]	Dmnl	zidz(UB of multi-objective[Objective]-Multi-objective function[Objective], UB of multi-objective[Objective]-LB of multi-objective[Objective])
Weighted fuzzy membership function[Objective]	Dmnl	zidz(Fuzzy membership function[Objective],Weight of objective[Objective])
Pareto-optimal function with weighted maxmin[Objective]	Dmnl	VMIN(Weighted fuzzy membership function[Objective!])

Note: LT = Lead Time,EI = Environmental Impact, LB = Lower Bound, UB = Upper Bound

11 Optimisation setup

The Pareto-optimal function is optimised through the optimisation setup of Vensim version 5.1d as shown in Table A-11.

Table A-11 Optimisation setup

Command	Input into the command
Type	Policy
Payoff Elements [Variable / Weight]	If supply chain cost is minimised, Multi-objective function [Cost] / -1 If supply chain Lead Time (LT) is minimised, Multi-objective function [LT] / -1 If supply chain Environmental Impact (EI) is minimised, Multi-objective function [EI] / -1 If Pareto-optimal function with weighted maxmin is optimised, Multi-objective function [Pareto-optimal function with weighted maxmin] / 1

Optimiser	Powell
Active parameters	1<=Locational priority of product MP (t=1,...10) [Product MP]<=2 1<=Locational priority of product DC (t=1,...10) [Product DC]<=2 1<=Locational priority of component MP (t=1,...10) [Component MP]<=2 1<=Locational priority of component DC (t=1,...10) [Component DC]<=2 1<=Locational priority of supplier (t=1,...10) [Supplier]<=2 1<=Local mode score of product MP (t=1,...10) [Product,Local mode]<=2 1<=Global mode score of product MP (t=1,...10) [Product,Global mode]<=2 1<=Local mode score of product DC (t=1,...10) [Product,Local mode]<=2 1<=Global mode score of product DC (t=1,...10) [Product,Global mode]<=2 1<=Local mode score of component MP (t=1,...10) [Component,Local mode]<=2 1<=Global mode score of component MP (t=1,...10) [Component,Global mode]<=2 1<=Local mode score of component DC (t=1,...10) [Component,Local mode]<=2 1<=Global mode score of component DC (t=1,...10) [Component,Global mode]<=2 1<=Local mode score of supplier (t=1,...10) [Material,Local mode]<=2 1<=Global mode score of supplier (t=1,...10) [Material,Global mode]<=2 1<=Local mode score of supplier (t=1,...10) [Material,Local mode]<=2 1<=Global mode score of supplier (t=1,...10) [Material,Global mode]<=2 Minimum order quantity of product MP <= Lotsize of product MP(t=1,...10) [Product MP,Product] <= Production capacity of product MP Minimum order quantity of product DC <= Lotsize of product DC (t=1,...10) [Product DC,Product] <= Warehousing capacity of product DC Minimum order quantity of component MP <= Lotsize of component MP (t=1,...10) [Component MP,Component] <= Production capacity of component MP Minimum order quantity of component DC <= Lotsize of component DC (t=1,...10) [Component DC,Component] <= Warehousing capacity of component DC Minimum order quantity of supplier<= Lotsize of supplier (t=1,...10) [Supplier,Material] <= Production capacity of supplier

Note: Local mode can be 16-ton truck, 40-ton truck, or Rail; Global mode can be Air (A) or Sea (S)

APPENDIX B

INPUT PARAMETERS OF CASE STUDY 1

The supply chain networks of cryogenic storage tank manufacturing company are structured with five stages. They include suppliers, component manufacturing plant (component MP), component warehouses (component DCs), product assembling plants (product MPs), and customers as shown in Figure 4-1-1. The values of 1 are consequently input into supplier $\rightarrow$ component MP, component MP $\rightarrow$ component DC, component DC $\rightarrow$ product MP, and product MP $\rightarrow$ customer. They involve two strategic decisions (domains) including designs of facility networks and supply networks as follows.

<u>Domain 1: Facility Network Design (FND)</u>

1 Product demand module

The product demand module requires six input parameters. They include baseline product volume (matrix 1-1) and its growth rate (matrix 1-2), baseline locational selection of product MP (matrix 1-3), distance: product MP $\rightarrow$ customer (matrix 1-4), feasible mode of product MP (matrix 1-5), growth rate of currency depreciation of product MP (matrix 1-6).

Baseline product volume (items)

$$= \begin{bmatrix} 7 & 0 & 0 \\ 0 & 9 & 0 \\ 0 & 5 & 0 \\ 0 & 0 & 52 \end{bmatrix}_{\text{Cutomer x Product}} \qquad (1\text{-}1)$$

Growth rate of product volume (dimensionless)

$$= 0.082 \qquad (1\text{-}2)$$

Baseline locational selection of product MP (dimensionless)

$$= \begin{bmatrix} 1 & 0 \end{bmatrix}_{\text{1 x ProductMP}} \qquad (1\text{-}3)$$

Distance: product MP $\rightarrow$ customer (kilometres)

$$= \begin{bmatrix} 5.0 & 2{,}303.2 & 5.0 & 5.0 \\ 2{,}303.2 & 5.0 & 2{,}303.2 & 2{,}303.2 \end{bmatrix}_{\text{ProductMP x Customer}} \qquad (1\text{-}4)$$

Feasible mode of product MP (dimensionless)

$$= \begin{bmatrix} 0 & 0 & 1 & 0 & 1 \\ 0 & 1 & 1 & 0 & 1 \\ 0 & 1 & 1 & 0 & 1 \end{bmatrix}_{Product \times Mode} \quad (1\text{-}5)$$

Growth rate of currency depreciation of product MP (dimensionless)

$$= \begin{bmatrix} 0.0350 & 0.0162 \end{bmatrix}_{1 \times ProductMP} \quad (1\text{-}6)$$

2 Product manufacturing and warehousing module

The product manufacturing and warehousing module requires nine input parameters. They include production unit time of product MP (matrix 2-1), setup time of product MP (matrix 2-2), baseline energy unit consumption of product MP (matrix 2-3), baseline energy unit price of product MP (matrix 2-4) and its growth rate (matrix 2-5), baseline labour unit cost of component MP (matrix 2-6) and its growth rate (matrix 2-7), environmental impact driver of energy consumption (matrix 2-8), and energy type selection of product MP (matrix 2-9).

Production unit time of product MP (hours per item)

$$= \begin{bmatrix} 238.10 & 210.70 & 70.60 \\ 150.88 & 133.55 & 44.76 \end{bmatrix}_{ProductMP \times Product} \quad (2\text{-}1)$$

Setup time of product MP (hours)

$$= \begin{bmatrix} 19.43 & 17.20 & 17.30 \\ 31.75 & 28.11 & 28.26 \end{bmatrix}_{ProductMP \times Product} \quad (2\text{-}2)$$

Baseline energy unit consumption of product MP (mega joules per item)

$$= \begin{bmatrix} 133{,}402 & 67{,}914 & 3{,}265 \\ 170{,}458 & 86{,}779 & 4{,}172 \end{bmatrix}_{ProductMP \times Product} \quad (2\text{-}3)$$

Baseline energy unit price of product MP (THB per mega joule)

$$= \begin{bmatrix} 0.7833 & 0.7385 \end{bmatrix}_{1 \times ProductMP} \quad (2\text{-}4)$$

Growth rate of energy price of product MP (dimensionless)

$$= \begin{bmatrix} 0.0548 & 0.0893 \end{bmatrix}_{1 \times ProductMP} \quad (2\text{-}5)$$

Baseline labour unit cost of product MP (THB per hour)

$$= \begin{bmatrix} 680.97 & 1{,}428.63 & 1{,}863.11 \\ 3{,}595.54 & 7{,}543.18 & 9{,}837.22 \end{bmatrix}_{ProductMP \times Product} \quad (2\text{-}6)$$

Growth rate of wage rate of product MP (dimensionless)

$$= \begin{bmatrix} 0.1239 & 0.0162 \end{bmatrix}_{1 \times ProductMP} \quad (2\text{-}7)$$

Environmental impact driver of energy consumption (points per mega joule)

$$= \begin{bmatrix} 0.0024 & 0.0029 & 0.0038 & 0.0040 & 0.0047 & 0.0016 & 0.0037 & 0.0050 \end{bmatrix}_{1\,x\,Energy} \tag{2-8}$$

Energy type selection of product MP (dimensionless)

$$= \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}_{Product MP\ x\,Energy} \tag{2-9}$$

3 Product distribution module

The product distribution module requires nine input parameters. They include distance: product MPs $\rightarrow$ customers (matrix 1-4), speed: product MP $\rightarrow$ customer (matrix 3-1), production capacity of product MP (matrix 3-2), environmental impact driver of transportation (matrix 3-3), Bill of Materials (BOM) (matrix 3-4), transportation fixed cost: product MP $\rightarrow$ customer (matrix 3-5), baseline transportation unit cost: product MP $\rightarrow$ customer (matrix 3-6), proportion of fuel unit cost to transportation unit cost of product MP (matrix 3-7), and growth rate of fuel price of product MP (matrix 3-8).

Speed: product MP $\rightarrow$ customer (kilometres per hour)

$$= \begin{bmatrix} 878.5 & 80.0 & 60.0 & 39.0 & 25.5 \end{bmatrix}_{1\,x\,Mode} \tag{3-1}$$

Production capacity of product MP (items)

$$= \begin{bmatrix} 15 & 17 & 52 \\ 15 & 17 & 52 \end{bmatrix}_{Product MP\ x\,Product} \tag{3-2}$$

Environmental impact driver of transportation (points per kilogram-kilometre)

$$= \begin{bmatrix} 7.66e-005 & 1.76e-005 & 8.51e-006 & 1.52e-005 & 8.06e-005 \end{bmatrix}_{1\,x\,Mode} \tag{3-3}$$

BOM (kilograms per item)

$$= \begin{bmatrix} 9.45 & 0 & 0 & 0 & 0 & 0 & 2,482.71 & 8,361.27 & 6,729.02 \\ 6.61 & 0 & 4.40 & 0 & 0 & 0 & 1,065.63 & 3,716.12 & 4,476.11 \\ 0 & 19.4 & 0 & 4.70 & 2.60 & 2.40 & 775.85 & 146.30 & 1,341.41 \end{bmatrix}_{Product\,x\,Material} \tag{3-4}$$

16-ton truck fixed cost: product MP $\rightarrow$ customer (THB)

$$= \begin{bmatrix} 0 & 0 & 6,740 & 6,740 \\ 0 & 6,740 & 0 & 0 \end{bmatrix}_{Product MP\ x\,Customer} \tag{3-5-1}$$

40-ton truck fixed cost: product MP $\rightarrow$ customer (THB)

$$= \begin{bmatrix} 6,520 & 0 & 6,520 & 6,520 \\ 0 & 6,520 & 0 & 0 \end{bmatrix}_{Product MP\ x\,Customer} \tag{3-5-2}$$

Sea fixed cost: product MP $\rightarrow$ customer (THB)

$$= \begin{bmatrix} 0 & 6,000 & 0 & 0 \\ 6,000 & 0 & 6,000 & 6,000 \end{bmatrix}_{Product MP\ x\,Customer} \tag{3-5-3}$$

Baseline 16-ton truck unit cost: product MP $\longrightarrow$ customer (THB per kilogram-kilometre)

$$=\begin{bmatrix}0 & 0 & 0.000913 & 0.000913\\ 0 & 0.002430 & 0 & 0\end{bmatrix}_{ProductMP\ x\ Customer} \quad (3\text{-}6\text{-}1)$$

Baseline 40-ton truck unit cost: product MP $\longrightarrow$ customer (THB per kilogram-kilometre)

$$=\begin{bmatrix}0.000782 & 0 & 0.000782 & 0.000782\\ 0 & 0.002077 & 0 & 0\end{bmatrix}_{ProductMP\ x\ Customer} \quad (3\text{-}6\text{-}2)$$

Baseline sea unit cost: product MP $\longrightarrow$ customer (THB per kilogram-kilometre)

$$=\begin{bmatrix}0 & 1.40e-006 & 0 & 0\\ 3.60e-006 & 0 & 3.60e-006 & 3.60e-006\end{bmatrix}_{ProductMP\ x\ Customer} \quad (3\text{-}6\text{-}3)$$

Proportion of fuel unit cost to transportation unit cost of product MP (dimensionless)

$$=\begin{bmatrix}0.512 & 0.599 & 0.599 & 0.526 & 0.621\\ 0.512 & 0.599 & 0.599 & 0.526 & 0.621\end{bmatrix}_{ProductMP\ x\ Mode} \quad (3\text{-}7)$$

Growth rate of fuel price of product MP (dimensionless)

$$=\begin{bmatrix}0.0322 & 0.0510\end{bmatrix}_{1\ x\ ProductMP} \quad (3\text{-}8)$$

4 Component demand module

The component demand module requires nine input parameters. They include Bill of Components (BOC) (matrix 4-1), baseline locational selection of component MP (matrix 4-2) and component DC (matrix 4-3), distance: component MP $\rightarrow$ component DC (matrix 4-4) and component DC $\rightarrow$ product MP (matrix 4-5), feasible mode of component MP (matrix 4-6) and component DC (matrix 4-7), and growth rate of currency depreciation of component MP (matrix 4-8) and component DC (matrix 4-9).

BOC (dimensionless)

$$=\begin{bmatrix}1 & 0 & 0\\ 0 & 1 & 0\\ 0 & 0 & 1\end{bmatrix}_{Product\ x\ Component} \quad (4\text{-}1)$$

Baseline locational selection of component MP (dimensionless)

$$=\begin{bmatrix}1\end{bmatrix}_{1\ x\ ComponentMP} \quad (4\text{-}2)$$

Baseline locational selection of component DC (dimensionless)

$$=\begin{bmatrix}1 & 0\end{bmatrix}_{1\ x\ ComponentDC} \quad (4\text{-}3)$$

Distance: component MP $\longrightarrow$ component DC (kilometres)

$$=\begin{bmatrix}58.7 & 2{,}303.2\end{bmatrix}_{ComponentMP\ x\ ComponentDC} \quad (4\text{-}4)$$

(4-5)

Distance: component DC $\longrightarrow$ product MP (kilometres)

$$= \begin{bmatrix} 5 & 0 \\ 0 & 5 \end{bmatrix}_{\text{Component DC x Product MP}}$$

Feasible mode of component MP (dimensionless)

$$= \begin{bmatrix} 0 & 0 & 1 & 1 & 1 \\ 0 & 1 & 1 & 1 & 1 \\ 0 & 1 & 1 & 1 & 1 \end{bmatrix}_{\text{Component x Mode}} \tag{4-6}$$

Feasible mode of component DC (dimensionless)

$$= \begin{bmatrix} 0 & 0 & 1 & 0 & 0 \\ 0 & 1 & 1 & 0 & 0 \\ 0 & 1 & 1 & 0 & 0 \end{bmatrix}_{\text{Component x Mode}} \tag{4-7}$$

Currency depreciation of component MP (dimensionless)

$$= \begin{bmatrix} 0.0350 \end{bmatrix}_{\text{1 x Component MP}} \tag{4-8}$$

Currency depreciation of component DC (dimensionless)

$$= \begin{bmatrix} 0.0350 & 0.0162 \end{bmatrix}_{\text{1 x Component DC}} \tag{4-9}$$

5 Component manufacturing and warehousing module

The component manufacturing and warehousing module requires thirteen input parameters. They include production unit time of component MP (matrix 5-1), setup time of component MP (matrix 5-2), warehousing unit time of component DC (matrix 5-3), baseline energy unit consumption of component MP (matrix 5-4) and its improvement rate (matrix 5-5), baseline energy unit price of component MP (matrix 5-6) and its growth rate (matrix 5-7), baseline labour unit cost of component MP (matrix 5-8) and its growth rate (matrix 5-9), baseline labour unit cost of component DC (matrix 5-10) and its growth rate (matrix 5-11), environmental impact driver of energy consumption (matrix 2-9), and energy type of component MP (matrix 5-12) and component DC (matrix 5-13).

Production unit time of component MP (hours per item)

$$= \begin{bmatrix} 555.51 & 491.71 & 164.79 \end{bmatrix}_{\text{Component MP x Component}} \tag{5-1}$$

Setup time of component MP (hours)

$$= \begin{bmatrix} 45.35 & 40.14 & 40.36 \end{bmatrix}_{\text{Component MP x Component}} \tag{5-2}$$

Warehousing unit time of component DC (hours per item)

$$=\begin{bmatrix}24 & 12 & 4\\24 & 12 & 4\end{bmatrix}_{\text{Component DC x Component}} \tag{5-3}$$

Baseline energy unit consumption of component MP (mega joules per item)

$$=\begin{bmatrix}311{,}272 & 158{,}466 & 7{,}619\end{bmatrix}_{\text{Component MP x Component}} \tag{5-4}$$

Baseline energy unit price of component MP (THB per mega joule)

$$=\begin{bmatrix}0.7833\end{bmatrix}_{\text{1 x Component MP}} \tag{5-6}$$

Growth rate of energy price of component MP (dimensionless)

$$=\begin{bmatrix}0.0548\end{bmatrix}_{\text{1 x Component MP}} \tag{5-7}$$

Baseline labour unit cost of component MP (THB per mega joule)

$$=\begin{bmatrix}537.68 & 607.19 & 1{,}809.38\end{bmatrix}_{\text{Component MP x Component}} \tag{5-8}$$

Growth rate of labour cost of component MP (dimensionless)

$$=\begin{bmatrix}0.1239\end{bmatrix}_{\text{1 x Component MP}} \tag{5-9}$$

Baseline labour unit cost of component DC (THB per mega joule)

$$=\begin{bmatrix}160.65 & 107.10 & 53.55\\848.23 & 565.49 & 282.74\end{bmatrix}_{\text{Component DC x Component}} \tag{5-10}$$

Growth rate of labour cost of component DC (dimensionless)

$$=\begin{bmatrix}0.1239 & 0.0162\end{bmatrix}_{\text{1 x Component DC}} \tag{5-11}$$

Energy type selection of component MP (dimensionless)

$$=\begin{bmatrix}1 & 0 & 0 & 0 & 0 & 0 & 0 & 0\end{bmatrix}_{\text{Component MP x Energy}} \tag{5-12}$$

Energy type selection of component DC (dimensionless)

$$=\begin{bmatrix}1 & 0 & 0 & 0 & 0 & 0 & 0 & 0\\1 & 0 & 0 & 0 & 0 & 0 & 0 & 0\end{bmatrix}_{\text{Component DC x Energy}} \tag{5-13}$$

6 Component distribution module

The component distribution module requires fifteen input parameters. They include environmental impact driver of transportation (matrix 3-3), distance: component MP $\rightarrow$ component DC (matrix 4-4) and component DC $\rightarrow$ product MP (matrix 4-5), speed: component MP $\rightarrow$ component DC (matrix 6-1) and component DC $\rightarrow$ product MP (matrix 6-2), production capacity of component MP (matrix 6-3) and component DC (matrix 6-4), transportation fixed cost: component MP $\rightarrow$ component DC (matrix 6-5) and component DC $\rightarrow$ product MP (matrix 6-6), baseline transportation unit cost: component MP $\rightarrow$ component DC (matrix 6-7) and component DC $\rightarrow$ product MP (matrix 6-8), proportion of fuel unit cost to transportation unit cost of component MP (matrix 6-9) and component DC (matrix 6-10), and growth rate of fuel price of component MP (matrix 6-11) and component DC (matrix 6-12).

Speed: component MP $\rightarrow$ component DC (kilometres per hour)

$$= \begin{bmatrix} 878.5 & 80.0 & 60.0 & 39.0 & 25.5 \end{bmatrix}_{1 \text{ x Mode}} \tag{6-1}$$

Speed: component DC $\rightarrow$ product MP (kilometres per hour)

$$= \begin{bmatrix} 878.5 & 80.0 & 60.0 & 39.0 & 25.5 \end{bmatrix}_{1 \text{ x Mode}} \tag{6-2}$$

Production capacity of component MP (items)

$$= \begin{bmatrix} 15 & 17 & 52 \end{bmatrix}_{\text{Component MP x Component}} \tag{6-3}$$

Production capacity of component DC (items)

$$= \begin{bmatrix} 15 & 17 & 52 \\ 15 & 17 & 52 \end{bmatrix}_{\text{Component DC x Component}} \tag{6-4}$$

16-ton truck fixed cost: component MP $\rightarrow$ component DC (THB)

$$= \begin{bmatrix} 6{,}740 & 0 \end{bmatrix}_{\text{Component MP x Component DC}} \tag{6-5-1}$$

40-ton truck fixed cost: component MP $\rightarrow$ component DC (THB)

$$= \begin{bmatrix} 6{,}520 & 0 \end{bmatrix}_{\text{Component MP x Component DC}} \tag{6-5-2}$$

Rail fixed cost: component MP $\rightarrow$ component DC (THB)

$$= \begin{bmatrix} 4{,}000 & 0 \end{bmatrix}_{\text{Component MP x Component DC}} \tag{6-5-3}$$

Sea fixed cost: component MP $\rightarrow$ component DC (THB)

$$= \begin{bmatrix} 0 & 6{,}000 \end{bmatrix}_{\text{Component MP x Component DC}} \tag{6-5-4}$$

16-ton truck fixed cost: component DC $\rightarrow$ product MP (THB)

$$= \begin{bmatrix} 6{,}740 & 0 \\ 0 & 6{,}740 \end{bmatrix}_{\text{Component DC x Product MP}} \tag{6-6-1}$$

40-ton truck fixed cost: component DC $\rightarrow$ product MP (THB)

$$= \begin{bmatrix} 6{,}520 & 0 \\ 0 & 6{,}520 \end{bmatrix}_{\text{Component DC x Product MP}} \tag{6-6-2}$$

Baseline 16-ton truck unit cost: component MP $\rightarrow$ component DC (THB per kilogram-kilometre)

$$= \begin{bmatrix} 0.000913 & 0 \end{bmatrix}_{\text{Component MP x Component DC}} \tag{6-7-1}$$

Baseline 40-ton truck unit cost: component MP $\rightarrow$ component DC (THB per kilogram-kilometre)

$$= \begin{bmatrix} 0.0007818 & 0 \end{bmatrix}_{\text{Component MP x Component DC}} \tag{6-7-2}$$

Baseline rail unit cost: component MP $\rightarrow$ component DC (THB per kilogram-kilometre)

$$= \begin{bmatrix} 0.0002304 & 0 \end{bmatrix}_{\text{Component MP x Component DC}} \tag{6-7-3}$$

Baseline sea unit cost: component MP $\rightarrow$ component DC (THB per kilogram-kilometre)

$$= \begin{bmatrix} 0 & 1.40e-006 \end{bmatrix}_{\text{Component MP x Component DC}} \quad (6\text{-}7\text{-}4)$$

Baseline 16-ton truck unit cost: component DC $\rightarrow$ product MP (THB per kilogram-kilometre)

$$= \begin{bmatrix} 0.000913 & 0 \\ 0 & 0.002426 \end{bmatrix}_{\text{Component DC x Product MP}} \quad (6\text{-}8\text{-}1)$$

Baseline 40-ton truck unit cost: component DC $\rightarrow$ product MP (THB per kilogram-kilometre)

$$= \begin{bmatrix} 0.0007818 & 0 \\ 0 & 0.0020774 \end{bmatrix}_{\text{Component DC x Product MP}} \quad (6\text{-}8\text{-}2)$$

Proportion of fuel unit cost to transportation unit cost of component MP (dimensionless)

$$= \begin{bmatrix} 0.512 & 0.599 & 0.599 & 0.526 & 0.621 \end{bmatrix}_{\text{Component MP x Mode}} \quad (6\text{-}9)$$

Proportion of fuel unit cost to transportation unit cost of component DC (dimensionless)

$$= \begin{bmatrix} 0.512 & 0.599 & 0.599 & 0.526 & 0.621 \end{bmatrix}_{\text{Component DC x Mode}} \quad (6\text{-}10)$$

Growth rate of fuel price of component MP (dimensionless)

$$= \begin{bmatrix} 0.0322 & 0 \end{bmatrix}_{\text{1 x Component MP}} \quad (6\text{-}11)$$

Growth rate of fuel price of component DC (dimensionless)

$$= \begin{bmatrix} 0.0322 & 0.0510 \end{bmatrix}_{\text{1 x Component DC}} \quad (6\text{-}12)$$

Domain 2: Supply Network Design (SND)

7 Material demand module

The material demand module requires four input parameters. They include growth rate of currency depreciation of component MP (matrix 4-8), baseline supplier selection (matrix 7-1), distance: supplier $\rightarrow$ component MP (matrix 7-2), and feasible mode of supplier (matrix 7-3).

Baseline supplier selection (dimensionless)

$$= \begin{bmatrix} 1 & 0 & 1 & 0 & 1 & 0 & 1 & 1 & 0 & 0 & 0 & 0 \end{bmatrix}_{\text{1 x Supplier}} \quad (7\text{-}1)$$

Distance: supplier $\rightarrow$ component MP (kilometres)

$$= \begin{bmatrix} 13{,}739.9 & 8{,}835.5 & 17.4 & 8{,}924.1 & 45.1 & 51.1 & 42.3 & 50.0 & 35.1 & 47.6 & 30.4 & 40.4 \end{bmatrix}_{\text{Component MP x Supplier}} \quad (7\text{-}2)$$

Feasible mode of supplier (dimensionless)

$$= \begin{bmatrix} 0 & 1 & 1 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 & 1 & 1 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 1 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}_{\text{Mode x Material}} \quad (7\text{-}3)$$

8 Material procurement module

The material procurement module requires three input parameters. They include growth rate of currency depreciation of supplier (matrix 8-1), material unit price (matrix 8-2), and environmental impact driver of material extraction (matrix 8-3).

Growth rate of currency depreciation of supplier (dimensionless)

$$= \begin{bmatrix} 0 & 0.0825 & 0.0350 & 0.0825 & 0.0350 & 0.0350 & 0.0350 & 0.0350 & 0.0350 & 0.0350 & 0.0350 & 0.0350 \end{bmatrix}_{1 \times \text{Supplier}} \quad (8\text{-}1)$$

Material unit price (THB per kilogram)

$$= \begin{bmatrix} 12{,}944.7 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 2{,}550.1 & 5{,}096.6 & 2{,}490.7 & 3{,}118.6 & 0 & 0 & 0 & 0 \\ 0 & 3{,}507.7 & 7{,}010.5 & 3{,}426.0 & 4{,}289.6 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 3{,}928.9 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 5{,}404.2 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 3.82 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 3.78 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 118.61 & 28.12 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 117.42 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 117.43 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 28.40 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 28.11 \end{bmatrix}_{\text{Supplier} \times \text{Material}} \quad (8\text{-}2)$$

Environmental impact driver of material extraction (points per kilogram)

$$= \begin{bmatrix} 0.051 & 0.128 & 0.128 & 2.197 & 2.197 & 0.128 & 0.059 & 0.128 & 0.059 \end{bmatrix}_{1 \times \text{Material}} \quad (8\text{-}3)$$

9 Material distribution module

The material distribution module requires eight input parameters. They include environmental impact driver of transportation (matrix 3-3), distance: supplier $\rightarrow$ component MP (matrix 7-2), speed: supplier $\rightarrow$ component MP (matrix 9-1), production capacity of supplier (matrix 9-2), transportation fixed cost: supplier $\rightarrow$ component MP (matrix 9-3), baseline transportation unit cost: supplier $\rightarrow$ component MP (matrix 9-4), proportion of fuel unit cost to transportation unit cost of supplier (matrix 9-5), and growth rate of fuel price of supplier (matrix 9-6).

Speed: supplier $\rightarrow$ component MP (kilometres per hour)

$$= \begin{bmatrix} 878.5 & 80.0 & 60.0 & 39.0 & 25.5 \end{bmatrix}_{1 \times \text{Mode}} \quad (9\text{-}1)$$

Production capacity of supplier (kilograms)

$$= \begin{bmatrix} 48{,}000 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 48{,}000 & 48{,}000 & 48{,}000 & 48{,}000 & 0 & 0 & 0 & 0 \\ 0 & 48{,}000 & 48{,}000 & 48{,}000 & 48{,}000 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 48{,}000 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 48{,}000 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 48{,}000 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 48{,}000 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 48{,}000 & 48{,}000 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 48{,}000 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 48{,}000 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 48{,}000 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 48{,}000 \end{bmatrix}_{\text{Supplier x Material}} \quad (9\text{-}2)$$

Air fixed cost: supplier $\rightarrow$ component MP (THB)

$$= [4{,}600 \quad 4{,}400 \quad 0 \quad 4{,}400 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0]_{\text{Component MP x Supplier}} \quad (9\text{-}3\text{-}1)$$

16-ton truck fixed cost: supplier $\rightarrow$ component MP (THB)

$$= [0 \quad 0 \quad 6{,}740 \quad 0 \quad 6{,}740 \quad 6{,}740 \quad 6{,}740 \quad 6{,}740 \quad 6{,}740 \quad 6{,}740 \quad 6{,}740 \quad 6{,}740]_{\text{Component MP x Supplier}} \quad (9\text{-}3\text{-}2)$$

40-ton truck fixed cost: supplier $\rightarrow$ component MP (THB)

$$= [0 \quad 0 \quad 6{,}520 \quad 0 \quad 6{,}520 \quad 6{,}520 \quad 6{,}520 \quad 6{,}520 \quad 6{,}520 \quad 6{,}520 \quad 6{,}520 \quad 6{,}520]_{\text{Component MP x Supplier}} \quad (9\text{-}3\text{-}3)$$

Sea fixed cost: supplier $\rightarrow$ component MP (THB)

$$= [6{,}000 \quad 6{,}000 \quad 0 \quad 6{,}000 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0]_{\text{Component MP x Supplier}} \quad (9\text{-}3\text{-}4)$$

Baseline air unit cost: supplier $\rightarrow$ component MP (THB per kilogram-kilometre)

$$= [0.0157 \quad 0.0186 \quad 0 \quad 0.0184 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0]_{\text{Component MP x Supplier}} \quad (9\text{-}4\text{-}1)$$

Baseline 16-ton truck unit cost: supplier $\rightarrow$ component MP (THB per kilogram-kilometre)

$$= 0.000913 \quad (9\text{-}4\text{-}2)$$

Baseline 40-ton truck unit cost: supplier $\rightarrow$ component MP (THB per kilogram-kilometre)

$$= 0.0007818 \quad (9\text{-}4\text{-}3)$$

Baseline sea unit cost: supplier $\rightarrow$ component MP (THB per kilogram-kilometre)

$$= [4.70e\text{-}007 \quad 3.44e\text{-}007 \quad 0 \quad 3.44e\text{-}007 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0]_{\text{Component MP x Supplier}} \quad (9\text{-}4\text{-}4)$$

Proportion of fuel unit cost to transportation unit cost of supplier (dimensionless)

$$= [0.512 \quad 0.599 \quad 0.599 \quad 0.526 \quad 0.621]_{\text{Supplier x Mode}} \quad (9\text{-}5)$$

Growth rate of fuel price of supplier (dimensionless)

$$= [0.063 \quad 0.132 \quad 0.032 \quad 0.132 \quad 0.032 \quad 0.032 \quad 0.032 \quad 0.032 \quad 0.032 \quad 0.032 \quad 0.032 \quad 0.032]_{\text{1 x Supplier}} \quad (9\text{-}6)$$

10 Optimisation setup

The optimisation setup requires eight input parameters. They include production capacity of product MP (matrix 3-2), production capacity of component MP (matrix 6-3), warehousing capacity of component DC (matrix 6-4), production capacity of supplier (matrix 9-2), minimum order quantity of product MP (matrix 10-1), minimum order quantity of component MP (matrix 10-2), minimum order quantity of component DC (matrix 10-3), and minimum order quantity of supplier (matrix 10-4).

Minimum order quantity of product MP (items)

$$= \begin{bmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \end{bmatrix}_{ProductMP \times Product} \tag{10-1}$$

Minimum order quantity of component MP (items)

$$= \begin{bmatrix} 1 & 1 & 1 \end{bmatrix}_{ComponentMP \times Component} \tag{10-2}$$

Minimum order quantity of component DC (items)

$$= \begin{bmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \end{bmatrix}_{ComponentDC \times Component} \tag{10-3}$$

Minimum order quantity of supplier (kilograms)

$$= \begin{bmatrix} 12,000 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 12,000 & 12,000 & 12,000 & 12,000 & 0 & 0 & 0 & 0 \\ 0 & 12,000 & 12,000 & 12,000 & 12,000 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 12,000 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 12,000 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 12,000 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 12,000 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 12,000 & 12,000 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 12,000 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 12,000 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 12,000 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 12,000 \end{bmatrix}_{Supplier \times Material} \tag{10-4}$$

APPENDIX C

FORMAL TESTS OF CASE STUDY 1

Formal tests are conducted to validate the individual Decision Support System (DSS) for Supply Chain Network Design (SCND) of cryogenic storage tank manufacturing company. They include: (1) structure confirmation, (2) parameter confirmation, (3) dimensional consistency, and (4) extreme-condition tests. These tests are demonstrated with the baseline system of cryogenic storage tank manufacturing company over the three planning years in case that the product assembling (product MP) in Thailand is selected for making and delivering the 2-nd product model to Taiwanese customers by sea mode.

The structure- and parameter-confirmation along with dimensional consistency is successfully tested as shown in Table C-1. The successful test of extreme-condition is presented in Tables C-2 and C-3. The three tables shows parameters (column 1), their dimensions (column 2), their mathematical equations (column 3), and their values over the three planning years (columns 4 to 6).

Table C-1 reveals that the parameter values do not contradict the structure (causal loop diagrams) of the individual DSS. Moreover, the parameter values are identical to those generated from the individual DSS. Furthermore, the dimensions of right- and left-hand sides of each mathematical equation are consistent.

Table C-1 Structure- and parameter-confirmation, and dimensional consistency tests

Parameter	Dimension	Mathematical equation	Year		
			2011	2012	2013
Growth rate of product volume	%	Constant	8.2%	8.2%	8.2%
Increment of product volume (t)	Items	Product volume (t-1) x Growth rate of product volume	0	9 x 8.2% = 0.74	10 x 8.2% = 0.82
Product volume (t)	Items	INTEG(Increment of product volume (t), Baseline product volume)	9 + 0 = 9	9 + 0.74 = 9.74	10 + 0.82 = 10.82
Integer product volume (t)	Items	if then else (integer(Product volume (t)) = Product volume (t), Product volume (t), integer(Product volume (t) + 1)	9	10	11
Locational selection of product MP (t, Thailand)	Dmnl	Binary variable for locational selection of product MP (t, Thailand)	1	1	1
Distance: product MP=>customer	Kilometers	Constant	2,303.2	2,303.2	2,303.2
Product order allocation: customer=>product MP (t, Thailand)	Items	Integer product volume (t) x Locational selection of product MP (t, Thailand) x zidz(Distance: product MP=> customer, Distance: product MP=> customer)	9 x 1 x (2,303.2 / 2,303.2) = 9	10 x 1 x (2,303.2 / 2,303.2) = 10	11 x 1 x (2,303.2 / 2,303.2) = 11

Global mode selection of product MP (t, Sea)	Dmnl	Constant (Air, Sea=1 and others=0)	1	1	1
Local mode selection of product MP (t, Sea)	Dmnl	Constant (T16, T40, Rail=1 and others=0)	0	0	0
Feasible mode of product MP (t, Sea)	Dmnl	Constant (T16, T40, Sea=1 and others=0)	1	1	1
Mode selection: product MP=>customer (t, Sea)	Dmnl	if then else(Product order allocation: customer=>product MP (t) > 0, if then else(Distance: product MP=>customer (t) > 1000, Global mode selection of product MP (t, Sea), Local mode selection of product MP (t, Sea)) x zidz(Feasible mode of product MP (t, Sea), Feasible mode of product MP (t, Sea)),0)	1 x (1 / 1) = 1	1 x (1 / 1) = 1	1 x (1 / 1) = 1
Product order distribution: product MP=>customer (t, Thailand, Sea)	Items	Product order allocation: customer=> product MP (t, Thailand) x Mode selection: product MP=>customer (t, Sea)	9 x 1 x 1 = 9	10 x 1 x 1 = 10	10 x 1 x 1 = 10
Lotsize of product MP (t)	Items	Constant	1	1	1
Lotsize: product MP=>customer (t, Thailand, Sea)	Items	if then else(Lotsize of product MP (t) >Product order allocation: customer=> product MP (t, Thailand, Sea), Product order allocation: customer=>product MP (t, Thailand, Sea), Lotsize of product MP (t)) x zidz(Product order allocation: customer=> product MP (t, Thailand, Sea), Product order allocation: customer=>product MP (t, Thailand, Sea)) x Mode selection: product MP=>customer (t, Sea)	1 x (9 / 9) x 1 = 1	1 x (10 / 10) x 1 = 1	1 x (11 / 11) x 1 = 1
Integer lotsize: product MP=>customer (t, Thailand, Sea)	Items	if then else(Lotsize: product MP=> customer (t, Thailand, Sea) - integer(Lotsize: product MP=> customer (t, Thailand, Sea)) < 0.01, Lotsize: product MP=>customer (t, Thailand, Sea),integer(Lotsize: Product MP=>customer(t, Thailand, Sea))+1)	1	1	1
Number of roundtrip: product MP=>customer (t, Thailand, Sea)	Dmnl	zidz(Product order distribution: product MP=>customer (t, Thailand, Sea), Integer lotsize: product MP=> customer (t, Thailand, Sea))	9 / 1 = 9	10 / 1 = 10	11 / 1 = 11
Integer number of roundtrip: product MP=>customer (t, Thailand, Sea)	Dmnl	if then else(Number of roundtrip: product MP=>customer (t, Thailand, Sea) - integer(Number of roundtrip: product MP=>customer (t, Thailand, Sea))< 0.01,Number of roundtrip: product MP=>customer (t, Thailand, Sea), integer(Number of roundtrip: product MP=>customer (t, Thailand, Sea))+1)	9	10	11
Total product order distribution: product MP=>customer (t, Thailand, Sea)	Items	Integer lotsize: product MP=>customer (t, Thailand, Sea) x Integer number of roundtrip: product MP=>customer (t, Thailand, Sea)	1 x 9 = 9	1 x 10 = 10	1 x 11 = 11
Service level: product MP=>customer (t)	%	if then else(zidz(SUM(Total product order distribution: product MP=> customer(t, Thailand!, Sea!)), Integer product volume (t)) > 1,1, zidz(SUM(Total product order distribution: product MP=>customer (t, Thailand!, Sea!)),Integer product volume (t))	9 / 9 = 100%	10 / 10 = 100%	10 / 10 = 100%
Startup of product MP (t, Thailand)	Dmnl	if then else(SUM(Product order distribution: product MP=>customer (t, Thailand, Sea!))> 0:AND::NOT:Binary variable for locational selection of product MP (t, Thailand),1, 0)	0	0	0

Shutdown of product MP (t, Thailand)	Dmnl	if then else(SUM(Product order distribution: product MP=>customer (t, Thailand, Sea!))= 0:AND:Binary variable for locational selection of product MP (t, Thailand),1,0)	0	0	0
Binary variable for locational selection of product MP (t, Thailand)	Dmnl	INTEG((Startup of product MP (t, Thailand) - Shutdown of product MP (t, Thailand)), Baseline locational selection of product MP (t, Thailand))	0 – 0 + 1 = 1	0 – 0 + 1 = 1	0 – 0 + 1 = 1
Growth rate of currency depreciation of product MP (Thailand)	%	Constant	3.5%	3.5%	3.5%
Increment of currency depreciation of product MP (t, Thailand)	Dmnl	Currency depreciation of product MP (t-1, Thailand) x Growth rate of currency depreciation of product MP (Thailand)	0	1 x 3.5% = 0.035	1.035 x 3.5% = 0.036
Currency depreciation of product MP (t, Thailand)	Dmnl	INTEG(Increment of currency depreciation of product MP (t, Thailand), Baseline currency depreciation of product MP (t, Thailand))	1 + 0 = 1	1 + 0.035 = 1.035	1.035 + 0.036 = 1.071
Shutdown cost of product MP(t, Thailand)	THB	Constant	0	0	0
Startup cost of product MP(t, Thailand)	THB	Constant	0	0	0
Locational selection cost of product MP (t, Thailand)	THB	((Shutdown of product MP (t, Thailand) x Shutdown cost of product MP (t, Thailand)) + (Startup of product MP (t, Thailand) x Startup cost of product MP (t, Thailand))) x Currency depreciation of product MP (t, Thailand)	((0 x 0) + (0 x 0)) x 1 = 0	((0 x 0) + (0 x 0)) x 1.035 = 0	((0 x 0) + (0 x 0)) x 1.071 = 0

Table C-2 reveals that the system outputs correspond with knowledge of the real system when the value of 0 (zero) is assigned to the lot-size of product MP in Thailand. It causes impossible number of roundtrips and zero service level because product orders are not distributed from product MP in Thailand to customers.

Table C-2 Direct extreme-condition test (Lot-size of product MP = 0)

Parameter	Dimension	Mathematical equation	Year		
			2011	2012	2013
Lotsize of product MP (t)	Items	Constant	0	0	0
Lotsize: product MP=>customer (t, Thailand, Sea)	Items	if then else(Lotsize of product MP (t) >Product order allocation: customer=> product MP (t, Thailand, Sea), Product order allocation: customer=>product MP (t, Thailand, Sea), Lotsize of product MP (t)) x zidz(Product order allocation: customer=> product MP (t, Thailand, Sea), Product order allocation: customer=>product MP (t, Thailand, Sea)) x Mode selection: product MP=> customer (t, Sea)	0 x (9 / 9) x 1 = 0	0 x (10 / 10) x 1 = 0	0 x (11 / 11) x 1 = 0

Integer lotsize: product MP=>customer (t, Thailand, Sea)	Items	if then else(Lotsize: product MP=> customer (t, Thailand, Sea) - integer(Lotsize: product MP=>customer (t, Thailand, Sea)) < 0.01, Lotsize: product MP=>customer (t, Thailand, Sea),integer(Lotsize: product MP=> customer (t, Thailand, Sea))+1)	0	0	0
Number of roundtrip: product MP=>customer (t, Thailand, Sea)	Dmnl	zidz(Product order distribution: product MP=>customer (t, Thailand, Sea), Integer lotsize: product MP=> customer (t, Thailand, Sea))	zidz(9, 0) = 0	zidz(10, 0) = 0	zidz(11, 0) = 0
Integer number of roundtrip: product MP=>customer (t, Thailand, Sea)	Dmnl	if then else(Number of roundtrip: product MP=>customer (t, Thailand, Sea) - integer(Number of roundtrip: product MP=>customer (t, Thailand, Sea))< 0.01,Number of roundtrip: product MP=>customer (t, Thailand, Sea), integer(Number of roundtrip: product MP=>customer (t, Thailand, Sea))+1)	0	0	0
Total product order distribution: product MP=>customer (t, Thailand, Sea)	Items	Integer lotsize: product MP=>customer (t, Thailand, Sea) x Integer number of roundtrip: product MP=>customer (t, Thailand, Sea)	0 x 0 = 0	0 x 0 = 0	0 x 0 = 0
Service level: product MP=>customer (t)	%	if then else(zidz(SUM(Total product order distribution: product MP=>customer (t, Thailand!, Sea!)), Integer product volume (t)) > 1,1, zidz(SUM(Total product order distribution: product MP=>customer (t, Thailand!, Sea!)),Integer product volume (t))	0 / 9 = 0%	0 / 10 = 0%	0 / 11 = 0%

Table C-3 reveals that the system outputs correspond with knowledge of the real system when the air mode is assigned to the mode selection of product MP in Thailand. It causes impossible number of roundtrips and zero service level because of the infeasible air mode. It cannot distribute product order from product MP in Thailand to customers.

Table C-3 Direct extreme-condition test (Mode selection of product MP = Air)

Parameter	Dimension	Mathematical equation	Year		
Global mode selection of product MP (t, Air)	Dmnl	Constant (Air, Sea=1 and others=0)	1	1	1
Local mode selection of product MP (t, Air)	Dmnl	Constant (T16, T40, Rail=1 and others=0)	0	0	0
Feasible mode of product MP (t, Air)	Dmnl	Constant (T16, T40, Sea=1 and others=0)	0	0	0
Mode selection: product MP=>customer (t, Air)	Dmnl	if then else(Product order allocation: customer=>product MP (t) > 0, if then else(Distance: product MP=>customer (t) > 1000, Global mode selection of product MP (t, Air), Local mode selection of product MP (t, Air)) x zidz(Feasible mode of product MP (t, Air), Feasible mode of product MP (t, Air)),0)	zidz(0, 0) x 1 = 0	zidz(0, 0) x 1 = 0	zidz(0, 0) x 1 = 0
Product order distribution: product MP=>customer (t, Thailand, Air)	Items	Product order allocation: customer=> product MP (t, Thailand) x Mode selection: product MP=>customer (t, Air)	9 x 1 x 0 = 0	10 x 1 x 0 = 0	10 x 1 x 0 = 0
Lotsize of product MP (t)	Items	Constant	1	1	1

Lotsize: product MP=>customer (t, Thailand, Air)	Items	if then else(Lotsize of product MP (t) >Product order allocation: customer=> product MP (t, Thailand, Air), Product order allocation: customer=>product MP (t, Thailand, Air), Lotsize of product MP (t)) x zidz(Product order allocation: customer=> product MP (t, Thailand, Air), Product order allocation: customer=>product MP (t, Thailand, Air)) x Mode selection: product MP =>customer (t, Air)	1 x (9 / 9) x 0 = 0	1 x (10 / 10) x 0 = 0	1 x (11 / 11) x 0 = 0
Integer lotsize: product MP=>customer (t, Thailand, Air)	Items	if then else(Lotsize: product MP=> customer (t, Thailand, Air) - integer(Lotsize: product MP=>customer (t, Thailand, Air)) < 0.01, Lotsize: product MP=>customer (t, Thailand, Air),integer(Lotsize: product MP=>customer (t, Thailand, Air))+1)	0	0	0
Number of roundtrip: product MP=>customer (t, Thailand, Air)	Dmnl	zidz(Product order distribution: product MP =>customer (t, Thailand, Air), Integer lotsize: product MP=> customer (t, Thailand, Air))	zidz(0, 0) = 0	zidz(0, 0) = 0	zidz(0, 0) = 0
Integer number of roundtrip: product MP=>customer (t, Thailand, Air)	Dmnl	if then else(Number of roundtrip: product MP=>customer (t, Thailand, Air) - integer(Number of roundtrip: product MP=>customer (t, Thailand, Air)) < 0.01, Number of roundtrip: product MP=>customer (t, Thailand, Air), integer(Number of roundtrip: product MP=>customer (t, Thailand, Air))+1)	0	0	0
Total product order distribution: product MP=>customer (t, Thailand, Air)	Items	Integer lotsize: product MP=>customer (t, Thailand, Air) x Integer number of roundtrip: product MP=>customer (t, Thailand, Air)	0 x 0 = 0	0 x 0 = 0	0 x 0 = 0
Service level: product MP=>customer (t)	%	if then else(zidz(SUM(Total product order distribution: product MP=>customer (t, Thailand!, Air!)), Integer product volume (t)) > 1,1, zidz(SUM(Total product order distribution: product MP=>customer (t, Thailand!, Air!)),Integer product volume (t))	0 / 9 = 0%	0 / 10 = 0%	0 / 11 = 0%

APPENDIX D
INPUT PARAMETERS OF CASE STUDY 2

The supply chain networks of automotive part manufacturing company are structured with three stages. They include suppliers, product manufacturing plants (product MPs), and customers as shown in Figure 4-2-1. The values of 1 are consequently input into supplier$\rightarrow$product MP and product MP$\rightarrow$customer. They involve two strategic decisions (domains) including designs of facility networks and supply networks as follows.

Domain 1: Facility Network Design (FND)

1 Product demand module

The product demand module requires six input parameters. They include baseline product volume (matrix 1-1) and its growth rate (matrix 1-2), baseline locational selection of product MP (matrix 1-3), distance: product MP$\rightarrow$customer (matrix 1-4), feasible mode of product MP (matrix 1-5), growth rate of currency depreciation of product MP (matrix 1-6).

Baseline product volume (items)

$$= \begin{bmatrix} 150{,}000 & 0 & 0 & 0 & 150{,}000 & 0 \\ 60{,}000 & 0 & 0 & 0 & 0 & 0 \\ 0 & 170{,}000 & 0 & 170{,}000 & 0 & 0 \\ 0 & 0 & 100{,}000 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 100{,}000 \end{bmatrix}_{\text{Cutomer x Product}} \tag{1-1}$$

Growth rate of product volume (dimensionless)

$$= 0.109 \tag{1-2}$$

Baseline locational selection of product MP (dimensionless)

$$= [1]_{\text{1 x Product MP}} \tag{1-3}$$

Distance: product MP $\longrightarrow$ customer (kilometres)

$$= [5.0 \quad 4{,}629.6 \quad 52.2 \quad 2{,}442.6 \quad 1{,}249.2]_{\text{Product MP x Customer}} \tag{1-4}$$

Feasible mode of product MP (dimensionless)

$$= \begin{bmatrix} 1 & 0 & 1 & 0 & 0 & 1 \\ 1 & 1 & 0 & 1 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 1 & 0 & 1 & 1 & 1 \\ 1 & 0 & 1 & 0 & 0 & 0 \end{bmatrix}_{\text{Mode x Product}} \tag{1-5}$$

Growth rate of currency depreciation of product MP (dimensionless)

$$= \left[0.0350\right]_{1 \times ProductMP} \tag{1-6}$$

2 Product manufacturing module

The product manufacturing and warehousing module requires nine input parameters. They include production unit time of product MP (matrix 2-1), setup time of product MP (matrix 2-2), baseline energy unit consumption of product MP (matrix 2-3), improvement rate of energy consumption of product MP (matrix 2-4), baseline energy unit price of product MP (matrix 2-5) and its growth rate (matrix 2-6), baseline labour unit cost of component MP (matrix 2-7) and its growth rate (matrix 2-8), environmental impact driver of energy consumption (matrix 2-9), and energy type selection of product MP (matrix 2-10).

Production unit time of product MP (hours per item)

$$= \left[0.0174 \quad 0.0179 \quad 0.0169 \quad 0.0270 \quad 0.0239 \quad 0.0852\right]_{ProductMP \times Product} \tag{2-1}$$

Setup time of product MP (hours)

$$= \left[4.79 \quad 47.87 \quad 124.82 \quad 47.87 \quad 4.79 \quad 134.19\right]_{ProductMP \times Product} \tag{2-2}$$

Baseline energy unit consumption of product MP (mega joules per item)

$$= \left[90.67 \quad 90.67 \quad 90.67 \quad 90.67 \quad 90.67 \quad 5.58\right]_{ProductMP \times Product} \tag{2-3}$$

Improvement rate of energy consumption of product MP (dimensionless)

$$= \left[0.05\right]_{1 \times ProductMP} \tag{2-4}$$

Baseline energy unit price of product MP (THB per mega joule)

$$= \left[0.7833\right]_{1 \times ProductMP} \tag{2-5}$$

Growth rate of energy price of product MP (dimensionless)

$$= \left[0.0548\right]_{1 \times ProductMP} \tag{2-6}$$

Baseline labour unit cost of product MP (THB per hour)

$$= \left[4{,}252 \quad 5{,}715 \quad 1{,}333 \quad 2{,}941 \quad 2{,}503 \quad 344\right]_{ProductMP \times Product} \tag{2-7}$$

Growth rate of labour cost of product MP (dimensionless)

$$= \left[0.1239\right]_{1 \times ProductMP} \tag{2-8}$$

Environmental impact driver of energy consumption (points per mega joule)

$$= \left[0.0024 \quad 0.0029 \quad 0.0038 \quad 0.0040 \quad 0.0047 \quad 0.0016 \quad 0.0037 \quad 0.0050\right]_{1 \times Energy} \tag{2-9}$$

Energy type selection of product MP (dimensionless)

$$= \left[1 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0\right]_{ProductMP \times Energy} \tag{2-10}$$

3 Product distribution module

The product distribution module requires nine input parameters. They include distance: product MPs $\rightarrow$ customers (matrix 1-4), speed: product MP $\rightarrow$ customer (matrix 3-1), production capacity of product MP (matrix 3-2), environmental impact driver of transportation (matrix 3-3), Bill of Materials (BOM) (matrix 3-4), transportation fixed cost: product MP $\rightarrow$ customer (matrix 3-5), baseline transportation unit cost: product MP $\rightarrow$ customer (matrix 3-6), proportion of fuel unit cost to transportation unit cost of product MP (matrix 3-7), and growth rate of fuel price of product MP (matrix 3-8).

Speed: product MP $\rightarrow$ customer (kilometres per hour)

$$= \begin{bmatrix} 878.5 & 80.0 & 60.0 & 39.0 & 25.5 \end{bmatrix}_{1 \text{ x Mode}} \quad (3\text{-}1)$$

Production capacity of product MP (items)

$$= \begin{bmatrix} 22{,}000 & 17{,}000 & 10{,}000 & 17{,}000 & 17{,}000 & 10{,}000 \end{bmatrix}_{\text{ProductMP x Product}} \quad (3\text{-}2)$$

Environmental impact driver of transportation (points per kilogram-kilometre)

$$= \begin{bmatrix} 7.66e-005 & 1.76e-005 & 8.51e-006 & 1.52e-005 & 8.06e-005 \end{bmatrix}_{1 \text{ x Mode}} \quad (3\text{-}3)$$

BOM (kilograms per item)

$$= \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.298 & 0 & 0 & 0.300 & 0 \\ 0 & 3.200 & 0.300 & 0.250 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.300 & 0.250 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0.003 & 0 & 0 & 0 & 0 & 0.100 & 0 & 0 & 0.469 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0.100 & 0.280 & 0 & 0.460 & 0 & 0 & 0 \\ 0.010 & 4.300 & 0.300 & 0.250 & 0.274 & 0 & 0 & 0 & 0 & 0.240 & 0 & 0.048 \end{bmatrix}_{\text{Product x Material}} \quad (3\text{-}4)$$

Air fixed cost: product MP $\rightarrow$ customer (THB)

$$= \begin{bmatrix} 0 & 4{,}800 & 0 & 4{,}700 & 4{,}700 \end{bmatrix}_{\text{ProductMP x Customer}} \quad (3\text{-}5\text{-}1)$$

16-ton truck fixed cost: product MP $\rightarrow$ customer (THB)

$$= 6{,}740 \quad (3\text{-}5\text{-}2)$$

40-ton truck fixed cost: product MP $\rightarrow$ customer (THB)

$$= 6{,}520 \quad (3\text{-}5\text{-}3)$$

Sea fixed cost: product MP $\rightarrow$ customer (THB)

$$= 6{,}000 \quad (3\text{-}5\text{-}4)$$

Baseline air unit cost: product MP $\rightarrow$ customer (THB per kilogram-kilometre)

$$= \begin{bmatrix} 0 & 0.01771 & 0 & 0.01515 & 0.02321 \end{bmatrix}_{\text{ProductMP x Customer}} \quad (3\text{-}6\text{-}1)$$

Baseline 16-ton truck unit cost: product MP $\rightarrow$ customer (THB per kilogram-kilometre)

$$= 0.000913 \quad (3\text{-}6\text{-}2)$$

Baseline 40-ton truck unit cost: product MP $\longrightarrow$ customer (THB per kilogram-kilometre)

$$= 0.000782 \tag{3-6-3}$$

Baseline sea unit cost: product MP $\longrightarrow$ customer (THB per kilogram-kilometre)

$$= \begin{bmatrix} 0 & 5.19e-007 & 0 & 5.43e-007 & 1.88e-006 \end{bmatrix}_{\text{ProductMP x Customer}} \tag{3-6-4}$$

Proportion of fuel unit cost to transportation unit cost of product MP (dimensionless)

$$= \begin{bmatrix} 0.512 & 0.599 & 0.599 & 0.526 & 0.621 \end{bmatrix}_{\text{ProductMP x Mode}} \tag{3-7}$$

Growth rate of fuel price of product MP (dimensionless)

$$= \begin{bmatrix} 0.0322 \end{bmatrix}_{\text{1 x ProductMP}} \tag{3-8}$$

Domain 2: Supply Network Design (SND)

4 Material demand module

The material demand module requires four input parameters. They include growth rate of currency depreciation of product MP (matrix 1-6), baseline supplier selection (matrix 4-1), distance: supplier $\rightarrow$ product MP (matrix 4-2), and feasible mode of supplier (matrix 4-3).

Baseline supplier selection (dimensionless)

$$= \begin{bmatrix} 0 & 1 & 0 & 1 & 1 & 1 & 1 & 1 & 1 & 0 & 1 & 0 & 1 & 0 \end{bmatrix}_{\text{1 x Supplier}} \tag{4-1}$$

Distance: supplier $\longrightarrow$ component MP (kilometres)

$$= \begin{bmatrix} 14.8 & 50.4 & 50.4 & 103.0 & 1{,}249.2 & 50.4 & 40.9 & 14.8 & 50.4 & 14.8 & 78.8 & 50.4 & 78.8 & 14.8 \end{bmatrix}_{\text{ProductMP x Supplier}} \tag{4-2}$$

Feasible mode of supplier (dimensionless)

$$= \begin{bmatrix} 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 0 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 0 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \end{bmatrix}_{\text{Mode x Material}} \tag{4-3}$$

5 Material procurement module

The material procurement module requires three input parameters. They include growth rate of currency depreciation of supplier (matrix 5-1), material unit price (matrix 5-2), and environmental impact driver of material extraction (matrix 5-3).

Growth rate of currency depreciation of supplier (dimensionless)

$$= \begin{bmatrix} 0.035 & 0.035 & 0.035 & 0.035 & 0.008 & 0.035 & 0.035 & 0.035 & 0.035 & 0.035 & 0.035 & 0.035 & 0.035 & 0.035 \end{bmatrix}_{\text{1 x Supplier}} \tag{5-1}$$

Material unit price (THB per kilogram)

$$
= \begin{bmatrix}
2,102 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
2,100 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 116.7 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 106.0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 171.0 & 174.0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 145.0 & 231.0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 232.2 & 191.0 & 76.0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 442.0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 43.0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 42.7 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 246.0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 593.0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 590.0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 247.6 & 0
\end{bmatrix}_{\text{Supplier x Material}} \tag{5-2}
$$

Environmental impact driver of material extraction (points per kilogram)

$$
= \begin{bmatrix} 0.440 & 0.440 & 0.059 & 0.059 & 0.059 & 0.059 & 0.059 & 0.059 & 0.059 & 0.059 & 0.059 & 0.059 \end{bmatrix}_{\text{1 x Material}} \tag{5-3}
$$

6 Material distribution module

The material distribution module requires eight input parameters. They include environmental impact driver of transportation (matrix 3-3), distance: supplier $\rightarrow$ product MP (matrix 4-2), speed: supplier $\rightarrow$ product MP (matrix 6-1), production capacity of supplier (matrix 6-2), transportation fixed cost: supplier $\rightarrow$ product MP (matrix 6-3), baseline transportation unit cost: supplier $\rightarrow$ product MP (matrix 6-4), proportion of fuel unit cost to transportation unit cost of supplier (matrix 6-5), and growth rate of fuel price of supplier (matrix 6-6).

Speed: supplier $\longrightarrow$ product MP (kilometres per hour)

$$
= \begin{bmatrix} 878.5 & 80.0 & 60.0 & 39.0 & 25.5 \end{bmatrix}_{\text{1 x Mode}} \tag{6-1}
$$

Production capacity of supplier (kilograms)

$$= \begin{bmatrix} 24{,}000 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 24{,}000 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 24{,}000 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 24{,}000 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 24{,}000 & 24{,}000 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 24{,}000 & 24{,}000 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 24{,}000 & 24{,}000 & 24{,}000 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 24{,}000 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 24{,}000 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 24{,}000 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 24{,}000 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 24{,}000 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 24{,}000 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 24{,}000 & 0 \end{bmatrix}_{\text{Supplier x Material}} \quad (6\text{-}2)$$

Air fixed cost: supplier $\longrightarrow$ product MP (THB)

$$= \begin{bmatrix} 0 & 0 & 0 & 0 & 4{,}700 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}_{\text{ProductMP x Supplier}} \quad (6\text{-}3\text{-}1)$$

16-ton truck fixed cost: supplier $\longrightarrow$ product MP (THB)

$$= 6.740 \quad (6\text{-}3\text{-}2)$$

40-ton truck fixed cost: supplier $\longrightarrow$ product MP (THB)

$$= 6{,}520 \quad (6\text{-}3\text{-}3)$$

Sea fixed cost: supplier $\longrightarrow$ product MP (THB)

$$= \begin{bmatrix} 0 & 0 & 0 & 0 & 6{,}000 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}_{\text{ProductMP x Supplier}} \quad (6\text{-}3\text{-}4)$$

Baseline air unit cost: supplier $\longrightarrow$ product MP (THB per kilogram-kilometre)

$$= \begin{bmatrix} 0 & 0 & 0 & 0 & 0.02321 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}_{\text{ProductMP x Supplier}} \quad (6\text{-}4\text{-}1)$$

Baseline 16-ton truck unit cost: supplier $\longrightarrow$ product MP (THB per kilogram-kilometre)

$$= 0.000913 \quad (6\text{-}4\text{-}2)$$

Baseline 40-ton truck unit cost: supplier $\longrightarrow$ product MP (THB per kilogram-kilometre)

$$= 0.0007818 \quad (6\text{-}4\text{-}3)$$

Baseline sea unit cost: supplier $\longrightarrow$ product MP (THB per kilogram-kilometre)

$$= \begin{bmatrix} 0 & 0 & 0 & 0 & 1.88e-006 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}_{\text{ProductMP x Supplier}} \quad (6\text{-}4\text{-}4)$$

Proportion of fuel unit cost to transportation unit cost of supplier (dimensionless)

$$= \begin{bmatrix} 0.512 & 0.599 & 0.599 & 0.526 & 0.621 \end{bmatrix}_{\text{Supplier x Mode}} \quad (6\text{-}5)$$

Growth rate of fuel price of supplier (dimensionless)

$$= \begin{bmatrix} 0.032 & 0.032 & 0.032 & 0.032 & 0.016 & 0.032 & 0.032 & 0.032 & 0.032 & 0.032 & 0.032 & 0.032 & 0.032 & 0.032 \end{bmatrix}_{\text{1 x Supplier}} \quad (6\text{-}6)$$

7 Optimisation setup

The optimisation setup requires four input parameters. They include production capacity of product MP (matrix 3-2), production capacity of supplier (matrix 6-2), minimum order quantity of product MP (matrix 7-1), and minimum order quantity of supplier (matrix 7-2).

Minimum order quantity of product MP (items)

$$= \begin{bmatrix} 11{,}000 & 10{,}700 & 2{,}950 & 7{,}100 & 8{,}000 & 6{,}300 \end{bmatrix}_{\text{Product MP x Product}} \tag{7-1}$$

Minimum order quantity of supplier (kilograms)

$$= \begin{bmatrix}
12{,}000 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
12{,}000 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 12{,}000 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 12{,}000 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 12{,}000 & 12{,}000 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 12{,}000 & 12{,}000 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 12{,}000 & 12{,}000 & 12{,}000 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 12{,}000 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 12{,}000 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 12{,}000 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 12{,}000 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 12{,}000 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 12{,}000 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 12{,}000 & 0
\end{bmatrix}_{\text{Supplier x Material}} \tag{7-2}$$

APPENDIX E
INPUT PARAMETERS OF CASE STUDY 3

The supply chain networks of roof sheet manufacturing company are structured with two stages. They include suppliers and product manufacturing plants (product MPs) as shown in Figure 4-3-1. The value of 1 is consequently input into supplier$\rightarrow$product MP. It involves design of supply networks.

<u>Supply Network Design (SND)</u>

1 Material demand module

The material demand module requires six input parameters. They include baseline product volume (matrix 1-1) and its growth rate (matrix 1-2), BOM (matrix 1-3), baseline supplier selection (matrix 1-4), distance: supplier$\rightarrow$product MP (matrix 1-5), and feasible mode of supplier (matrix 1-6).

Baseline product volume (kilograms)

$$= 1e + 006 \tag{1-1}$$

Growth rate of product volume (dimensionless)

$$= 0.10 \tag{1-2}$$

BOM (kilograms per item)

$$= \begin{bmatrix} 0.5862 & 0.0003 & 0.0003 & 0.0144 & 0.0020 & 0.2414 & 0.1264 & 0.01634 & 0.0003 & 0.0287 \end{bmatrix}_{\text{Product x Material}} \tag{1-3}$$

Baseline supplier selection (dimensionless)

$$= \begin{bmatrix} 1 & 1 & 1 & 1 & 1 & 0 & 0 & 1 & 1 & 1 \end{bmatrix}_{\text{1 x Supplier}} \tag{1-4}$$

Distance: supplier$\rightarrow$product MP (kilometres)

$$= \begin{bmatrix} 1,700 & 5 & 900 & 5 & 8,100 & 8,500 & 8,600 & 9,800 & 7,200 & 12,800 \end{bmatrix}_{\text{Product MP x Supplier}} \tag{1-5}$$

Feasible mode of supplier (dimensionless)

$$= \begin{bmatrix} 0 & 0 & 0 & 0 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 1 & 1 & 1 & 1 & 1 \end{bmatrix}_{\text{Mode x Supplier}} \tag{1-6}$$

2 Material procurement module

The material procurement module requires three input parameters. They include growth rate of currency depreciation of supplier (matrix 2-1), material unit price (matrix 2-2), and environmental impact driver of material extraction (matrix 2-3).

Growth rate of currency depreciation of supplier (dimensionless)

$$= \begin{bmatrix} -0.0060 & -0.0060 & -0.0060 & -0.0060 & -0.0239 & -0.0239 & 0.0156 & 0.1412 & 0.0162 & 0 \end{bmatrix}_{1 \times Supplier} \quad (2\text{-}1)$$

Material unit price (AUD per kilogram)

$$= \begin{bmatrix} 2.50 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0.80 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1.20 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 2.60 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 2.06 & 1.26 & 1.14 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1.80 & 1.10 & 1.00 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1.79 & 1.09 & 0.99 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 5.16 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 2.35 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 2.50 \end{bmatrix}_{Supplier \times Material} \quad (2\text{-}2)$$

Environmental impact driver of material extraction (points per kilogram)

$$= \begin{bmatrix} 0.353 & 0.353 & 0.353 & 0 & 0.051 & 0.051 & 0.051 & 0.353 & 0 & 0.353 \end{bmatrix}_{1 \times Material} \quad (2\text{-}3)$$

3 Material distribution module

The material distribution module requires eight input parameters. They include distance: supplier $\rightarrow$ product MP (matrix 1-6), speed: supplier $\rightarrow$ product MP (matrix 3-1), production capacity of supplier (matrix 3-2), environmental impact driver of transportation (matrix 3-3), baseline transportation unit cost: supplier $\rightarrow$ product MP (matrix 3-4), proportion of fuel unit cost to transportation unit cost of supplier (matrix 3-5), and growth rate of fuel price of supplier (matrix 3-6).

Speed: supplier $\rightarrow$ component MP (kilometres per hour)

$$= \begin{bmatrix} 878.5 & 80.0 & 60.0 & 48.3 & 25.5 \end{bmatrix}_{1 \times Mode} \quad (3\text{-}1)$$

Production capacity of supplier (kilograms)

$$= \begin{bmatrix} 60{,}000 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 60{,}000 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 60{,}000 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 60{,}000 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 60{,}000 & 60{,}000 & 60{,}000 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 60{,}000 & 60{,}000 & 60{,}000 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 60{,}000 & 60{,}000 & 60{,}000 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 60{,}000 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 60{,}000 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 60{,}000 \end{bmatrix}_{Supplier \times Material} \quad (3\text{-}2)$$

Baseline air unit cost: supplier $\rightarrow$ component MP (AUD per kilogram-kilometre)

$$= 0.00453 \quad (3\text{-}4\text{-}1)$$

Baseline 16-ton truck unit cost: supplier $\rightarrow$ component MP (AUD per kilogram-kilometre)

$$= 0.00170 \tag{3-4-2}$$

Baseline rail unit cost: supplier $\rightarrow$ component MP (AUD per kilogram-kilometre)

$$= 0.00018 \tag{3-4-2}$$

Baseline sea unit cost: supplier $\rightarrow$ component MP (AUD per kilogram-kilometre)

$$= 4e - 005 \tag{3-4-4}$$

Proportion of fuel unit cost to transportation unit cost of supplier (dimensionless)

$$= \begin{bmatrix} 0.512 & 0.599 & 0.599 & 0.526 & 0.621 \end{bmatrix}_{\text{Supplier x Mode}} \tag{3-5}$$

Growth rate of fuel price of supplier (dimensionless)

$$= \begin{bmatrix} 0.0150 & 0.0150 & 0.0150 & 0.0150 & 0.0905 & 0.0905 & 0.2153 & 0.0325 & 0.0510 & 0.0625 \end{bmatrix}_{\text{1 x Supplier}} \tag{3-6}$$

4 Optimisation setup

The optimisation setup requires two input parameters. They include production capacity of supplier (matrix 3-2), and minimum order quantity of supplier (matrix 4-1).

Minimum order quantity of supplier (kilograms)

$$= \begin{bmatrix} 12{,}000 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 12{,}000 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 12{,}000 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 12{,}000 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 12{,}000 & 12{,}000 & 12{,}000 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 12{,}000 & 12{,}000 & 12{,}000 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 12{,}000 & 12{,}000 & 12{,}000 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 12{,}000 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 12{,}000 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 12{,}000 \end{bmatrix}_{\text{Supplier x Material}} \tag{4-1}$$

APPENDIX F

INPUT PARAMETERS OF CASE STUDY 4

The supply chain networks of power boat manufacturing company are structured with two stages. They include suppliers and product manufacturing plants (product MPs) as shown in Figure 4-4-1. The value of 1 is consequently input into supplier $\rightarrow$ product MP. It involves design of supply networks.

Supply Network Design (SND)

1 Material demand module

The material demand module requires six input parameters. They include baseline product volume (matrix 1-1) and its growth rate (matrix 1-2), BOM (matrix 1-3), baseline supplier selection (matrix 1-4), distance: supplier $\rightarrow$ product MP (matrix 1-5), and feasible mode of supplier (matrix 1-6).

Baseline product volume (kilograms)

$$= 500 \tag{1-1}$$

Growth rate of product volume (dimensionless)

$$= 0.10 \tag{1-2}$$

BOM (kilograms per item)

$$= \begin{bmatrix} 60 & 240 & 60 & 15 & 1760 & 680 & 360 & 270 & 40 & 80 & 45 & 170 \end{bmatrix}_{\text{Product x Material}} \tag{1-3}$$

Baseline supplier selection (dimensionless)

$$= \begin{bmatrix} 1 & 1 & 1 & 1 & 1 & 1 & 1 \end{bmatrix}_{\text{1 x Supplier}} \tag{1-4}$$

Distance: supplier $\rightarrow$ product MP (kilometres)

$$= \begin{bmatrix} 900 & 1{,}800 & 50 & 700 & 100 & 1{,}800 & 6{,}900 \end{bmatrix}_{\text{Product MP x Supplier}} \tag{1-5}$$

Feasible mode of supplier (dimensionless)

$$= \begin{bmatrix} 0 & 1 & 0 & 0 & 0 & 1 & 1 \\ 1 & 0 & 1 & 1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 1 & 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 1 & 1 & 1 \end{bmatrix}_{\text{Mode x Supplier}} \tag{1-6}$$

2 Material procurement module

The material procurement module requires three input parameters. They include growth rate of currency depreciation of supplier (matrix 2-1, material unit price (matrix

2-2), preparation unit time of supplier (matrix 2-3), and environmental impact driver of material extraction (matrix 2-4).

Growth rate of currency depreciation of supplier (dimensionless)

$$= \begin{bmatrix} -0.0060 & -0.0060 & -0.0060 & -0.0060 & -0.0060 & -0.0239 & 0.0162 \end{bmatrix}_{1 \text{ x Supplier}} \tag{2-1}$$

Material unit price (AUD per kilogram)

$$= \begin{bmatrix} 12.04 & 0 & 0 & 2.67 & 19.80 & 0 & 0 & 0 & 7.75 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 3.88 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 4.19 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 5.00 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 3.75 \\ 10.84 & 0 & 1.03 & 0 & 0 & 1.20 & 3.33 & 3.72 & 3.50 & 0 & 0 & 0 \\ 8.78 & 2.80 & 0 & 0 & 0 & 0 & 0 & 0 & 2.84 & 0 & 0 & 0 \end{bmatrix}_{\text{Supplier x Material}} \tag{2-2}$$

Preparation time of supplier (hours per kilogram)

$$= 0.0005 \tag{2-3}$$

Environmental impact driver of material extraction (points per kilogram)

$$= \begin{bmatrix} 0.353 & 0.353 & 0.051 & 0 & 0.353 & 0.051 & 0.051 & 0.051 & 0 & 0.562 & 0.353 & 1.195 \end{bmatrix}_{1 \text{ x Material}} \tag{2-4}$$

3 Material distribution module

The material distribution module requires eight input parameters. They include distance: supplier $\rightarrow$ product MP (matrix 1-6), speed: supplier $\rightarrow$ product MP (matrix 3-1), production capacity of supplier (matrix 3-2), environmental impact driver of transportation (matrix 3-3), baseline transportation unit cost: supplier $\rightarrow$ product MP (matrix 3-4), proportion of fuel unit cost to transportation unit cost of supplier (matrix 3-5), and growth rate of fuel price of supplier (matrix 3-6).

Speed: supplier $\rightarrow$ component MP (kilometres per hour)

$$= \begin{bmatrix} 878.5 & 80.0 & 60.0 & 48.3 & 25.5 \end{bmatrix}_{1 \text{ x Mode}} \tag{3-1}$$

Production capacity of supplier (kilograms)

$$= \begin{bmatrix} 60{,}000 & 0 & 0 & 60{,}000 & 60{,}000 & 0 & 0 & 0 & 60{,}000 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 60{,}000 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 60{,}000 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 60{,}000 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 60{,}000 \\ 0 & 0 & 60{,}000 & 0 & 0 & 60{,}000 & 60{,}000 & 60{,}000 & 0 & 0 & 0 & 0 \\ 0 & 60{,}000 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}_{\text{Supplier x Material}} \tag{3-2}$$

Baseline air unit cost: supplier $\rightarrow$ component MP (AUD per kilogram-kilometre)

$$= 0.00453 \tag{3-4-1}$$

Baseline 16-ton truck unit cost: supplier $\rightarrow$ component MP (AUD per kilogram-kilometre)

$$= 0.00170 \tag{3-4-2}$$

Baseline rail unit cost: supplier $\rightarrow$ component MP (AUD per kilogram-kilometre)

$$= 0.00018 \tag{3-4-2}$$

Baseline sea unit cost: supplier $\rightarrow$ component MP (AUD per kilogram-kilometre)

$$= 4e - 005 \tag{3-4-4}$$

Proportion of fuel unit cost to transportation unit cost of supplier (dimensionless)

$$= \begin{bmatrix} 0.512 & 0.599 & 0.599 & 0.526 & 0.621 \end{bmatrix}_{\text{Supplier x Mode}} \tag{3-5}$$

Growth rate of fuel price of supplier (dimensionless)

$$= \begin{bmatrix} 0.0150 & 0.0150 & 0.0150 & 0.0150 & 0.0905 & 0.0905 & 0.2153 & 0.0325 & 0.0510 & 0.0625 \end{bmatrix}_{\text{1 x Supplier}} \tag{3-6}$$

4 Optimisation setup

The optimisation setup requires two input parameters. They include production capacity of supplier (matrix 3-2), and minimum order quantity of supplier (matrix 4-1).

Minimum order quantity of supplier (kilograms)

$$= \begin{bmatrix} 12,000 & 0 & 0 & 12,000 & 12,000 & 0 & 0 & 0 & 12,000 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 12,000 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 12,000 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 12,000 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 12000 \\ 0 & 0 & 12,000 & 0 & 0 & 12,000 & 12,000 & 12,000 & 0 & 0 & 0 & 0 \\ 0 & 12,000 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}_{\text{Supplier x Material}} \tag{4-1}$$