A Multi-Criteria Decision Analysis to Include Environmental, Social, and Cultural Issues in the Sustainable Aggregate Production Plans

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Abstract

Aggregate production planning (APP) that is an important concept of supply chain management (SCM), is one of the tools to determine production rates, inventory levels, and workforce requirements for fulfilling customer demands in a multi-period setting. Traditional APP models employ a single objective function to optimize monetary issues only. In this paper, we present a multi-objective APP model to analyze economic, social, environmental, and cultural pillars inclusively; moreover, each pillar includes several sub-pillars in the model. The resulting model includes an accurate representation of the problem with binary and continuous variables under sustainability considerations. We illustrate the effectiveness of the model in an appliance manufacturer and solve the problem using an exact solution method for multi-objective mixed-integer linear programs (MOMILP). We find a large number of the non-dominated (ND) points in the objective function space and analyze their trade-offs systematically. We show how this framework supports multiple criteria decision making process in the APP problems in the presence of sustainability considerations. Our approach provides a comprehensive analysis of the ND points of sustainable APP (SAPP) problems, and hence, the trade-offs of objective functions are insightful to the decision makers.

Keywords: Supply Chain Management, Sustainability, Aggregate Planning, Multi-Criteria Decision Analysis, Multi-Objective Optimization, Mixed-Integer Linear Programming

1. Introduction

The impacts of high-speed industrialization attract the attention of many practitioners and researchers to sustainability. Depletion of large amounts of non-renewable resources and the role of cultural and social issues in SCM are crucial points that deserve more attention. Thus, leading companies have started to make decisions compatible with the sustainability considerations by significant investments ([Chopra and Meindl, 2016](#)). The concepts of SCM spread out through the entire organization; hence, sustainability can be tied to SCM and play a vital role for improving the decisions of supply chain managers. Then, sustainable SCM (SSCM) is an important enabler of significant improvements for the society in long-term. SSCM evolves supply chains, their individuals, and behaviors such that non-economic issues are respected ([Hopkins et al., 2009](#); [PwC, 2013](#); [Arslan, 2011](#)).

Several factors increase the importance of sustainability. First, sustainability affects the company image; customers measure, compare, and rank the performance of these companies in sustainability. Then, sustainability adds value to the provided services or products, and hence, customers show tendency to these sustainable services/products ([Hopkins et al., 2009](#); [Melnik et al., 2010](#); [Bask et al., 2013](#)). Conversely, customers do not prefer non-sustainable products. Customers may pay more for sustainable products ([Trudel and Cotte, 2009](#)). Second, sustainability considerations may be initiated as a response to some pressures from government regulations ([Massaroni et al., 2015](#); [Varsei, 2016](#)). Third, natural resources depletion is a critical risk for the earth ([Chopra](#)

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and Meindl, 2016), and hence, to avoid dissolving a business, companies diversify their raw material/energy sources. Fourth, sustainability increases the performance of a company by being more appealing to the customers in competitive markets.

We observe that optimization and mathematical models deserve further discussion in terms of sustainability considerations since they are practically implementable for real-world problems (Davizón et al., 2015). The modification of traditional models by considering the requirements of sustainability is argued to be very important (Türkay, 2008; Benjaafar et al., 2013). On the other hand, multi-criteria decision making approaches are useful to consider economic, environmental, and social concerns which are termed as "Triple Bottom Line" (TBL), simultaneously (Elkington, 1998; Eskandarpour et al., 2015). Moreover, a decision maker may be interested in additional pillars not included in the TBL since three-dimensional models cannot completely characterize the bottom lines of sustainability (Cities and Governments, 2010). For example, the pillar of cultural concerns plays an essential role in sustainability and can be proposed as the fourth pillar (Yencken and Wilkinson, 2001; Soini et al., 2015; Astara, 2014).

We note that each pillar of sustainability has several sub-pillars. In terms of environmental aspects, energy and water consumption, using renewable energy sources, closed-loop supply chain, material selection, greenhouse gas (GHG) emission, etc. are mentioned in the literature. In terms of social aspects, working conditions, corporate social responsibility (CSR) projects, the effect of layoffs, working hours, training and education, child labor, diversity and equal opportunity, health and safety, etc. are discussed (Pfeffer, 2010; Massaroni et al., 2015; Varsei, 2016; Anvari and Turkey, 2017). However, the studies on SSCM, which intensely focus on both environmental pillar and social aspects of sustainability, attract relatively less interests (Salmona et al., 2010; Pfeffer, 2010; Brandenburg et al., 2014; Massaroni et al., 2015; Varsei, 2016).

SCM deals with several areas in a supply chain to improve material/information flow between the echelons; customer relationship management, procurement, manufacturing management, and product development are the cores of SCM. Manufacturing management is one of the main activities that is included in a supply chain and has a significant relationship with APP (Lackes, 2008; Towers and Ashford, 2001). When a supply chain manager needs to incorporate sustainability in SCM, focusing on manufacturing and planning are included in the most critical functions due to their strong effect on the pillars of sustainability. APP is the core activity in SCM that determines the amount of goods produced as well as planning the labor requirements. Therefore, we mainly focus on APP in this paper.

APP problems are represented through mathematical models which provide approximate solutions for macro planning at the firm level (Nahmias and Cheng, 2009). APP determines production rates, inventory levels, and workforce requirements of a production system to minimize the total costs — or maximize the total profit — while fulfilling customer demand in a certain period of time. Aggregation is vital for this planning since it is not possible to predict the timing and demand for individual items with any degree of accuracy. So, if an organization focuses on individual items, it will lose the flexibility to respond to the market (Stevenson et al., 2007). Then, an aggregate plan is provided for a representative product type. Note that disaggregation is required to translate an aggregate plan to more practical solutions and approaches at the lower decision levels of the firm (Nahmias and Cheng, 2009).

The main functionality of APP is to plan for tactical decisions where decisions in this level cover the next 2 to 18 months. However, a large number of issues can be included in APP, and hence, it can also appear as a powerful tool for considering strategic decisions which are closely connected with tactical decisions in the planning horizon. Then, APP programs enable to incorporate social and cultural aspects for establishments of an environment promoting sustainability. Therefore, a reformulation of an APP model meets the requirement of specific situations in practice and addresses economic criteria while discussing non-economic issues (Schroeder and Larson, 1986).

Eskandarpour et al. (2015) analyze 87 articles that consider mathematical models for supply chain networks. The study states that mixed-integer programs are the most used models and two third of the proposed models include more than one objective function. In some cases, multiple objective functions are used corresponding to the number of the pillars. The studies based on mathematical models adjust traditional models or present new mathematical models with sustainability considerations. The current literature mostly includes empirical studies rather than models and network designs based on the sustainability considerations (Salmona et al., 2010; Brandenburg

et al., 2014). We summarize the most important and related studies that use mathematical modeling for the sustainability considerations in Table 1. This table shows that the developed supply chain mathematical models do not inclusively consider several concerns to address sustainability considerations.

Table 1: A summary of mathematical model-based studies

Study	Env.	Soc.	Scope
Zhou et al. (2000); Chen and Andresen (2014); Bhinge et al. (2015)	✓	✓	Supply chain optimization
Tsoufas and Pappis (2008); Aviso et al. (2011)	✓	×	Supply chain optimization
Lu et al. (2007); Yamada et al. (2015)	✓	×	Supplier selection
Azadnia et al. (2015)	✓	✓	Supplier selection and order allocation
Türkay (2008)	✓	×	Energy production system design and operation
Dehghanian and Mansour (2009); Harraz and Galal (2011)	✓	✓	Recovery network design
Lee et al. (2010)	✓	×	Logistics network design
Arslan and Turkay (2013)	✓	✓	Economic order quantity
Chen et al. (2013); Hovelaque and Bironneau (2015)	✓	×	Economic order quantity
Pérez-Fortes et al. (2012)	✓	✓	Biomass energy system design and operation
Benjaafar et al. (2013)	✓	×	Lot-sizing
Santibañez-Aguilar et al. (2014)	✓	✓	Biorefinery site selection and operations planning
Validi et al. (2014)	✓	×	Capacitated distribution network design
Fareeduddin et al. (2015)	✓	×	Closed-loop supply chain network design
Soleimani et al. (2017)	✓	✓	Closed-loop supply chain network design
Garbie (2015)	✓	✓	Manufacturing enterprises
Schenker et al. (2015)	✓	×	Manufacturing planning
Türkay et al. (2016); Hahn and Brandenburg (2017)	✓	✓	Aggregate production planning
Anvari and Turkay (2017)	✓	✓	Hub location for food supply chain
Musavi and Bozorgi-Amiri (2017)	✓	✓	Facility location

In this paper, we aim to combine the concepts of APP with a number of sustainability considerations and propose a framework that supports the analysis of multiple criteria in decision making process. In terms of mathematical modeling, we present a SAPP model by the incorporation of the cultural vitality and placing a significant emphasis on social issues which are not sufficiently addressed in the literature. Our SAPP model is a MILP that includes both binary and continuous decision variables. Note that binary variables represent strategic or more important tactical decisions in many cases. One of the recent studies that redesign the APP model with economic viability, environmental responsibility, and social equity is proposed by Türkay et al. (2016). They reveal gaps in the current literature in terms of combining the economic, environmental, and social pillars within the APP models. Applying multi-criteria approaches for SAPP in chemical industries is also proposed while sustainability considerations are addressed by profit, overtime, and carbon emission as the sub-pillars of TBL (Hahn and Brandenburg, 2017). In this regard, we enrich the model by including several sub-pillars for the economic, environmental, social, and cultural pillars of sustainability.

The sustainability considerations in SCM and APP lead to a multi-criteria decision making problem, and hence, it is necessary to analyze the effect of these often-conflicting criteria systematically. In terms of the solution method and analysis of the framework, we find a large subset of the ND points such that each of them corresponds to a different binary solution or strategic decision. Therefore, we obtain a large number of strategic decisions that result in ND points or efficient solutions and are not considered in the cost-oriented solution approach. We also comprehensively analyze the trade-offs of four objective functions and solutions. We show the effectiveness of the framework on a household appliance manufacturer. We show that our multiple criteria decision analysis approach supports the decision making process in the SAPP problems and provides insightful ideas for decision makers in an industrial case study.

This paper is organized as follows. We define our problem, state the constraints and the terms of objective functions, and establish a link between the constraints/objective functions and sustainability in Section 2. Then, we establish our quad-objective programming model to address sustainability considerations in an APP problem in Section 3. In Section 4, we briefly describe our solution method for solving the quad-objective APP model and use it for an industrial case study. Next, we discuss the results to show a few managerial insights. Finally, we show our conclusions

and contributions in Section 5.

2. Problem Definition

Traditional APP models are cost-oriented; however, the widespread adoption of economic factors while ignoring environmental, social, and cultural issues in a supply chain is a flawed approach. The economic, environmental, social, and cultural issues build the pillars of an organization altogether. We aim to address sustainability considerations in a supply chain by building a multi-objective approach in APP. We remodel the traditional APP model and present a groundbreaking APP model with four objective functions and some constraints to assign equal importance to the economic, environmental, social, and cultural pillars.

Figure 1 shows our approach for each pillar of sustainability. For economic issues, we discuss the costs and aim to maximize profit. Then, in the environmental pillar, we address reducing GHG emission, non-renewable energy use, and integration of a renewable energy source into the system as sub-pillars. In terms of the social pillar, we focus on employee safety improvement, reducing work-family conflicts, employee gender equity, customer satisfaction level, and implementing CSR projects. In the pillar of cultural vitality, we discuss employee well-being and performing innovative projects for enriching the cultural environment towards environmental/social stewardship and inclusiveness. We consider these four pillars and sub-pillars in the objective functions and constraints.

Figure 1: The pillars and sub-pillars addressed in the SAPP model

In the traditional APP models, the following costs are considered: raw material, cost of regular and overtime working hours, cost of hiring and firing workers, inventory holding cost, stock-out cost, and subcontracting cost (Chopra and Meindl, 2016; Nahmias and Cheng, 2009; Stevenson et al., 2007; Russell and Taylor-Iii, 2008). We keep these costs and add the following monetary issues to our model.

- tax of carbon dioxide emission (calculated for the emission generated by production, inventory holding, and subcontract activities),
- electricity cost (calculated for the consumed electricity in production, inventory holding, and subcontract activities),
- cost of integration of a renewable energy source into the system (amortized cost with respect to the new energy source),
- cost of implementing CSR projects, and
- cost of substituting old technologies with new innovative technologies (amortized cost with respect to the innovative projects).

In order to address several sub-pillars in environmental, social, and cultural issues, we use different indicators. These indicators are shown in Table 2. Moreover, we show that either the indicators are used within constraints, or objective functions, or both. When an indicator is used in the constraints, a formulation of the indicator — for example the sum of the indicator over the planning horizon — is either restricted or considered for formulating a number of constraints. When an indicator is used within the objective functions, a formulation of that is either minimized/maximized or used to formulate other sub-pillars.

Table 2: Pillars, sub-pillars, and their indicators in SAPP

pillar	sub-pillar	indicator	obj. func.	con- straint
environ- ment	GHG emission	amount of GHG emission because of different activities	✓	✓
	consumed non-renewable energy	consumed electricity generated from non-renewable sources	✓	✓
		integration of a renewable energy source	✓	✓
society	employee safety	overtime working hours	✓	✓
		training newly hired workers	×	✓
	work-family conflicts	overtime working hours	✓	✓
	employee gender equity	number of female workers	✓	✓
		minimum proportion of the employees of a gender	×	✓
	Customer satisfaction level	number of stock-outs	✓	✓
culture	CSR projects	number of implemented CSR projects	✓	✓
	employee well-being	number of layoffs	✓	✓
	innovative projects	number of performed innovative projects	✓	✓

In Table 3, for each indicator, we report a number of issues which make the indicator important. In other words, the existence of these issues makes using the mentioned indicators reasonable. These issues motivate practitioners and researchers to control the indicators for establishing sustainable supply chains.

Regarding the environmental pillar, we assume that manufacturing, inventory holding, and subcontracting activities are the main activities where energy is used. Moreover, the emitted GHG or carbon dioxide is originated from these activities.

Table 3: Important indicators and their significance

indicator	related issues, significance, and motivations
amount of GHG emission and consumed electricity generated from non-renewable sources	air/water pollution, overusing non-renewable energy sources, overusing raw materials, damaging ecosystems, biodiversity loss, deforestation, increasing global average temperature (Handfield et al., 2005; Türkay, 2008; Aviso et al., 2011; Bhinge et al., 2015; Anvari and Turkay, 2017)
integration of a renewable energy source	independency from non-renewable energy sources
overtime working hours/ training newly hired workers	health, safety, and living condition of individuals, communities, customers, and stakeholders (Dyllick and Hockerts, 2002; Bhinge et al., 2015), a larger number of workplace accidents when overtime increases and training programs are not held (Türkay et al., 2016; May et al., 2015; Hrymak and Perezgonzalez, 2007; Bibowei, 2015; Wagstaff and Lie, 2011)
number of female workers/ minimum proportion of the employees of a gender	equal job opportunities regardless of ethnicity, gender, age, religion, disability, nationality, and sexuality (CAAWS, 2017), a powerful economy when percentage of female employees is high (Bhinge et al., 2015; European Parliament, 2016)
number of stock-outs	the right product in the right place at the right time (ECR, 2017)
number of implemented CSR projects	voluntarily CSR projects add value to the society and improve financial performance, company image improvement (Sarkis et al., 2010; Zimara and Eidam, 2015)
number of layoffs	physical and mental problems for a worker who got fired, tendency to violence and suicide increase with a layoff (Hawkes, 2001)
number of performed innovative projects	creativity, and innovation (Hawkes, 2001), low price, responsiveness, and high quality attract people to a product or a job (Melnyk et al., 2010), innovative systems are more environment-friendly, longer holidays and compensations when production capacity is larger

Organizations take social and ethical roles to solve the problems of society by CSR projects. Therefore, we consider that the implementation of CSR projects increases the social performance

and positively affects the customer demand. When companies invest on CSR projects, they also require to advertise and announce their contributions to the society. Regarding the type of project, when a project is implemented for one period, after a number of periods, the society positively reacts to the social contributions and is attracted to the products of these companies. The market's positive reaction to the project lasts for a number of periods. We assume that it lasts for one month.

Cultural heritage is an important and unique asset to humanity that cannot be replaced or renewed. Culture addresses creativity, knowledge, and diversity in sustainable development (Cities and Governments, 2010). Moreover, an intellectual wealth of any group is part of their culture and requires improvement. Although cultural issues can be interpreted as a part of the social pillar of sustainability, we separate culture as the fourth pillar to place more emphasis on it. We assume that while performing an innovative project in a period decreases the production capacity of that period, it improves the production capacity in the subsequent periods. Note that we call a project innovative if it results in a larger production capacity while less energy and less GHG is emitted. The lag between performing an innovative project and the affecting time varies from one to multiple periods. We assume that the size of the performed innovative projects is such that we can see the positive effects one period after the implementation. Then, an organization takes the advantages of the performed projects until the end of planning horizon.

In general, when an organization commits to CSR and innovative projects as a strategic priority, the individual projects can be implemented within several months and the results for some of these projects appear in one or a few months (e.g. energy efficiency improvement or changing the equipments in the assembly lines to accommodate female or disabled workers). Therefore, the effects of such innovative and CSR projects can be observed in short/medium-term which are within the scope of SAPP.

3. SAPP Model

A number of basic mathematical models and assumptions for APP problems are presented in the literature (Chopra and Meindl, 2016; Nahmias and Cheng, 2009; Stevenson et al., 2007; Russell and Taylor-Iii, 2008). We provide a mathematical programming model for APP problems with sustainability considerations that are discussed in Section 2. We establish the SAPP model with four objective functions using continuous and discrete decision variables. We address economic, environmental, social, and cultural concerns by several terms and indicators as discussed in Section 2 and Table 2. In Table 4, we define sets and parameters, and decision variables are defined in Table 5.

Let z_{eco} given in (1) be the objective function associated with the economic pillar to maximize the total profit.

$$\max z_{eco} = \sum_{t \in T} sp \times S_t \quad (1a)$$

$$- \sum_{t \in T} c_L \times h \times n_t \times (MW_t + FW_t) \quad (1b)$$

$$- \sum_{t \in T} (c_H \times (MH_t + FH_t) + c_F \times (MF_t + FF_t)) \quad (1c)$$

$$- \sum_{t \in T} c_O \times O_t \quad (1d)$$

$$- \sum_{t \in T} c_M \times P_t \quad (1e)$$

$$- \sum_{t \in T} c_I \times I_t \quad (1f)$$

$$- \sum_{t \in T} c_{SU} \times SU_t \quad (1g)$$

$$- \sum_{t \in T} c_{SO} \times SO_t \quad (1h)$$

$$- \sum_{t \in T} c_E \times (e_I \times I_t + e_P \times P_t + e_{SU} \times SU_t - e_t^{RE} \times X_t^{RE}) \quad (1i)$$

$$- \sum_{t \in T} c_{CT} \times (g_I \times I_t + g_P \times P_t + g_{SU} \times SU_t) \quad (1j)$$

$$- \sum_{t \in T} c_t^{RE} \times X_t^{RE} \quad (1k)$$

$$- \sum_{t \in T} \sum_{j \in J} c_{tj}^{CSR} \times CSR_{tj} \quad (1l)$$

$$- \sum_{t \in T} \sum_{k \in K} c_{tk}^{IN} \times Y_{tk}, \quad (1m)$$

where Eq (1a) is the revenue of selling products. (1b), (1c), and (1d) are the salary of employees, hiring/firing costs, and overtime costs, respectively. Material, inventory holding, subcontracting, and stock-out costs are presented in (1e), (1f), (1g), and (1h), respectively. Eq (1i) includes energy cost of inventory holding, manufacturing, and subcontracting activities with the saving originated from integrating a renewable energy source into the system. We assume that when a manufacturer integrates a renewable energy source into the system at period t , he spends c_t^{RE} for the integration. Then, he uses the supplied energy (e_t^{RE}) for the rest of the planning horizon. Hence, we consider this issue as shown in (1i). (1j) displays the tax of carbon dioxide emission because of inventory holding, manufacturing, and subcontracting activities. Equations (1k) and (1l) incorporate the cost of integrating a renewable energy source and the implementation of CSR projects, respectively. Eq (1m) demonstrates the net cost of performing innovative projects such that savings from the tax of reduced energy usage and GHG emission — as the results of innovation projects — are calculated within the net cost.

For the environmental pillar, let z_{env} given in (2) be the objective function that shows environmental issues.

$$\min z_{env} = \text{coef}_{env1} \left(\sum_{t \in T} (g_I \times I_t + g_P \times P_t + g_{SU} \times SU_t) \right) \quad (2a)$$

$$\begin{aligned} & - \sum_{t \in T} \sum_{k \in K} (g_{tk}^- \times Y_{tk}) \\ & + \text{coef}_{env2} \left(\sum_{t \in T} (e_I \times I_t + e_P \times P_t + e_{SU} \times SU_t) \right) \quad (2b) \\ & - \sum_{t \in T} (e_t^{RE} \times X_t^{RE}) - \sum_{t \in T} \sum_{k \in K} (e_{tk}^- \times Y_{tk}), \end{aligned}$$

where (2a) is the total GHG emission multiplied by coef_{env1} and (2b) is the total consumed non-renewable energy multiplied by coef_{env2} (coef_{env1} and coef_{env2} are used due to the unit and scale difference of the sub-pillars, and discussed in Section 4.2). Note that performing innovative projects decreases GHG emission and energy consumption (see terms $-\sum_{t \in T} \sum_{k \in K} (g_{tk}^- \times Y_{tk})$ and $-\sum_{t \in T} \sum_{k \in K} (e_{tk}^- \times Y_{tk})$ in (2a) and (2b), respectively). Moreover, integrating a renewable energy source into the system decreases the consumed energy generated by non-renewable sources as of $\sum_{t \in T} (e_t^{RE} \times X_t^{RE})$.

z_{soc} given in (3) is the objective function for the social pillar.

$$\min z_{soc} = \text{coef}_{soc1} \left(\sum_{t \in T} O_t \right) \quad (3a)$$

$$+ \text{coef}_{soc2} \left(\sum_{t \in T} (MW_t - FW_t) \right) \quad (3b)$$

Table 4: The sets and parameters of the SAPP

T	The set of periods in the planning horizon and $t = 1, \dots, T $.	J	The set of CSR projects and $j = 1, \dots, J $.
K	The set of innovative projects and $k = 1, \dots, K $.		
sp	Selling price of a product (\$/item)	c_L	Salary of one worker per hour (\$/(worker×hour))
c_H	Cost of hiring a new worker (\$/worker)	c_F	Cost of firing a worker (\$/worker)
c_M	Material cost per product (\$/item)	c_O	Overtime cost per hour per worker (\$/(worker×hour))
c_I	Holding cost per product in one period (\$/(item×period))	c_{SU}	Subcontracting cost per product (\$/item)
c_{SO}	Stock-out cost per product (\$/item)		Carbon dioxide tax per tonne of carbon dioxide emission (\$/tonne)
c_E	Electricity cost per unit of energy (\$/kWh)	c_{CT}	Integration cost of a renewable energy source into the system in period t (\$)
c_{tj}^{CSR}	Implementation cost of CSR project j in period t (\$)	c_t^{RE}	The net cost of performing innovative project k in period t (\$)
g_I	GHG emission per product held in the inventory in a period (tonne/(item×period))	c_{tk}^{IN}	
g_{SU}	GHG emission per product which is subcontracted (tonne/item)	g_P	GHG emission for manufacturing a product (tonne/item)
e_P	Electricity used for manufacturing a product (kWh/item)	e_I	Electricity used per product held in the inventory in a period (kWh/(item×period))
e_t^{RE}	Generated energy by integrating a renewable energy source if it is integrated in period t (kWh)	e_{SU}	Electricity used per subcontracted product (kWh/item)
e_{tk}^-	Average reduction in the consumed electricity during the remaining part of the planning horizon if innovative project k is performed in period t (kWh)		Average reduction in GHG emission during the remaining part of the planning horizon if innovative project k is performed in period t (tonne)
ξ_e	Permitted maximum consumed electricity from non-renewable sources during the planning horizon (kWh)	ξ_g	Permitted maximum of GHG emission during the planning horizon (tonne)
o_{Lim}	Overtime limit per worker in a period (hour/period)	l_{Lim}	Permitted maximum percentage of layoffs in a period (%)
in_{Lim}	Minimum number of performed innovative projects during the planning horizon (# of projects)	csr_{Lim}	Minimum number of implemented CSR projects during the planning horizon (# of projects)
fm	Minimum proportion of the employees of a gender (%)		Maximum number of subcontracted products in a period (item/period)
d_t	Demand in period t (item)	su_{Lim}	Customer satisfaction level (%)
h	Regular-time working hours per day (hour/day)	α	Demand increment rate in period t if CSR project j is implemented such that it shows its impact in period t (%)
p_M	Average number of products that can be manufactured in a day by one experienced male worker (item/(worker×day))	d_{tj}^+	
pf	Average productivity rate of a female worker (%)	n_t	Number of working days in period t (day)
ca_{tk}^+	Capacity increase in period t thanks to performing innovative project k in one of previous periods (item)	ph	Average productivity rate of a newly hired worker (%)
FW_0	Initial female workforce level (worker)	ca_{tk}^-	Capacity decrease in period t because of performing innovative project k in period t (item)
		MW_0	Initial male workforce level (worker)
		I_0	Initial inventory level (item)

Table 5: The decision variables of the SAPP

P_t	# of manufactured products in period t (item)	O_t	Overtime working hours in period t ((worker×hour)/period)
I_t	# of products in warehouse at the end of period t (item)	S_t	# of sold products in period t (item)
SU_t	# of subcontracted products in period t (item)	SO_t	# of stock-outs in period t (item)
FW_t	# of female workers in period t (worker)	MW_t	# of male workers in period t (worker)
FH_t	# of hired female workers at the beginning of period t (worker)		# of hired male workers at the beginning of period t (worker)
FF_t	# of fired female workers at the beginning of period t (worker)	MH_t	# of fired male workers at the beginning of period t (worker)
X_t^{RE}	1 if renewable energy source is integrated in period t , 0 otherwise	MF_t	1 if CSR project j is implemented and shows its impact in period t , 0 otherwise
Y_{tk}	1 if innovative project k is performed in period t , 0 otherwise	CSR_{tj}	1 if innovative project k has already been performed in a period before t , 0 otherwise
		Y_{tk}^A	

$$+ coef_{soc3} \left(\sum_{t \in T} SO_t \right) \quad (3c)$$

$$- coef_{soc4} \left(\sum_{t \in T} \sum_{j \in J} CSR_{tj} \right), \quad (3d)$$

where (3a) minimizes the overtime working hours to improve the safety of employees and reduces work-family conflicts. Regarding the employee gender equity, we assume that fm — and consequently the constraints given in (5d) and (5e) — avoids having a large difference between male

and female workers. Therefore, we use (3b) to assign more priority to hiring female workers. (3c) minimizes the total stock-outs to improve customer satisfaction level. Moreover, we use (3d) to maximize the number of implemented CSR projects.

z_{cul} given in (4) is the objective function that models the cultural pillar in the system.

$$\max z_{cul} = -coef_{cul1} \left(\sum_{t \in T} (MF_t + FF_t) \right) \quad (4a)$$

$$+ coef_{cul2} \left(\sum_{t \in T} \sum_{k \in K} Y_{tk}^A \right), \quad (4b)$$

where (4a) minimizes the number of layoffs during the planning horizon to improve employee well-being. (4b) maximizes the number of performed innovative projects. Moreover, note that (4b) gives preference to performing innovative projects in the earlier periods of the planning horizon in order to have the increased capacity available at later periods.

Next, we formulate the constraints of the SAPP model. These constraints are constructed based on the sustainability considerations that is discussed in Section 2. Constraints given in (5) refer to the constraints that conduct directly the sustainability considerations. Furthermore, constraints given in (6) refer to the constraints of the traditional APP problem and identify the type of decision variables.

$$\sum_{t \in T} (g_I \times I_t + g_P \times P_t + g_{SU} \times SU_t) - \sum_{t \in T} \sum_{k \in K} (g_{tk}^- \times Y_{tk}) \leq \xi_g, \quad (5a)$$

$$\sum_{t \in T} (e_I \times I_t + e_P \times P_t + e_{SU} \times SU_t - e_t^{RE} \times X_t^{RE}) - \sum_{t \in T} \sum_{k \in K} (e_{tk}^- \times Y_{tk}) \leq \xi_e, \quad (5b)$$

$$O_t \leq o_{Lim} \times (MW_t + FW_t), \forall t \in T, \quad (5c)$$

$$fm \times (MW_t + FW_t) \leq FW_t, \forall t \in T, \quad (5d)$$

$$fm \times (MW_t + FW_t) \leq MW_t, \forall t \in T, \quad (5e)$$

$$S_t \geq \alpha \times d_t \times (1 + \sum_{j \in J} d_{tj}^+ \times CSR_{tj}), \forall t \in T, \quad (5f)$$

$$\sum_{t \in T} \sum_{j \in J} CSR_{tj} \geq csr_{Lim}, \sum_{t \in T} \sum_{k \in K} Y_{tk} \geq in_{Lim}, \quad (5g)$$

$$l_{Lim} \times (FW_{t-1} + MW_{t-1}) \geq FF_t + MF_t, \forall t \in T, \quad (5h)$$

$$Y_{1k}^A = 0, \forall k \in K, \quad Y_{tk}^A = \sum_{t' \in \{1, 2, \dots, t-1\}} Y_{t'k}, \forall k \in K, \forall t \in T \setminus \{1\}, \quad (5i)$$

$$\sum_{t \in T} Y_{tk} \leq 1, \forall k \in K, \quad \sum_{t \in T} X_t^{RE} \leq 1, \forall t \in T, \quad (5j)$$

$$MW_t = MW_{t-1} + MH_t - MF_t, \quad FW_t = FW_{t-1} + FH_t - FF_t, \forall t \in T, \quad (6a)$$

$$I_t = I_{t-1} + P_t + SU_t - S_t, \forall t \in T, \quad (6b)$$

$$S_t + SO_t = d_t \times (1 + \sum_{j \in J} d_{tj}^+ \times CSR_{tj}), \forall t \in T, \quad (6c)$$

$$P_t \leq p_M \times n_t \times (MW_t + FW_t \times pf - (1 - ph) \times MH_t - (pf - ph) \times FH_t) + \frac{p_M}{h} \times O_t + \sum_{k \in K} (ca_{tk}^+ \times Y_{tk}^A - ca_{tk}^- \times Y_{tk}), \forall t \in T, \quad (6d)$$

$$SU_t \leq su_{Lim}, \forall t \in T, \quad (6e)$$

$$\begin{aligned}
FW_t, MW_t, FH_t, MH_t, FF_t, MF_t &\in \mathbb{Z}^+ \cup \{0\}, \forall t \in T, \\
P_t, I_t, S_t, SU_t, SO_t &\in \mathbb{Z}^+ \cup \{0\}, \forall t \in T, \\
O_t \geq 0, \forall t \in T, \quad X_t^{RE} &\in \{0, 1\}, \forall t \in T, \quad CSR_{tj} \in \{0, 1\}, \forall j \in J, \forall t \in T, \\
Y_{tk}, Y_{tk}^A &\in \{0, 1\}, \forall k \in K, \forall t \in T,
\end{aligned} \tag{6f}$$

where (5a) restricts the total GHG emission. We also consider the positive effect of performing innovative projects on GHG emission. (5b) restricts the consumed non-renewable energy based on electricity. In this constraint, we also consider the effect of integrating a renewable energy source and performing innovative projects. (5c) restricts overtime working hours per worker in each period. (5d) and (5e) satisfy employee gender equity in each period. (5f) prepares a lower bound for customer satisfaction level in each period. Note that we also consider demand change due to the implementation of CSR projects. (5g) forces our model to implement a minimum number of CSR and innovative projects during the planning horizon. (5h) restricts the number of layoffs in each period. (5i) provides a condition to check whether an innovative project has already been performed. (5j) satisfies the assumption by which each innovative project can be performed once. Moreover, we assume that a renewable energy source during the planning horizon can be integrated at most once. (6a) satisfies workforce balance in each period. (6b) satisfies inventory balance in each period. (6c) determines the number of stock-outs in line with sales and demand. In this constraint, we also consider the effect of implementing CSR projects on the demand. (6d) considers the productivity of different genders, training newly hired workers, and overtime working hours to find production capacity. We also assume that performing an innovative project in a period results in the decrease of production capacity in that period. However, it increases the production capacity in the next periods (see term $\sum_{k \in K} (ca_{tk}^+ \times Y_{tk}^A - ca_{tk}^- \times Y_{tk})$). (6e) restricts subcontracting capacity in each period. (6f) identifies the type of decision variables and non-negativity constraints. Note that one may assume that part-time employees are available in the aggregate plan. In this case, the number of male and female workers take non-integer values.

Theoretically, $FW_t, MW_t, FH_t, MH_t, FF_t, MF_t, P_t, I_t, S_t, SU_t$, and SO_t are positive integer decision variables for all $t \in T$ (first two lines of (6f)). These variables constitute a number of decisions in the SAPP model. However, binary decision variables ($Y_{tk}, Y_{tk}^A, X_t^{RE}$, and CSR_{tj} , where $t \in T, k \in K$, and $j \in J$) are directly related to strategic or more important tactical decisions. On the other hand, in order to reduce the complexity of the problem, we may assume that $FW_t, MW_t, FH_t, MH_t, FF_t, MF_t, P_t, I_t, S_t, SU_t$, and SO_t are nonnegative variables ($\in \mathbb{R}^+ \cup \{0\}$) for all $t \in T$. Then, we round the solutions of these variables to the nearest integer values; the result will be highly reliable in terms of feasibility and optimality. In summary, the SAPP model involves four objective functions, binary, and continuous decision variables. The resulting model leads to a Quad-Objective MILP (QOMILP).

In our case study in the next section, the numerical scale of non-zero integer decision variables are sufficiently large and in the scale of hundred or thousand. Then, we can relax them to non-negative real numbers without a significant change in the results.

4. Case Study and Solution Approach

In this paper, we illustrate the effectiveness of our SAPP model, solution approach, and analysis for supporting decision making in the presence of multiple criteria in a large manufacturer of household appliances in Turkey. This company exports products to many countries all around the globe. They have several facilities and production plants in Turkey, Europe, Far East, and Africa. They address sustainability as one of the core issues in their corporate agenda. For example, they have commissioned recycling facilities for old appliances. These types of activities have resulted in improvement of the image of the company to become one of the leaders in terms of green supply chain globally. In order to activate their SSCM strategies more, the stakeholders and managers of this company aim to prepare a master plan for the next 12 months that considers sustainability in their appliance manufacturing plants.

4.1. Customizing the SAPP Model Based on Case Study

In this case study, we add some features to our general SAPP model presented in Section 3 to satisfy the specific requirements of the manufacturer. Hence, our SAPP model includes the following additional constraints for satisfying these concerns.

- Inventory level at the end of each month should not be smaller than a specific amount. Let inv_t^{Lim} be the lower bound for the inventory level at period t . Then, the SAPP model includes $I_t \geq inv_t^{Lim}$ for $t = 1, \dots, 12$.
- The number of workers in manufacturing operations should be in a specific range. Let wn^L and wn^U be the lower and upper bound for the number of workers, respectively. Then, we add $wn^L \leq FW_t + MW_t \leq wn^U$ for $t = 1, \dots, 12$ to the set of constraints.
- There are no subcontracting activities due to quality assurance policies of the company.

We define three CSR and innovation projects ($|J| = |K| = 3$). The CSR projects include supporting female employees in workplaces, voluntary investments and support for healthcare systems and non-government organizations, and organizing campaigns to collect old products and replace them with new ones. These projects can be decided and advertised within a short period of time. So, they are applicable for APP problems.

In terms of innovative projects, we define them such that they provide more production capacity for the company one month after their implementation. Then, the company will be more responsive to the customers and during specific cultural, national, and religious holidays, more compensation can be extended to the workers. We list innovative projects as: setup of new production processes to improve efficiency, integrating new press machines in the system, and redesigning assembly lines with industry 4.0 and other efficient and innovative solutions. We focus on the levels of innovative projects which are implementable in one month and usable after that. The projects which require highly large amount of investments in long-terms of period are not in the scope of APP nor our problem.

For the rest of this paper, let S and x be the feasible region of the SAPP problem and decision variables for short, respectively. Moreover, $z_p(x)$ denotes the objective function value in pillar $p \in \{eco, \dots, cul\}$ when decision variables are fixed to x . We also report the values for the parameters in Supplementary Material SM1.

4.2. Normalizing the Objective Functions

We aim to find appropriate values for the coefficients used in z_{env} , z_{soc} , and z_{cul} . Since the scale and unit of the terms given in (2a)-(2b), (3a)-(3d), and (4a)-(4b) are incompatible, normalizing these coefficients is crucial. We use normalization method proposed by Kim and de Weck (2005). For instance, we calculate normalized coefficient for $coef_{env1}$ in the following steps (Augusto et al., 2012):

- Maximize $\frac{Eq(2a)}{coef_{env1}}$ subject to the feasible region S and call the optimal objective function value C^{max} .
- Minimize $\frac{Eq(2a)}{coef_{env1}}$ subject to the feasible region S and call the optimal objective function value C^{min} .
- Calculate $Coeff_{env1} := \frac{1}{C^{max} - C^{min}}$.

4.3. Finding Non-Dominated Points

We developed a QOMILP for the SAPP problem in Section 3. This problem consists of two maximization objective functions associated with the economic and cultural pillars and two minimization objective functions corresponding to the social and environmental pillars. Dealing with multiple objective functions challenges us to find ND points of the problem. A ND point or an efficient solution results in objective function values — in the objective space — that cannot be improved in all of objective functions simultaneously. Finding ND points is the most important task in multi-objective optimization.

In terms of exact solution methods, there are a number of algorithms for multi-objective linear programs (MOLP) that are basically designed based on multi-criteria simplex method (Wiecek et al., 2016; Yu and Zeleny, 1975). When we study multi-objective integer linear programs (MOILP), the feasible region is not convex as of MOLPs, and hence, these problems are highly complex. There are a few papers for finding all ND points of MOILPs; for instance, Ehrgott (2006), Özlen and Azizoglu (2009), Jorge (2009), Przybylski et al. (2010), Lokman and Köksalan (2013), Mavrotas and Florios (2013), and Ozlen et al. (2014) propose algorithms for solving MOILPs. A small number of studies exist in the literature with exact solution approach for finding the ND points of MOMILPs when the number of objective functions is greater than two (see Vincent et al. (2013), Belotti et al. (2013), Stidsen et al. (2014), Boland et al. (2015), Soyly and Yıldız (2016), and Fattahi and Turkay (2018) for solving bi-objective MILPs). We use the Generator of ND and Efficient Frontier (GoNDEF) method that ensures finding all or a large proportion of ND points for MOMILPs (Rasmi and Türkay, 2019). This method also enables generation of the ND points such that each of them is associated with a different binary solution. This feature for the generated solutions is not obtained if we use heuristic/metaheuristic methods for solving the QOMILP.

Next, we present the SAPP model in the following form to briefly explain the steps of GoNDEF. Note that all objective functions in (7) are shown in maximization form for simplicity.

$$\begin{aligned}
\max \quad & z_1(x_C, x_B) = z_{eco}(x_C, x_B) \\
\max \quad & z_2(x_C, x_B) = -z_{env}(x_C, x_B) \\
\max \quad & z_3(x_C, x_B) = -z_{soc}(x_C, x_B) \\
\max \quad & z_4(x_C, x_B) = z_{cul}(x_C, x_B) \\
\text{s.t.} \quad & A_C^1 x_C + A_B^1 x_B \leq b^1, \quad A_C^2 x_C + A_B^2 x_B = b^2, \\
& x_C \in \mathbb{R}^{n_C}, x_B \in \{0, 1\}^{n_B},
\end{aligned} \tag{7}$$

where $x = (x_C, x_B)$, x_C is the vector of continuous decision variables in dimension n_C , and x_B is the vector of binary decision variables in dimension n_B . Moreover, let matrices A_C^1 , A_C^2 , A_B^1 , and A_B^2 specify the coefficients of x_C and x_B for defining the equality/inequality constraints. Righthand side values are also shown by b^1 and b^2 . We also define point z^{Nadir} in the objective space such that $z_p^{Nadir} = \min\{z_p(x) \mid x \in S\}$ for $p = 1, \dots, 4$. Note that all points in the objective space dominate z^{Nadir} .

The SAPP model includes a number of continuous and binary decision variables (i.e. n_C and n_B , respectively). Therefore, if a vector of continuous and binary values establish a feasible solution for the SAPP, then the vector of binary values is termed as a binary solution. Reminding that binary decision variables, x_B , correspond to strategic or more important tactical decisions, we use GoNDEF for finding the ND points such that each ND point is associated with a different strategic or binary solution. Moreover, these solutions are efficient and their image onto the objective space are not dominated by other points. Hence, we explore the trade-off of the solutions and provide supportive information for the decision making process.

Let an *efficient binary solution* be a binary solution such that there is at least one ND point corresponding to this binary solution. In other words, if we fix the binary variables to this solution, a vector of continuous values exists for the remaining LP which results in a ND point. For generating the ND points of the QOMILP, GoNDEF iteratively solves single objective MILPs (*SOMILP*) in the form of the problem given in (8). The objective function of this problem is the Manhattan distance of objective function values from z^{Nadir} subject to the feasible regions updated iteratively.

$$\begin{aligned}
\max \quad & \sum_{p=1}^4 \epsilon_p \\
\text{s.t.} \quad & z_p(x_C, x_B) - \epsilon_p \geq z_p^{Nadir}, \quad \epsilon_p \geq 0, \quad p = 1, \dots, 4, \\
& A_C^1 x_C + A_B^1 x_B \leq b^1, \quad A_C^2 x_C + A_B^2 x_B = b^2, \\
& x_C \in \mathbb{R}^{n_C}, x_B \in \{0, 1\}^{n_B}.
\end{aligned} \tag{8}$$

At each iteration, a new potentially efficient binary solution is found; it is not definitely an efficient binary solution since we use some excluding constraints at each iteration and add them to (8). Note that no-good constraints and other excluding constraints are used to exclude binary solutions and the dominated cone of the ND points found, respectively. Therefore, repeated solutions are not obtained in solving the *SOMILP*s given in (8) at an iteration. In general, GoNDEF method consists of three main steps. Let *EIS* be the set of explored potentially efficient binary solutions. We set $EIS := \emptyset$ at the beginning of the algorithm and indicate binary solutions by x_B (see Rasmi and Türkay (2019) for detailed discussion).

- Step1 Solve the *SOMILP* such that the binary solutions in the set of *EIS* are excluded. If *SOMILP* is infeasible, then terminate the algorithm. Otherwise, the solution is potentially a ND point such as $\bar{z}$ which corresponds to $\bar{x}_B$ and $\bar{x}_B \notin EIS$. Then, update $EIS := EIS \cup \{\bar{x}_B\}$.
- Step2 Check the dominance of $\bar{z}$. If $\bar{z}$ is ND, $\bar{x}_B$ is an efficient binary solution, and hence, exclude the dominated cone of $\bar{z}$ from the feasible region of the *SOMILP* and go to Step1. If $\bar{z}$ is dominated, check if $\bar{x}_B$ is an efficient binary solution (this issue is computed by using excluding constraints iteratively).
- Step3 If $\bar{x}_B$ is an efficient binary solution, find a ND point corresponding to $\bar{x}_B$ and exclude its dominated cone from the feasible region of the *SOMILP*. Go to Step1.

We generate 591 ND points — corresponding to 591 different binary solutions — for the case study and analyze them in the following section to discuss the trade-off and the behavior of the objective functions. In order to denote the ND points in the following sections, let z^i be the i th ND point and assume that there exist n ND points. Note that there is no priority among the objective functions as we use a multi-objective optimization method.

4.4. Analysis of ND points and Trade-Offs

We obtain a number of ND points. Let $z_{max}^{eco} := (z_{eco}^*, z_{env}, z_{soc}, z_{cul})$ be a ND point in the objective space such that $z_{eco}^* := \max\{z_{eco}(x) \mid x \in S\}$. In other words, z_{eco}^* is the optimal objective function value if we consider the total profit only. z_{max}^{eco} is derived from a solution that does not result in a good performance in social, environmental, and cultural issues as the non-economic concerns. Then, we provide a framework to show that we can significantly improve sustainability in terms of the non-economic issues by allowing the economic performance to decrease slightly.

We report the performance of a ND point in four pillars by four numbers between 0 and 100. 0 refers to the worst performance and 100 indicates the best performance. ND point $\hat{z}$ which is equal to $(\hat{z}_{eco}, \hat{z}_{env}, \hat{z}_{soc}, \hat{z}_{cul})$ has the performance of 100 in the economic and cultural pillars if and only if $\hat{z}_p$ is equal to $\max\{z_p^i \mid i \in \{1, \dots, n\}\}$ for $p \in \{eco, cul\}$. If $p \in \{env, soc\}$, then $\hat{z}_p = \min\{z_p^i \mid i \in \{1, \dots, n\}\}$ results in the performance of 100. Note that we generate ND points such that z_{max}^{eco} , $z_{min}^{env} := (z_{eco}, z_{env}^*, z_{soc}, z_{cul})$, $z_{min}^{soc} := (z_{eco}, z_{env}, z_{soc}^*, z_{cul})$, and $z_{max}^{cul} := (z_{eco}, z_{env}, z_{soc}, z_{cul}^*)$ exist in the set of generated ND points ($z_{env}^* := \min\{z_{env}(x) \mid x \in S\}$, $z_{soc}^* := \min\{z_{soc}(x) \mid x \in S\}$, and $z_{cul}^* := \max\{z_{cul}(x) \mid x \in S\}$). Moreover, we assign the performance of 0 to $\hat{z}_p$ if and only if it is equal to $\min\{z_p^i \mid i \in \{1, \dots, n\}\}$ for $p \in \{eco, cul\}$ and $\max\{z_p^i \mid i \in \{1, \dots, n\}\}$ for $p \in \{env, soc\}$. Note that if the maximization of an objective function is desirable, finding the worst objective function value or the performance of 0 is not computed by minimizing the objective function since we report the performance in each pillar regarding the ND points. We show the performance in pillar p by $pf(z_p)$.

We also report $pf(z_p)$ for the other ND points based on the z_p value in the interval of $\max\{z_p^i \mid i \in \{1, \dots, n\}\}$ and $\min\{z_p^i \mid i \in \{1, \dots, n\}\}$. For example, $pf(z_{soc}) = \frac{\max\{z_{soc}^i \mid i \in \{1, \dots, n\}\} - z_{soc}}{\max\{z_{soc}^i \mid i \in \{1, \dots, n\}\} - \min\{z_{soc}^i \mid i \in \{1, \dots, n\}\}} \times 100$ where minimization of $z_{soc}(x)$ is desirable. For assessing the performance, we strongly believe that focusing on the ND points is more logical. There is no reason to come up with a solution dominated by other solutions. Then, we do not calculate the performance associated with an objective function value by its proportion to a range of objective function values corresponding to

the dominated points. Therefore, for instance, 1% decrease in the economic performance is not equal to 1% decrease in the total profit; it is equal to 0.0781% decrease in the total profit.

Table 6 shows the correlation coefficients between every two vectors of the performances of the ND points. Six values exist in this table other than 1's. We note that three of them are negative and their absolute values are greater than the positive numbers. It shows that the performances of the object functions are conflicting rather than harmonious, and hence, using multi-criteria optimization approaches is important. Moreover, the most negative number is -0.676 which indicates the correlation coefficient between environmental and social pillar. This value also shows that the behavior of social and environmental objective functions is opposite. We will discuss the reasons in this section later.

Table 6: The correlation coefficient matrix of the pillar performances when the ND points are considered

performance in	eco.	env.	soc.	cul.
eco.	1	0.426	-0.485	0.214
env.		1	-0.676	0.396
soc.			1	-0.654
cul.				1

We note that the performance in different issues are conflicting in many cases. Hence, obtaining the Ideal point as (100,100,100,100) is impossible. Then, designing a supportive framework for decision makers is an important task in the SSCM. We select some of ND points out of the generated ND points to compare their performance in different pillars in Figures 2 and 3. We also show the performance of these ND points in Table 7.

Figure 2: Exploring the performance trade-off between ND points

In Figure 2(a), we show the performance of z_{max}^{eco} by blue color; $pf(z_{eco}) = 100$, $pf(z_{soc}) = 27$, and the performance at this ND point is 0 for the environmental and cultural pillars. We show the performance of three other ND points in Figure 2(a) by red, yellow, and green colors. We denote that how fair decrements in the economic performance result in large and effective performance increase in non-economic issues. For example, if the manufacturer decides to allow the economic performance to decrease approximately 22% (such as the ND point associated with yellow color with the economic performance of 77.89), then the performance of environmental, social, and cultural issues can be improved by 61%, 36%, and 95%, respectively. The importance of this trade-off becomes more when we indicate that 22% decrease in the economic performance is equal to only 1.73% decrease in the total profit. This strategy is win-win since it significantly improves sustainability. This information is very supportive for decision makers to explore different strategies and find practical solutions based on their preferences.

In Figure 2(b), we show that focusing on environmental and cultural issues can result in a ND point (point associated with yellow color). However, we face a low performance in the social and economic pillars. Hence, similar to our discussion in Figure 2(a), we can find some ND points out of the generated ND points that fairly satisfy all pillars. For example, in the comparison between green and yellow solutions, there is a significant potentiality to capture a large performance in the economic and social pillars by small decrements in the other issues.

Figure 2(c) shows four ND points with very close economic performances. Small changes in the economic performance lead to different performances in non-economic issues. Therefore, decision makers consider different factors, accept small changes for their goals, and make a decision.

Table 7: The performance of the ND points shown in Figures 2 and 3

figure	$pf(z_{eco})$	$pf(z_{env})$	$pf(z_{soc})$	$pf(z_{cul})$	color
2(a)	100.00	0.00	27.08	0.00	blue
	87.89	69.56	35.34	100.00	red
	77.89	61.43	63.16	94.98	yellow
	63.29	37.19	97.27	78.84	green
2(b)	75.14	60.41	64.81	94.98	green
	68.02	21.59	100.00	66.52	blue
	66.49	40.92	87.11	86.91	red
	0.00	100.00	0.00	100.00	yellow
2(c)	70.55	41.14	73.99	98.27	green
	68.90	51.93	87.83	78.84	yellow
	66.65	26.01	100.00	66.52	blue
	64.74	38.14	96.32	78.84	red
3	69.63	49.31	81.80	86.91	blue
	74.90	62.07	79.35	78.84	red
	77.89	61.43	63.16	94.98	green

In Figure 3, we select three ND points based on three specific functions that logically come up with more balanced solutions. Let $pf(\bar{z}_p) := \frac{1}{n} \sum_{i=1}^n pf(z_p^i)$ for $p \in \{eco, \dots, cul\}$. Then, the blue color shows the solution that minimizes the Euclidean distance between ND points and $(\bar{z}_{eco}, \bar{z}_{env}, \bar{z}_{soc}, \bar{z}_{cul})$ and is calculated by $\min\{\sum_{p \in \{eco, \dots, cul\}} (pf(z_p^i) - pf(\bar{z}_p))^2 \mid i \in \{1, \dots, n\}\}$. Note that the minimum Manhattan distance — calculated by $\min\{\sum_{p \in \{eco, \dots, cul\}} |pf(z_p^i) - pf(\bar{z}_p)| \mid i \in \{1, \dots, n\}\}$ — is also provided by the ND point associated with blue color. Solution associated with red color minimizes the Euclidean distance between ND points and the Ideal point (calculated by $\min\{\sum_{p \in \{eco, \dots, cul\}} (pf(z_p^i) - 100)^2 \mid i \in \{1, \dots, n\}\}$) and the solution associated with green color minimizes the Manhattan distance between ND points and the Ideal point (calculated by $\min\{\sum_{p \in \{eco, \dots, cul\}} |pf(z_p^i) - 100| \mid i \in \{1, \dots, n\}\}$). Moreover, let $pf(\bar{z}^i) = \frac{1}{4} \sum_{p \in \{eco, \dots, cul\}} pf(z_p^i)$ for $i \in \{1, \dots, n\}$. Then, red solution also minimizes $\min\{\sum_{p \in \{eco, \dots, cul\}} (pf(z_p^i) - pf(\bar{z}^i))^2 \mid i \in \{1, \dots, n\}\}$ that results in a solution with the smallest variance in different pillars.

Figure 3: The performance of three ND points found using the specific functions suggested

We also analyze the strategic/tactical decisions that lead to the ND points. Let Z_{60} be the set of ND points that are leading to more balanced performance in all pillars. The ND points in Z_{60}

have performances greater than 60 in all pillars ($|Z_{60}| = 47$). In Table 8, we use the average value of different binary solutions corresponding to the ND points to analyze the impact of different strategic/tactical decisions. The second column shows the strategic/tactical decisions that result in z_{max}^{eco} . The average values of the strategic/tactical decisions in the ND points in the set Z_{60} and in the generated ND points are reported in the third and fourth columns.

Table 8: Summary of the strategic/tactical decisions correspond to the binary solutions of z_{max}^{eco} , Z_{60} , and the entire ND points

strategic/tactical decisions	z_{max}^{eco}	Avg. for NDs in Z_{60}	Avg. for the generated NDs
integration of a renewable energy source	0	1	0.99
number of times that CSR project 1 is implemented	0	3.73	9.08
number of times that CSR project 2 is implemented	2	3.24	7.05
number of times that CSR project 3 is implemented	0	10.37	10.99
performing innovative project 1	0	1	0.998
performing innovative project 2	1	1	1
performing innovative project 3	0	1	0.998

Integrating a renewable energy source, implementing CSR projects, and performing innovative projects increase sustainability in a SAPP problem. These projects directly improve environmental, social, and cultural issues, respectively. Moreover, sometimes they indirectly affect other issues and improve them. Table 8 shows that the maximized total profit without concerning about sustainability is obtained by very few attention to the integration of a renewable energy source, CSR, and innovative projects. However, ND points in Z_{60} are obtained by a significant attention to these projects.

In addition, although integration of a renewable energy source and performing innovative projects are vital for sustainability, implementing CSR projects in all periods may not be a sustainable win-win strategy resulting in balanced solutions. In the comparison of the third and fourth columns of Table 8, there is a significant difference in the number of CSR projects 1 and 2. Frequently implementation of CSR projects results in demand increase, more manufacturing and holding inventory activities, and decrease in the environmental performance. However, it improves the social and economic performance. Therefore, side-effects of a social-oriented activity must be considered.

Next, we briefly analyze the sensitivity of the economic objective function respect to changes in the parameters. We categorize basic parameters to two groups: 1- α , o_{Lim} , fm , and l_{Lim} which affect social-cultural objective function values directly, and 2- ξ_g and ξ_e which impact the environmental objective function value directly.

In Figure 4(a,b), by the horizontal axis, we decrease the value of α and fm , and increase the value of o_{Lim} and l_{Lim} simultaneously. Hence, the parameters change such that social-cultural issues are less respected. We observe that larger economic objective function values are obtainable by this approach (Figure 4(a)). Moreover, Figure 4(b) shows that, as we expect, the sum of the social and cultural objective function values increases or the social-cultural performance worsens.

We also examine the economic and environmental objective functions when ξ_g and ξ_e increase. We observe that if we set these parameters such that the environmental performance reduces, then larger economic objective function values are obtainable. However, after a level of environmental parameters, very small improvements in the economic objective function value is possible (Figure 4(c)). On the other hand, after that level, the environmental objective function apparently worsens.

4.5. Managerial Insights

The provided solutions in Figure 3 or the set Z_{60} are useful since they give us more balanced solutions with performance which is not very far from the Ideal point. However, decision makers may prefer different solutions due to specific priorities or preferences. Generally, we point out a number of managerial insights regarding the SAPP problem and case study presented:

- We can approach an APP problem with sustainability considerations in five steps: 1- providing a multi/quad-objective mathematical model, 2- customizing the model based on the real problem, 3- normalizing the objective functions, 4- solving the multi-objective optimization problem to find ND points, and 5- finding the trade-off of different solutions and more balanced solutions and analyzing them.

Figure 4: Sensitivity analysis when the parameters correspond social-cultural criteria worsen (a,b), and when the parameters associate the environmental pillar worsen (c,d)

- Regarding the economic pillar, we consider sustainability-related costs such as carbon tax and energy cost that improve the economic objective function in terms of sustainability.
- Different indicators can be used in SAPP to address environmental, social, and cultural concerns. We present a number of these indicators in Table 2. Moreover, we show the way by which the indicators can be reflected in the objective functions and constraints of the SAPP model.
- As we generate 591 ND points for the case study problem, a large number of ND points exist for real-world problems. In many cases, objective functions are conflicting, and hence, there are an exponentially large number of the ND points resulting in different performances and trade-offs. These solutions are compatible with different managerial approaches. We presented how some solutions assign a larger priority to some criteria.
- In many real-world problems, binary decision variables represent strategic or more important tactical decisions. For instance, making decision in multiple period of time for integrating renewable energy sources, performing innovative projects, and implementing CSR projects are represented by binary variables in the case study. There are a large number of ND points corresponding to different binary solutions. Hence, decision makers should note that there may exist many win-win strategies.
- In column three of Table 8, we observe that a balanced/win-win solution is not obtainable without sustainability-oriented projects. As seen in the case study problem, using energy from renewable sources and performing innovative/CSR projects are very important to have a sustainable supply chain. Decision makers should consider that the level of these projects may unbalance the results. Then, their side-effects are required to be accurately discussed. In general, conflicting objective functions cause debatable issues in sustainability.
- Some strategies increase the performance in social/cultural issues and demand, simultaneously. Decision makers should note that an increased demand may result in negative effects on the environment. Moreover, in column three of Table 8, we observe that the level of the implemented CSR projects is not equal to their maximum possible value (e.g. 12) for more balanced solutions. Thus, some CSR projects result in a lower performance in the environmental pillar for the company. However, they may lead to less energy consumption by the

customers that improves environmental factors. For example, collecting old products and replacing them with new ones has a similar impact.

5. Conclusions and Future Research Directions

In this paper, we present a framework that supports multiple criteria decision making in the SAPP problems. We propose a QOMILP for these problems and address the economic, environmental, social, and cultural pillars simultaneously. Moreover, we enrich the consideration of each pillar by taking different practical sub-pillars into account. In this model, we put a significant emphasis on social issues that are infrequently addressed in the literature comparing with the environmental issues. In addition, we add cultural issues to the problem separated from the social pillar to comprehensively analyze four pillars of sustainability. We modify a solution method for QOMILPs to find a large number of ND points for our model that correspond to different strategies. Then, we show our analysis approach on a case study in the appliance manufacturing industry.

In the appliance manufacturing industry, maximizing the total profit without sustainability considerations results in a low performance in non-economic issues where the objective functions are conflicting. We show that how on-purpose small decrements in the total profit result in a significant performance increase for non-economic issues or sustainability. The manufacturer can reach high performances in the social, environmental, and cultural pillars by less than 2% decrease in the total profit. Moreover, in order to support decision making process, we use different functions to filter some unbalanced solutions out. The results are insightful for decision makers; however, they may modify the results based on their preference.

We show that using energy from renewable sources and implementing CSR/innovative projects improve sustainability and result in more balanced solutions. However, the projects that increase demand may lead to a lower performance in the environmental pillar. Therefore, decision makers require a comprehensive information about indirect effects of these projects.

We also show that there are a large number of strategic decisions that provide win-win solutions to the problem. Moreover, based on each strategic decision, there exist a large number of tactical and operational decisions which result in ND points. We describe that exploring the trade-off of the ND points constructively supports decision making process, and hence, decision makers reach balanced and practical solutions that address sustainability considerations. Furthermore, the proposed framework gives insights to decision makers for considering sustainability with their preferences and finding win-win paths to their goals.

We also see a potentiality for further studies in the future regarding SAPP. For example, an inclusive analysis is required to explore long-term effects of CSR projects on environmental issues. As we discuss in this paper, these projects may decrease the environmental performance of the manufacturer; however, from consumer point of view, total consumed energy is decreased, and the environmental performance is improved. Moreover, a study to discuss the impacts of CSR projects on the consumerism is important.

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Supplementary Material:

A Multi-Criteria Decision Analysis to Include Environmental, Social, and Cultural Issues
in the Sustainable Aggregate Production Plans

SM1: Parameters of the Case Study

Table 1: The values for parameters in the case study (\$ refers to the currency which is Turkish lira in the case study)

t	month	1	2	3	4	5	6	7	8	9	10	11	12
d_t	item	217823	217316	260104	256002	317527	329603	312316	383955	310242	267525	245584	195383
h	hour/day	8											
n_t	day	20	20	27	25	24	20	18	25	23	25	26	20
p_M	item/(worker×day)	4.8											
MW_0	worker	1674											
FW_0	worker	226											
I_0	item	84757											
sp	\$/item	1463											
c_L	\$/ (worker×hour)	19.06											
c_H	\$/worker	1000											
c_F	\$/worker	3500											
c_M	\$/item	732											
c_O	\$/ (worker×hour)	28.6											
c_I	\$/ (item×period)	9.86											
c_{SO}	\$/item	950											
c_{CT}	\$/tonne	150											
c_E	\$/kWh	410											
c_t^{RE}	\$	3000000	2750000	2500000	2250000	2000000	1750000	1500000	1250000	1000000	750000	500000	250000
c_{t1}^{CSR}	\$	3750000	3750000	3750000	3750000	3750000	3750000	4250000	4250000	4250000	4250000	4250000	4250000
c_{t2}^{CSR}	\$	3000000	3000000	3000000	3000000	4000000	4000000	4000000	5000000	5000000	5000000	5000000	5000000
c_{t3}^{CSR}	\$	3500000	3500000	3500000	3500000	3500000	3500000	3500000	3500000	3500000	3500000	3500000	3500000
c_{t1}^{IN}	\$	9000000	8250000	7500000	6750000	6000000	5250000	4500000	3750000	3000000	2250000	1500000	750000
c_{t2}^{IN}	\$	6000000	5500000	5000000	4500000	4000000	3500000	3000000	2500000	2000000	1500000	1000000	500000
c_{t3}^{IN}	\$	12000000	11000000	10000000	9000000	8000000	7000000	6000000	5000000	4000000	3000000	2000000	1000000
wn^L	worker	1650											
wn^U	worker	2750											
g_I	tonne/(item×period)	0.0048											
g_P	tonne/item	0.0379											
e_I	kWh/(item×period)	0.0057											
e_P	kWh/item	0.1346											
e_t^{RE}	kWh	1800	1650	1500	1350	1200	1050	900	750	600	450	300	150
ξ_g	tonne	150000											
ξ_e	kWh	500000											
α	%	0.975											
l_{Lim}	%	0.1											
o_{Lim}	hour/period	20											
f_m	%	0.3											
ph	%	0.6											
pf	%	0.97											
d_{t1}^+	%	0.014	0.014	0.014	0.014	0.014	0.014	0.017	0.017	0.017	0.017	0.017	0.017
d_{t2}^+	%	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
d_{t3}^+	%	0.021	0.021	0.018	0.018	0.015	0.014	0.015	0.013	0.015	0.017	0.019	0.024
ca_{t1}^-	item	13000	13000	11500	12250	16000	20000	21000	18500	16000	13000	11250	11250
ca_{t2}^-	item	10000	10000	9250	9750	12750	16000	16750	14750	13000	10250	9000	9000
ca_{t3}^-	item	16000	16000	14500	15500	21500	28000	29500	25500	22000	16500	14000	14000
ca_{t1}^+	item	12000	12000	12000	12000	12000	12000	12000	12000	12000	12000	12000	12000
ca_{t2}^+	item	7000	7000	7000	7000	7000	7000	7000	7000	7000	7000	7000	7000
ca_{t3}^+	item	15000	15800	19000	18500	23000	24000	22500	28000	22500	19500	18000	13500
g_{t1}	tonne	1518	1380	1242	1104	966	828	690	552	414	276	138	0
g_{t2}	tonne	731	665	600	532	465	399	332	266	200	133	66	0
g_{t3}	tonne	3028	2815	2558	2308	1998	1674	1370	992	690	425	182	0
e_{t1}	kWh	4290	3900	3510	3120	2730	2340	1950	1560	1170	780	390	0
e_{t2}	kWh	2310	2100	1890	1680	1470	1260	1050	840	630	420	210	0
e_{t3}	kWh	8411	7818	7106	6412	5550	4650	3806	2756	1912	1181	506	0
inv_t^{Lim}	item	72439	86701	85334	105842	109868	104105	127985	103414	89175	81861	65128	65000
csr_{Lim}	# of projects	1											
in_{Lim}	# of projects	1											