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A green supply chain network design model for enhancing competitiveness and sustainability of companies in high north arctic regions

Hao Yu[1], Wei Deng Solvang[1], Chen Chen[2]

[1] Department of Industrial Engineering, Narvik University College, Postboks 385 Lodve gate 2, NO-8505 Narvik, Norway.
[2] Northern Research Institute Narvik AS.Postboks 250, NO-8504 Narvik, Norway.

Abstract
To survive in today's competitive and ever-changing marketplace, companies need not only to engage in their products and/or services, but also to focus on the management of the whole supply chain. Effectively managing and balancing the profitability and interconnection of each player in the supply chain will improve the overall supply chain surplus as well as individual profit. However, it is extremely difficult to simultaneously optimize several objectives in design and planning of a supply chain, i.e., cost-minimization, risk-minimization, responsiveness-maximization, etc., which are somehow conflict with one another. Furthermore, the natural and infrastructural challenges in high north arctic regions make it become much more difficult and complicated to design and develop cost-efficient, highly responsive, environmentally friendly, and sustainable supply chain network. In order to provide companies in high north arctic regions with decision support tool for the design and planning of theirs supply chain networks, a green supply chain network design (GrSCND) model is formulated in this study based on multi-objective mixed integer programming (MIP). The optimal trade-off among several conflicting objectives is the focus of this GrSCND model aiming to enhance both competitive competence and sustainability of companies and supply chains operated in high north regions. In addition, a numerical experiment is also given to present a deep insight of the GrSCND model.
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Keywords: Green supply chain; Network model; Competitiveness; Sustainability; High north Arctic regions.

1. Introduction

To survive in today's competitive and ever-changing marketplace, companies need not only to engage in their products and/or services, but also to focus on the management of the whole supply chain. A typical supply chain includes raw material/component supplier, manufacturer, distributor, retailer, and customer [1]. Effectively managing and balancing the profitability and interconnections of each player in the supply chain will improve the overall supply chain surplus as well as individual profit. Conventionally, the objective of supply chain network design is to maximize the overall profit generated through balancing the total costs and responsiveness to customer needs. A poor responsiveness to meet the customer needs will decrease customer satisfaction, and therefore increase the risk of losing sales. In order to achieve high responsiveness to the rapid-changing market, a more flexible manufacturing system should be applied, which sacrifices economies of scale and results in high production and transportation costs. The break-even point which optimizes the overall supply chain performance in terms of both cost and responsiveness has been extensively addressed in previous studies through bi-objective programming.

However, for the companies and supply chains operated in high north arctic regions, more challenges, i.e., inhospitable and extreme climate, absence or poor infrastructure [2], and complicated terrain and environment, make it very difficult to deliver high responsive products and/or services with low costs, and relatively high supply chain risks are imposed as well. Besides, environmental issues, i.e., vulnerable eco-environmental system and higher sensitivity to greenhouse gas emissions, must be taken into account in the decisional process of supply chain network design (SCND) considering that CO_2 emissions have increased rapidly over past decades. Furthermore, population density in high north arctic regions is extremely low (For instance, the population density in three counties located in northern Norway is $7/km^2$ in Nordland, $6/km^2$ in Tromsø, and $2/km^2$ in Finnmark [3]), hence, the transportation of small amount of raw materials and/or finished products over very long distance is quite common in this sparsely populated area, which dramatically increases the costs of transportation. Due to the aforementioned reasons, the supply chain network faces more challenges than those which are operated in densely populated areas [4].

In order to tackle those challenges and provide decision supporttool for the companies and supply chains operated in high north arctic regions, we aim in our study to develop the theoretical framework and computational model for green supply chain network design (GrSCND) in order to enhance both competitive competence and sustainability of companies of this area. The proposed theoretical framework and computational model aim to optimize the overall supply chain performance through balancing the trade-off among costs, risks, and greenhouse gas (GHG) emissions. In addition, the adopted methodology for model formulation is based on multi-objective mixed integer programming (MIP), and an numerical experiment is also given to present a deep insight and applicability of the GrSCND model developed in this research.

The rest of this article is organized as follows. Section 2 provides an extensive literature review of green supply chain management (GrSCM) and GrSCND models. Section 3 formulates the theoretical framework and computational model for GrSCND in high north arctic regions, and the method for model solution is also given in this section. Section 4 presents the numerical experiment, and section 5 concludes this article with a future outlook.

2. Literature review

The concept of green supply chain management (GrSCM) has been introduced and extensively studied for almost two decades. The first attempts to define GrSCM can be found in late 1990s (see ref. [5]), and the most cited definition of GSCM [6] is given by Srivastava [7] which defines GrSCM as "Integrating environmental thinking into supply-chain management, including product design, material sourcing and selection, manufacturing processes, delivery of the final product to the end customers as well as end-of-life management of the product after its useful life." GrSCM is also referred as environmental logistics [8], green logistics [9], sustainable supply chains [10], and sustainable supply network management [11, 12], and a number of review articles contributed to both theoretical and practical development of GrSCM are recently published by Seuring and Muller [13], Carter and Rogers [14], Sarkis et al. [15], Ali and Searcy [6], and Ashby et al. [16]. To achieve GrSCM, two types of "greenness" are divided by researchers [7]: green product design [17] and green operations, and the green operations, i.e., network design problem [18-20], sustainable waste management [20-22], and material flow [22] of a supply chain, are the focus of this research.

Network design is the logical place at which strategic decisions should be made for GrSCM [23]. Designing the physical network structure of a supply chain is called supply chain network design (SCND) [24]. Due to its significant influence on supply chain's performance, resilience, profits, and competitive competence [25], SCND is believed to be one of the most important strategic decisions in supply chain management, which affects the long-term profitability and sustainability of a supply chain. To take into account environmental or "green" thinking in SCND, a large number of articles have contributed to develop both theoretical and computational models for green supply chain network design (GrSCND). Wang et al. [26] develop a bi-objective optimization model for GrSCND, which aims to balance the trade-off between overall costs and environmental influence in terms of CO_2 emissions. The "Pareto optimal" solutions are employed for model computation, and a comprehensive numerical experiment is also conducted in this study. Elhedhli and Merrick [23] propose a mathematical model for reducing carbon emissions in GrSCND. The carbon emissions are monetized and converted into environmental pollution costs, and the model aims to minimize the overall system costs including fixed and variable facility costs, production costs, as well as environmental pollution costs. Govindan et al. [27] introduce a two-stage bi-objective location-routing model with time-windows for GrSCND, and the optimal balance of costs and greenhouse gas emissions is the goal of this model. The optimal supply chain network configuration is determined through selecting appropriate number and locations of facilities as well as the route within each stage. A large number of GrSCND models and practices incorporating cost objective with emission objective of greenhouse gas (GHG) can also be found in Yu and Solvang [20], Quariguasi-Frota-Neto et al. [28], Harris et al. [29], Ulbeda et al. [30], and Adballah et al. [31].

To consider different influencing factors in GrSCND other than GHG emissions, Jamshidi et al. [32] develop a bi-objective mathematical model for GrSCND, which simultaneously minimizes the overall system costs and environmental impacts. The environmental impacts in this study are measured by the amount of hazardous gases, i.e., CO, NO_2 and volatile organic particles, generated by facility operations and transportation of goods within the supply chain. Latha Shankar et al. [33] pose a bi-objective optimization model for strategic planning and material flow decisions of a three-echelon supply chain network. The focus of this model is the optimal balance between system operating costs and the fill rate of customer demands. Sheu and Lin [34] incorporate multi-objective mixed integer programming (MIP) and hierarchical cluster analysis method to configure and optimize global logistics network. The proposed model aims to minimize the network investments, while maximize the total profits generated by the supply chain and satisfaction rate of customer demands, and the weighted sum utility method is employed in this research for model computation.

To take into account of the changes in input parameters with time horizon, Yu et al. [22] formulate a multi-period dynamic model for managing and operating the reverse network of waste management system in an environmentally friendly manner. The proposed model aims to simultaneously minimize the system operating costs and environmental risks imposed by waste recycling and disposal through optimally managing the material flow between different facilities at each time period. A three-stage dynamic model for open-loop reverse supply chain and logistics network planning is developed by Ene and Ozturk [35], which aims to maximize the overall network costs of product recovery and disposal. Zeballos et al. [36] propose a multi-product and multi-period mathematical model for optimal planning of closed-loop supply chains through the minimization of net costs (expected costs minus expected revenue through recycling and remanufacturing), and both forward flows and reverse flows are formulated in this model. It is noted that the input parameters in this model are assumed to be stochastic in nature and therefore exist great uncertainties, and a reduced scenario tree is applied to achieve a reasonable representation of the original problem so that the model can be resolved.

Dealing with uncertainties in input parameters is another focus in GrSCND. Pishvaee and Razmi [37] formulate a fuzzy mathematical programming for GrSCND. This model aims to balance the trade-off between costs and environmental impact, and the environmental impact is measured by eco-indicator 99 which is a life cycle assessment-based (LCA-based) method. Further, an interactive fuzzy solution approach is also established for model computation. Ramezani et al. [38] develop a multi-stage, multi-period and multi-product optimization model for closed-loop SCND with fuzzy environment, and the goal of this model is to simultaneously minimize the costs, delivery time, and defects of raw materials acquired from suppliers. Amin and Zhang [39] propose a bi-objective model for closed-loop SCND with inexact input information on demands and return, and the balance between the minimization of costs and maximization of the use of environmentally friendly materials is the focus of this research.

Through the extensive literature review of GrSCND models and practices, two characteristics can be identified. One is most previous researches use bi-objective optimization approach in order to balance the trade-off between costs and environment impacts, and the other is the indicator of environmental impacts is most frequently measured by GHG emissions. Besides, other objectives i.e., amount of hazardous gases, customer satisfaction rate, etc., are formulated as well in some previous models, and the time-varying and uncertain parameters have also been extensively focused in GrSCND. There is no denying the fact that costs and GHG emissions are the most crucial influencing factors in GrSCND, but more focus and emphasis have to be attached to the risks and reliability of the supply chains operated in high north arctic regions where natural and infrastructural challenges, i.e., poor and limited transport access (e.g. railway transportation is unavailable in most arctic regions), significant influence of inhospitable

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and extreme climate (e.g. the road transportation may be closed for several days due to avalanche), etc., bring more complexities in GrSCND. A poorly planned supply chain network without considering supply chain risks in this area will result in extremely high costs, high risks, high GHG emissions and poor responsiveness, which will then lead to the failure of a company or a supply chain in pursuing long-term profitability and sustainability. Therefore, it is of significant importance to account supply chain risks in the decisional process of GrSCND in high north arctic regions, however, it is extremely difficult to find such an instance from previous researches. Therefore, in order to fill the literature gap, the theoretical framework and mathematical model for GrSCND of a three-stage supply chain operated in high north arctic regions are formulated in this paper so that the supply chain costs, GHG emissions and risks are simultaneously considered in GrSCND.

3. Model

3.1 Theoretical framework

In this section, the theoretical framework of a general three-stage forward supply chain is first formulated in Figure 1. As shown in the figure, the proposed theoretical supply chain network is comprised of four levels of entities: supplier, producer, warehouse and customer, and those entities are communicated and connected through three flows: material flow, information flow and capital flow. The material flow in this supply chain network starts from upstream raw material suppliers and moves via intermediate production plants and warehouses towards end customers, and the information and capital flow in opposite direction from end customers towards suppliers.

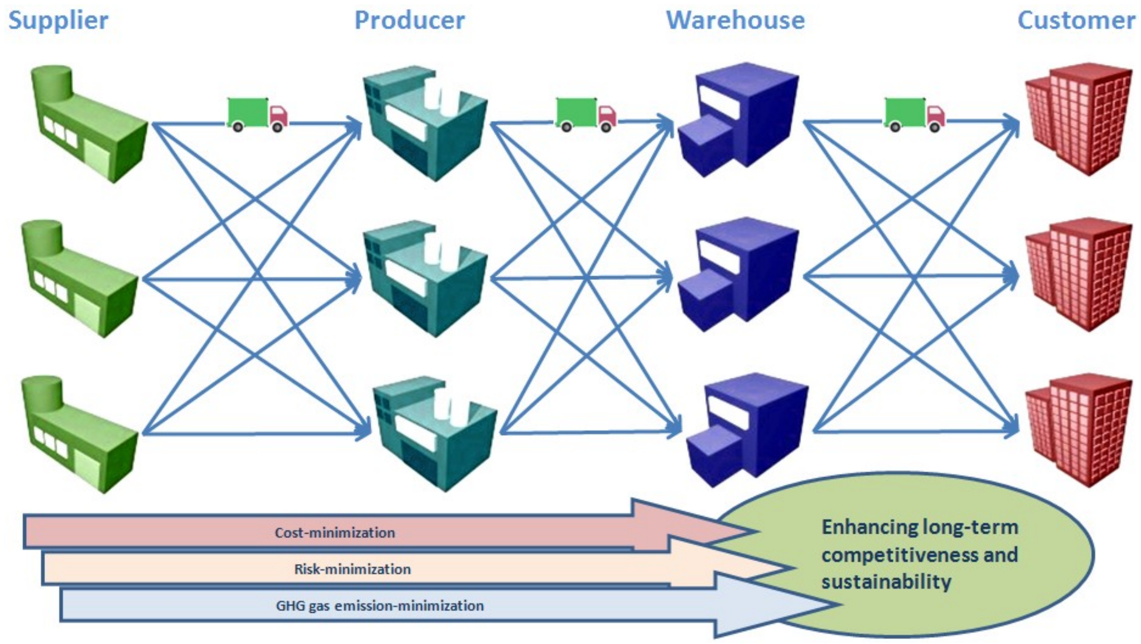

Figure 1. Theoretical framework of GrSCND of a three-stage supply chain operated in high north arctic regions

Conventionally, the focus of GrSCND is to simultaneously minimize the costs and GHG emissions of a supply chain, however, it is also of great significance to decrease the risks and increase reliability of a supply chain operated in high north arctic regions due to the complex natural and infrastructural challenges discussed in previous section. Therefore, in order to tackle this challenge, the optimal trade-off among cost-minimization, risk-minimization and GHG emission-minimization will be focused in this research so that long-term competitive competence, profitability and sustainability can be achieved.

3.2 Mathematical model

The proposed MIP model aims to determine, in an optimal manner, the number and locations of potential facilities, selection of suppliers, and the inter-facility material flow in each stage of a supply chain. The indices, input parameters and decision variables are first given as follows:

Indices	
s	The set of suppliers (s=1, 2, 3,…, S)
p	The set of candidate locations for production plants (p=1, 2, 3,…, P)
w	The set of candidate locations for warehouses (w=1, 2, 3,…, W)
c	The set of customers (c=1, 2, 3,…, C)

Input parameters	
PC_s	The unit purchasing costs for raw materials and components at supplier s
FC_p, FC_w	The fixed costs for production plant p and warehouse w
C_p, C_w	The unit operational costs (e.g. production costs, inventory costs, packaging costs, etc.) of production plant p and warehouse w
TC_{sp}, TC_{pw}, TC_{wc}	The unit transportation costs between supplier s and production plant p, production plant p and warehouse w, warehouse w and customer c
EMS_{sp}, EMS_{pw}, EMS_{wc}	The GHG emission factor between supplier s and production plant p, production plant p and warehouse w, warehouse w and customer c
DIS_{sp}, DIS_{pw}, DIS_{wc}	The transport distance between supplier s and production plant p, production plant p and warehouse w, warehouse w and customer c
LD_{sp}, LD_{pw},LD_{wc}	The average load of transport vehicles between supplier s and production plant p, production plant p and warehouse w, warehouse w and customer c
RK_s	The risk index of suppler s
RK_{sp}, RK_{pw}, RK_{wc}	The risk index of the transportation between supplier s and production plant p, production plant p and warehouse w, warehouse w and customer c
CD_c	The demands of customer c
IF	An infinite positive number
MPR_p	The material-to-product rate at production plant p which specifies how many materials are needed for producing one product
ITR_w	The inventory turnover rate at warehouse w which specifies the ratio of outgoing products and incoming products
CAP_s, CAP_p, CAP_w	The capacity of supplier s, production plant p, and warehouse w

Decision variables	
S_s	If S_s=1, supplier s is selected, and if S_s=0, otherwise
X_p	If X_p=1, candidate location p is selected for opening production plant, and if X_p=0, otherwise
X_w	If X_w=1, candidate location w is selected for opening warehouse, and if X_w=0, otherwise
AT_{sp}, AT_{pw}, AT_{wc}	The amount of raw materials or finished products transported between supplier s and production plant p, production plant p and warehouse w, warehouse w and customer c

$$\text{Min } OBJ1=\sum_{s=1}^{S} PC_s S_s(\sum_{p=1}^{P} AT_{sp}) + \sum_{p=1}^{P} X_p(FC_p + \sum_{s=1}^{S} C_p AT_{sp}) + \sum_{w=1}^{W} X_w(FC_w + \sum_{p=1}^{P} C_w AT_{pw}) + \sum_{s=1}^{S}\sum_{p=1}^{P} TC_{sp}AT_{sp} + \sum_{p=1}^{P}\sum_{w=1}^{W} TC_{pw}AT_{pw} + \sum_{w=1}^{W}\sum_{c=1}^{C} TC_{wc}AT_{wc} \tag{1}$$

$$\text{Min } OBJ2=\sum_{s=1}^{S}\sum_{p=1}^{P} EMS_{sp}\frac{AT_{sp}DIS_{sp}}{LD_{sp}} + \sum_{p=1}^{P}\sum_{w=1}^{W} EMS_{pw}\frac{AT_{pw}DIS_{pw}}{LD_{pw}} + \sum_{w=1}^{W}\sum_{c=1}^{C} EMS_{wc}\frac{AT_{wc}DIS_{wc}}{LD_{wc}} \tag{2}$$

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$$\text{Min } OBJ3 = \sum_{s=1}^{S} RK_s S_s (\sum_{p=1}^{P} AT_{sp}) + \sum_{s=1}^{S}\sum_{p=1}^{P} RK_{sp} AT_{sp} + \sum_{p=1}^{P}\sum_{w=1}^{W} RK_{pw} AT_{pw} + \sum_{w=1}^{W}\sum_{c=1}^{C} RK_{wc} AT_{wc} \quad (3)$$

Eqs.(1), (2) and (3) are objective functions of this multi-objective MIP model for GrSCND in high north arctic regions. Eq. (1) is the cost-minimization objective function which takes into account the costs for supplier selection. The first part of this equation represents the purchasing costs of the raw materials from suppliers, and the second and third parts represent the fixed and operational costs of potential production plant and warehouse, and the last three parts represent the transportation costs in each stage. The purchasing costs and operational costs are directly proportional to the amount of raw materials and components purchased, and the transportation costs are directly proportional to the quantity transported in each stage. Eq. (2) is the GHG emission-minimization objective function. GHG emissions are very important environmental indicator especially for high north arctic regions where the GHG emissions have more negative influence on the ozone. In this model, the GHG emissions are directly proportional to the distance and amount transported, and it is inversely proportional to the load of transport vehicle. It is noted that the emission factor is applied for quantifying the equivalent GHG emissions, and it is determined by the type of transport vehicle, road condition as well as other influencing factors. Eq. (3) is the risk-minimization objective function in which the methodology developed by Yu and Goh [40] to quantify supply chain risks is employed and adapted accordingly. The first part of this equation represents the potential risks of supplier in fulfilling the demands of producer, and the other parts represent the potential transportation risks. The risk index of supplier is determined by inherent risks, supplier's capacity, supplier's reliability and reputation, and the risk index of transportation is influenced by transporter's reliability, probability of infrastructural risks, probability of natural disaster, etc. Besides, in order to fulfill the requirement for material flow, facility capacity as well as other restrictions, thirteen sets of model constraints are also formulated as follows.

Subject to:

$$CD_c = \sum_{w=1}^{W} AT_{wc}\ , \text{For} c = 1, \dots, C \quad (4)$$

$$ITR_w \sum_{p=1}^{P} AT_{pw} = \sum_{c=1}^{C} AT_{wc}\ , \text{For} w = 1, \dots, W \quad (5)$$

$$MPR_P \sum_{s=1}^{S} AT_{sp} = \sum_{w=1}^{W} AT_{pw}\ , \text{For } p = 1, \dots, P \quad (6)$$

$$\sum_{p=1}^{P} AT_{sp} \le CAP_s, \text{For } s = 1, \dots, S \quad (7)$$

$$\sum_{s=1}^{S} AT_{sp} \le CAP_p, \text{For } p = 1, \dots, P \quad (8)$$

$$\sum_{w=1}^{W} AT_{pw} \le CAP_w, \text{For } w = 1, \dots, W \quad (9)$$

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$$S_s \leq IF \sum_{p=1}^{P} AT_{sp} \text{ , For } s = 1, \ldots, S \tag{10}$$

$$X_p \leq IF \sum_{p=1}^{P} AT_{sp} \text{ , For } p = 1, \ldots, P \tag{11}$$

$$X_w \leq IF \sum_{p=1}^{P} AT_{pw} \text{ , For } w = 1, \ldots, W \tag{12}$$

$$AT_{sp} \leq S_s X_p IF, \text{ For } s = 1, \ldots, S, p = 1, \ldots . P \tag{13}$$

$$AT_{pw} \leq X_p X_w IF, \text{ For } p = 1, \ldots, P, w = 1, \ldots . W \tag{14}$$

$$AT_{wc} \leq X_w IF, \text{ For } w = 1, \ldots, W, c = 1, \ldots . C \tag{15}$$

$$S_s, X_p, X_w \in \{0, 1\}, \text{ For} s = 1, \ldots, S, p = 1, \ldots, P, w = 1, \ldots, W \tag{16}$$

Eq. (4) restricts the demands of each customer must be fulfilled. Eqs. (5) and (6) are the requirements of material flow balance, which specify the relationship between the amount of incoming raw materials and the quantity of outgoing finished products at production plant *p* and warehouse *w*. It is noted that the defect rate should be taken into consideration in determining the value of *MPR* at production plant *p*. Eqs. (7), (8) and (9) are capacity constraints, which restrict the maximum quantity served by supplier *s*, production plant *p*, and warehouse *w* cannot exceed their corresponding capacities. Eq. (10) restricts supplier *s* will not be selected if it doesn't supply raw materials or components to any producers. Eqs. (11) and (12) ensure the candidate locations for production plant *p* and warehouse *w* will not be selected if they do not perform any functions. Eq. (13) guarantees the producer *p* can be served by supplier *s* only when both supplier *s*and candidate location *p* for opening production plant are selected. Eq. (14) restricts the finished products from producer *p* can be stored at warehouse *w* only when both candidate location *p* for opening production plant and candidate location *w* for opening warehouse are chosen. Eq. (15) ensures the demands of customer *c* can be served by warehouse *w* only when candidate location *w* is selected for building new warehouse. Eq. (16) is the binary constraint of decision variables. In addition, all the indices and input parameters of this multi-objective MIP model for GrSCND belong to non-negative domain.

3.3 Model solution

In order to composite multiple objective functions with different measures of units, the weighted sum utility method developed by Sheu and Lin [34] is employed in this research to composite the three objective functions of this GrSCND model, and similar practices of this method can also be found in Yu et al. [22], Nema and Gupta [41], and Sheu [42]. Before the weighted sum utility method is formulated, the notations of some adjustable parameters, benchmark parameters and response variables are first given as follows.

Adjustable parameters	
WT_{OBJ1}, WT_{OBJ2}, WT_{OBJ3}	The weight of cost-utility, GHG emission-utility, and risk-utility
Benchmark parameters	
$OBJ1_{min}$, $OBJ2_{min}$, $OBJ3_{min}$	The individual minimum achievable value of cost-minimization objective, GHG emission-minimization objective, and risk-minimization objective
$OBJ1_{max}$, $OBJ2_{max}$, $OBJ3_{max}$	The individual maximum achievable value cost-minimization objective, GHG emission-minimization objective, and risk-minimization objective

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Response variables	
OBJ1, *OBJ2*, *OBJ3*	The actual value of cost-minimization objective, GHG emission-minimization objective, and risk-minimization objective
UT_{OBJ1}, UT_{OBJ2}, UT_{OBJ3}	The individual cost-utility, GHG emission-utility, and risk-utility
UT	The composite utility

$$\text{Min}UT = WT_{OBJ\,1}UT_{OBJ\,1} + WT_{OBJ\,2}UT_{OBJ\,2} + WT_{OBJ\,3}UT_{OBJ\,3} \tag{17}$$

Eq. (17) is the objective function of the weighted sum utility method and aims to minimize the weighted sum utility of each objective function. The weight of each individual utility presents the relative importance of each objective function determined by decision-makers. Eqs. (18), (19) and (20) illustrate the method for calculating the individual utility of each objective function. In Eq. (18), $OBJ1_{max}$ minus $OBJ1_{min}$ denotes the theoretically maximum deviation between the maximum achieve costs and the minimum achievable costs, which can be used as the benchmark for calculating the individual utility, and *OBJ1* minus $OBJ1_{min}$ represents the deviation between actual value and minimum achievable value. The numerator and denominator in this equation share the same unit, and the unit can then be eliminated, and this method also applies for Eqs. (19) and (20).Therefore, the individual utility of each objective function becomes unit less and can be directly summed by giving the corresponding weights. The summation of the weights of those three objectives in this model is regulated to 1, so the theoretically minimum achievable individual utility is 0 when the actual value *OBJ* equals to the minimum achievable value OBJ_{min}, and the theoretical achievable maximum individual utility is 1 when the actual value *OBJ* equals to the maximum achievable value OBJ_{max}.

$$UT_{OBJ\,1} = \frac{OBJ1 - OBJ1_{min}}{OBJ1_{max} - OBJ1_{min}} \tag{18}$$

$$UT_{OBJ\,2} = \frac{OBJ2 - OBJ2_{min}}{OBJ2_{max} - OBJ2_{min}} \tag{19}$$

$$UT_{OBJ\,3} = \frac{OBJ1 - OBJ1_{min}}{OBJ1_{max} - OBJ1_{min}} \tag{20}$$

4. Numerical experiment

In this section, a numerical experiment is given to present a deep insight of the proposed multi-objective MIP model for GrSCND in high north arctic regions. The numerical experiment is performed based upon a hypothetical case of a three-stage supply chain network, including supplier, producer, warehouse and customer, operated in high north arctic regions, and the producer sources from domestic and international suppliers, and it mainly serves local customers. In order to design and maintain an efficient and sustainable supply chain with relatively low risks, the supply chain manager has to make several crucial decisions, i.e., the number and locations of production plants and warehouses to be opened, selection of suppliers, the amount purchased from each selected supplier, the amount of finished products stored in which warehouse, and the customer demands are served from which warehouse. The proposed GrSCND model is applied for decision support in this case.

The hypothetical supply chain network is comprised of 7 raw material suppliers, 5 candidate locations for production plant, 5 candidate locations for warehouse, and 4 end customers. Table 1 gives the unit purchasing costs, capacity and risk index of each supplier *s*, and the fixed costs, unit operational costs and capacity of the candidate locations for production plant *p* and warehouse *w* are presented in this table as well. The material-to-production rates MPR_p of candidate location *p1*, *p2*, *p3*, *p4*, *p5* are 0.8, 0.7, 0.8, 0.6 and 0.7, respectively. The inventory turnover rate ITR_w of each potential warehouse is assumed to be equal, and it is 0.8. It is noted that the units of input parameters are given as unit cost (uc), unit weight (uw) and unit distance (ud) to represent the genericity, and they can easily and accordingly specified into a certain measure of units in a real world case study.

Tables 2, 3 and 4 present the unit transportation costs, distance and risk index of the 1st stage inter-facility transportation between supplier *s* and producer *p*, the 2nd stage inter-facility transportation between producer *p* and warehouse *w*, and the 3rd stage inter-facility transportation between warehouse *w* and customer *c*, respectively. The transportation of raw materials from suppliers to producers is suppliers' responsibility in this supply chain. Because the same type of vehicles are used for transporting raw materials from one supplier to all the producers, the GHG emission factor EMS_{sp} and average load LD_{sp} are assumed to be equal in all the outbound transportation of supplier s, where EMS_{s1p}=0.7 1/ud, EMS_{s2p}=0.81/ud, EMS_{s3p}=0.8 1/ud, EMS_{s4p}=0.7 1/ud, EMS_{s5p}=0.9 1/ud, EMS_{s6p}=0.75 1/ud, EMS_{s7p}=0.6 1/ud, and LD_{s1p}=4 uw, LD_{s2p}=6 uw, LD_{s3p}=8 uw, LD_{s4p}=6 uw, LD_{s5p}=12 uw, LD_{s6p}=8 uw and LD_{s7p}=12 uw, respectively. The transportation of finished products in stages 2 and 3 is outsourced to a 3rd party logistics (3PL) company, and the same type of transport vehicles are used to perform the transportations, so all the GHG emission factors and average load in 2nd and 3rd stage inter-facility transportation are assumed to be equal, where EMS_{pw}=EMS_{wc}=0.8 1/ud and LD_{pw}=LD_{wc}=4 uw, respectively. It is noted that the GHG emission-minimization objective function *OBJ2* and risk-minimization objective function *OBJ3* are quantified through calculating the emission index and risk index, which are relative value. The optimal solution of objective function *OBJ2* and *OBJ3* are achieved through comparing different scenarios, and the absolute value of individual scenario is meaningless. Furthermore, objective function *OBJ2* and *OBJ3* are unitless, and the unit 1/ud of emission factors EMS_{sp}, EMS_{pw} and EMS_{wc}, and 1/uw of risk index RK_{sp}, RK_{pw} and RK_{wc} are applied in order to eliminate the units of Eqs. 2 and 3, respectively.

Table 1. Input parameters of supplier *s*, candidate locations for production plant *p*, and candidate locations for warehouse *w*

Supplier	Parameters			Producer	Parameters			Warehouse	Parameters		
	PC_s [uc][a]	CAP_s[uw][b]	RK_s		FC_p [uc]	C_p [uc]	CAP_p [uw]		FC_w[uc]	C_w [uc]	CAP_w [uw]
s_1	760	500	0.2	p_1	500000	750	300	w_1	220000	80	250
s_2	320	100	0.5	p_2	480000	870	250	w_2	290000	65	350
s_3	400	140	0.4	p_3	515000	745	400	w_3	175000	95	200
s_4	80	500	0.3	p_4	450000	960	350	w_4	240000	75	350
s_5	102	350	0.7	p_5	475000	905	325	w_5	310000	60	450
s_6	115	450	0.3								
s_7	110	400	0.5								

[a]uc=unit currency, the same abbreviation is also applied in subsequent parts of this section.
[b]uw=unit weight, the same abbreviation is also applied in subsequent parts of this section.

Table 2. The unit transportation costs, distance and risk index of the 1st stage inter-facility transportation between supplier *s* and producer *p*

Supplier	Parameter TC_{sp}[uc]					Parameter DIS_{sp} [ud][c]					Parameter RK_{sp} [1/uw][d]				
	p_1	p_2	p_3	p_4	p_5	p_1	p_2	p_3	p_4	p_5	p_1	p_2	p_3	p_4	p_5
s_1	80	75	95	45	60	8	7.5	9	3	5.5	0.8	0.6	0.85	0.5	0.55
s_2	102	90	75	40	65	9.2	7	6	3.5	5	0.95	0.8	0.7	0.5	0.55
s_3	55	60	70	65	65	4.5	5	6.5	5.5	5.7	0.45	0.75	0.6	0.65	0.55
s_4	80	90	95	40	75	8.2	8.7	9	3.2	9	0.65	0.85	0.9	0.5	0.65
s_5	55	105	95	45	75	4.5	9.7	8.8	3.2	6.5	0.45	0.95	0.8	0.55	0.8
s_6	58	90	75	102	70	5.9	8.8	7.2	9.8	6.4	0.6	0.7	0.8	0.95	0.65
s_7	75	45	60	95	55	7.1	3.8	6.2	10.1	6.7	0.7	0.5	0.75	0.85	0.6

[c]ud=unit distance, the same abbreviation is also applied in subsequent parts of this section.
[d]1/uw=1/unit weight, the same abbreviation is also applied in subsequent parts of this section.

Table 3. The unit transportation costs, distance and risk index of the 2nd stage inter-facility transportation between producer *p* and warehouse *w*

Producer	Parameter TC_{pw}[uc]					Parameter DIS_{pw} [ud]					Parameter RK_{pw} [1/uw]				
	w_1	w_2	w_3	w_4	w_5	w_1	w_2	w_3	w_4	w_5	w_1	w_2	w_3	w_4	w_5
p_1	65	55	40	50	55	7	6	5.5	6.5	6	0.8	0.6	0.5	0.5	0.55
p_2	45	75	55	50	45	5	5.5	4.5	5	4.5	0.4	0.9	0.6	0.6	0.5
p_3	75	45	50	55	65	7.5	5	5.3	6	6.5	0.8	0.5	0.5	0.5	0.7
p_4	70	55	45	65	75	7.2	6	4.8	6.2	7.3	0.8	0.7	0.5	0.6	0.7
p_5	45	75	55	60	50	5	5.7	5.5	5.5	5	0.5	0.75	0.6	0.6	0.5

Table 4. The unit transportation costs, distance and risk index of the 3rd stage inter-facility transportation between warehouse w and customer c

Warehouse	Parameter TC_{wc}[uc]				Parameter DIS_{wc} [ud]				Parameter RK_{wc} [1/uw]			
	c_1	c_2	c_3	c_4	c_1	c_2	c_3	c_4	c_1	c_2	c_3	c_4
w_1	80	82	75	65	9	9.5	8	7.5	0.9	0.8	0.7	0.6
w_2	55	90	95	45	6	9.5	10	4.5	0.6	0.85	0.9	0.55
w_3	75	60	55	65	7.5	5.5	5	6	0.7	0.6	0.6	0.6
w_4	65	70	75	95	7	6.5	7.2	9	0.65	0.65	0.7	0.85
w_5	45	55	85	80	5	6	9.5	9	0.5	0.55	0.9	0.85

In order to test the performance of the proposed multi-objective GrSCND model, the model is coded and resolved by using Lingo solver, and all the model computations are performed on a Inter(R) Core(TM)2 2.13 GHz computer with 2 GB RAM and 150 GB hard drive capacity under Windows 7 operating system. The tested weights of cost utility, GHG emission utility and risk utility are set to 0.4, 0.3 and 0.3, respectively. The time consumed and iterations performed to calculate individual maximum and minimum costs, individual maximum and minimum GHG emissions, individual maximum and minimum risks, and minimum overall utility are presented in Table 5, and the objective value of those scenarios are also given in this table. It is illustrated from the result, the calculation of individual cost-minimization objective and overall utility are much more complicated and time consuming than the calculation of GHG emission-minimization objective and risk-minimization objective due to the larger number of integer variables and nonlinear variables. Besides, it is also shown from the table that, in this GrSCND model, the calculation of maximum achievable value is much easier and less time consuming than the calculation of minimum achievable value.

Table 5. The objective value, time consumed and iterations performed of each scenario

Scenario	Objective value	Time (s)	Iterations
Maximum individual costs	5246727 uc	4	1421
Minimum individual costs	2859436 uc	8	58513
Maximum individual GHG emissions	3010.529	1	549
Minimum individual GHG emissions	1462.585	1	332
Maximum individual risks	2320.375	1	437
Minimum individual risks	1335.4	1	1247
Minimum weighted sum utility	0.0914942	14	32474

Table 6 presents the selection of suppliers, selection of candidate locations for production plants and warehouses, as well as the value of corresponding weighted sum utility of four selected scenarios: individual minimum costs, individual minimum GHG emissions, individual minimum risks and minimum overall sum weighted utility. It is noted that the maximum value of each individual scenario is not taken into consideration in this comparison, because they are introduced in weighted sum utility method as bench mark parameters to represent the "worst solution" and determine maximum achievable deviation between the "best solution" and the "worst solution" of each scenario, and the independent comparison of the "worst solutions" is therefore meaningless to achieve the optimal solution in this case study. As shown in the table, the individual minimum costs objective has the best weighted sum utility comparing with the other two individual scenarios, and suppliers *s4*, *s5*, *s7*, candidate locations *p1*, *p3*, *p5*, *w3* and w5 are chosen in this scenario. The increase of the overall sum weighted utility are mainly contributed by the individual risk utility which equals to 0.3149, and this is caused by the relatively high risk index in 1st stage transportation of this scenario. When the optimal value of individual GHG emission objective is achieved, suppliers *s3*, *s4*, *s5*, *s7*, candidate locations *p1*, *p2*, *p3*, *p4*, *w2*, *w3* and *w5* are selected. In this scenario, both costs and GHG emissions are increased, the significant increase in cost utility (0.3749) due to more suppliers selected and more facilities opened is the main contributor in the increase of overall weighted sum utility, besides, the individual risk utility is relatively high as well. When the individual risk objective function reaches its optimal value, suppliers *s1*, *s3*, *s6*, and candidate locations *p1*, *p2*, *p3*, *w3* and *w5* are selected. In this scenario, both cost utility and GHG emission utility increase significantly. In order to have higher reliability and lower risks of suppliers, the purchasing costs of raw materials are increased dramatically, and the value of cost utility will then be increased to 0.3831 which takes the largest share of the overall weighted utility. Furthermore, the GHG emission utility increases to 0.3594 due to the increased numbers of transportation of raw materials and finished products in this scenario. If the system performance of optimal overall weighted sum utility is converted to 100%, the system performance of individual minimum costs, individual minimum GHG emissions and individual minimum risks can accordingly be converted to 71.6%, 40.7% and 25.5%, respectively, which is illustrated in Figure 2.

Table 6. The value of weighted sum utility, and selection of suppliers and candidate locations of the four selected scenarios

Scenario	Weighted sum utility	Supplier							Producer					Warehouse				
		s_1	s_2	s_3	s_4	s_5	s_6	s_7	p_1	p_2	p_3	p_4	p_5	w_1	w_2	w_3	w_4	w_5
MinIC[e]	0.127762				■	■		■	■		■		■			■		■
MinIGE[f]	0.223926			■	■	■		■	■	■	■	■			■	■		■
MinIR[g]	0.359397	■		■			■		■	■	■		■	■	■	■		■
MinWSU[h]	0.0914942						■	■	■	■	■					■		■

[e]MinIC=minimum individual costs, the same abbreviation is also applied in subsequent parts of this section.
[f]MinIGE=minimum individual GHG emissions, the same abbreviation is also applied in subsequent parts of this section.
[g]MinIR=minimum individual risks, the same abbreviation is also applied in subsequent parts of this section.
[h]MinWSU=minimum weighted sum utility, the same abbreviation is also applied in subsequent parts of this section.

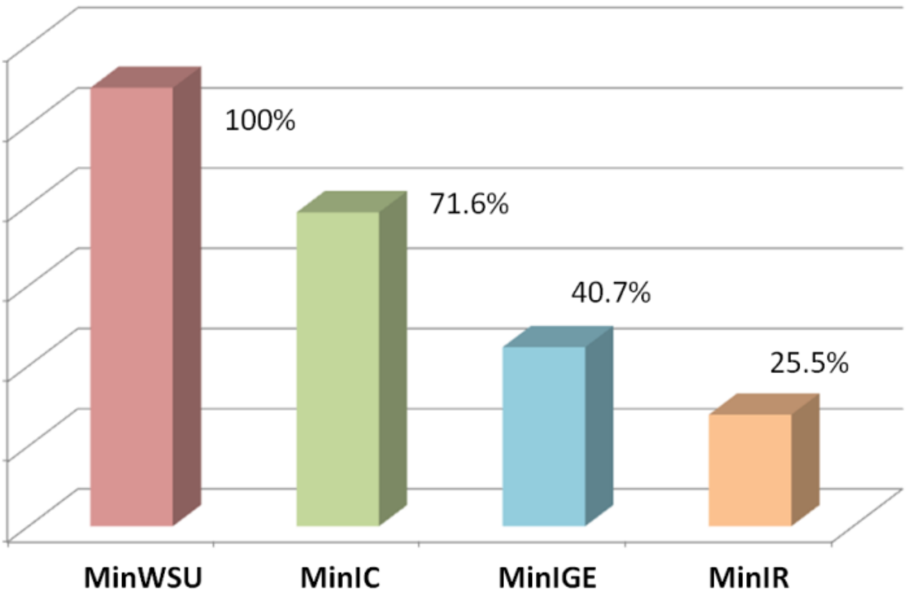

Figure 2. Comparison of the overall system performance of the four selected scenarios

When the overall weighted sum utility objective function achieves its optimal value, suppliers *s6*, *s7*, candidate locations *p1*, *p2*, *p3*, *w3* and *w5* are chosen. Table 7 illustrates the amount of raw materials and/or finished products transported between different facilities at each stage of the supply chain. It is noted that the result achieved in this scenario is mostly influenced by the cost utility due to its relatively large weight, and the result also compromises with the GHG emission utility and risk utility in order to balance the trade-off among those objectives. For instance, the selection of suppliers in optimal overall weighted scenario is achieved through balancing the cost utility and risk utility associated with the purchase and transportation of raw materials. Supplier *s4* has the lowest unit purchasing price and relatively low risk index, however, it is not chosen due to its high unit costs and risk index with respect to the transportation of raw materials, and suppliers *s6* and *s7* are therefore selected to maximize the overall system performance.

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The optimal number, locations and inter-facility transportation of raw materials and/or finished products are determined by using the proposed GrSCND model, and the result is achieved through balancing the trade-off among cost utility, GHG emission utility and risk utility. The result is quite convincing, and further sensitive analysis can also be performed, if necessary, to test how and to what extend the optimal supply chain network configuration can be affected by different objectives.

Table 7. The amount of raw materials and/or finished products transported between different facilities at each stage

`		*s6*	*s7*	*p1*	*p2*	*p3*	*w3*	*w5*
AT_{sp} [uw]	*p1*	300						
	p2		250					
	p3	143.75	150					
AT_{pw} [uw]	*w3*					200		
	w5			240	175	35		
AT_{wc} [uw]	*c1*							120
	c2						10	240
	c3						40	
	c4						110	

5. Conclusion

This work has presented a novel research on GrSCND model for companies and supply chains operated in high north arctic regions, where natural and infrastructural challenges bring more complexities in GrSCND than other regions, in order to enhance both competitive competence and sustainability. Compared with previous researches, the formulation and minimization of supply chain risks and reliability are taken into consideration in this study, which is an extremely important influencing factor accounted in the design and planning of supply chains operated in this region. The proposed computational model is formulated based upon multi-objective MIP method which aims to determine the number, locations and inter-facility transportation of raw materials and/or finished products through simultaneously minimizing the overall supply chain costs, GHG emissions and risks, and weighted sum utility method is employed to composite those objectives with different measures of units. A numerical experiment is performed as well to explicitly present the applications of the proposed multi-objective MIP model for GrSCND in high north regions, and Lingo solver is applied in coding and resolving the computational optimization problems.

The model is developed primarily for the design and planning of supply chains operated in high north regions, however, it is also perfectly applicable for the supply chains operated in other regions where the consideration of supply chain risks plays an important role. Besides, the selection of suppliers is also taken into account in this model, which is another crucial influencing factor for GrSCND. For example, in a global supply chain network, the reliability and safety of suppliers in some countries or regions may be significantly affected by some influencing factors, i.e., political stability, tax and tariff, infrastructure, etc., so it is of great importance to account the selection of suppliers in the decisional process of GrSCND so as to minimize the supply chain risks.

The mathematical model is formulated and developed under certain input parameters, however, the design and planning of supply chain network is always a strategic decision which has significant influence on long-term profitability, competitiveness and sustainability of a supply chain, and some input parameters may have great changes within its life span, furthermore, some parameters are stochastic in nature and impossible to be quantified accurately, and this will dramatically increase the level of difficulty in dealing with uncertainties. Therefore, the appropriate treatment of uncertain and stochastic input parameters are suggested for further improvement of the multi-objective MIP model for GrSCND in high north arctic regions.

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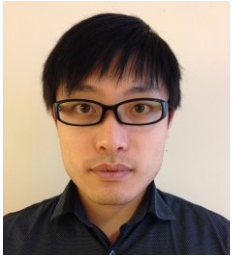

Hao Yu received his B.Eng degree in Environmental Engineering from Beijing Institute of Petrochemical Technology, P.R. China, in 2008, and his M.Sc degree in Industrial Engineering from Narvik University College, Norway, in 2012. He is currently working as a research assistant at Department of Industrial Engineering, Narvik University College. His research interests include computational optimization, operational research, mathematical modelling as well as their applications in supply chain management, transportation and logistics network design, and waste management.
E-mail address: Hao.Yu@hin.no

Wei Deng Solvang received her M.Sc. in the field of Production Engineering at Narvik University College, Norway in 1997. In 2001, she received her Ph.D. from Norwegian University of Science and Technology, Norway, in the field of performance measurement in managing supply chains. Dr. Solvang is currently working as Associated Professor at Narvik University College, Norway. She has over extensive publications at peer-reviewed international conferences and journals. Her main interest fields are supply chain management and sustainable logistics. She is a member of the Nordic Logistics Research Network (NOFOMA), Production and Operations Management Society (POMS) and the Association of European Operational Research Society as well as the Supply Chain Council. Dr. Solvang is also the Department Head of Industrial Engineering at Narvik University College, Norway.
E-mail address: wds@hin.no

Chen Chen received her Bachelor degree in Biology from Faculty of Life Science in Hubei University, P.R. China, in 2008, and her M.Sc degree in Energy and Environmental Technology from Telemark University College, Norway, in 2011. She started a PhD work at Norut Narvik AS since then. The main task of her PhD work is to optimize a conceptual designed integrated chemical complex with natural gas and locally sourced minerals as the main raw materials.
E-mail address: chen@tek.norut.no

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