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A System Dynamics Framework for Analyzing The Impacts of Industrial Solid Waste Recycling on Sustainable Supply Chain Performance[*]

Endüstriyel Katı Atık Geri Dönüşümünün Sürdürülebilir Tedarik Zinciri Performansı Üzerindeki Etkilerinin Analizi için Bir Sistem Dinamiği Çerçevesi

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Abstract: In this study, it's aimed to propose a performance measurement model that will reveal the effects of recycling industrial solid waste on sustainable supply chain performance. Furthermore, it's aimed to evaluate the effects of plastic, glass, steel and aluminum recycling on economic and environmental sustainability performance with the proposed model. It's expected that the scope of this model and the determination of the recycling results of different industrial wastes with the same indicators will contribute to the literature. After running the model for two-year period, the contribution of recycled plastics to sustainability performance will reach 39%, glasses 31%, steels 44% and aluminums 47%. The largest contribution rate of recycling in terms of energy consumption is in aluminums. In terms of cost and profitability criteria including opportunity cost, the highest contribution rate is in steels.

Keywords: Industrial Waste Management, Recycling, Simulation, Sustainable Supply Chain, System Dynamics

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Öz: Bu çalışmada, endüstriyel katı atıkların geri dönüştürülmesinin sürdürülebilir tedarik zinciri performansı üzerindeki etkilerini ortaya çıkaracak bir performans ölçüm modeli önerilmesi amaçlanmaktadır. Ayrıca önerilen modeli kullanarak plastik, cam, çelik ve alüminyum geri dönüşümünün ekonomik ve çevresel sürdürülebilirlik performansı üzerindeki etkilerinin değerlendirilmesi de amaçlanmaktadır. Bu modelin kapsamı ve farklı endüstriyel atıkların geri dönüşüm sonuçlarının aynı göstergelerle belirlenmesinin literatüre katkı sağlayacağı beklenmektedir. Modelin iki yıllık dönem için çalıştırılmasından sonra geri dönüştürülmüş plastiklerin sürdürülebilirlik performansına katkısı %39, camların %31, çeliklerin %44 ve alüminyumların %47'ye ulaşacağı görülmüştür. Enerji tüketimi açısından geri dönüşümün en büyük katkı oranı alüminyumlardadır. Maliyet ve fırsat maliyetini dahil eden karlılık kriterleri açısından ise en yüksek katkı oranı çeliklerdedir.

Anahtar Kelimeler: Endüstriyel Atık Yönetimi, Geri Dönüşüm, Simülasyon, Sürdürülebilir Tedarik Zinciri, Sistem Dinamiği

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1. Introduction

Waste management is an important part of sustainable production and consumption. Sustainable waste management ensures the protection of natural resources, reduces environmental risks, and ensures the economy of waste (Kumar et al., 2017; Farrokh et al., 2018). Regular increase in waste production due to the excessive consumption and industrialization requires an efficient waste management system for the economy and society. However, the complexity of recycling activities and the uncertainties in the process make it difficult for businesses to handle their wastes in a sustainable way (Zacho and Mosgaard, 2016; Rada, 2016; Weeks et al., 2021). Failure of waste management causes businesses to bear both economical (Farel et al., 2013; Ding et al., 2016; Giannis et al., 2017) and environmental risks and obstacles (Das, 2018; Yu and Solvang, 2018; Dubey et al., 2020).

A significant portion of wastes consists of materials that are eliminated from the production process for various reasons, such as defective raw materials and manufacturing defects (Kumar and Kumar, 2014). Businesses mostly prefer to sell their industrial solid wastes as scrap but ignore the potential benefits of recycling. Many studies have been conducted in the literature on the impact of waste management on business performance (Lenort vd., 2017, Osiro vd., 2018, Wang vd., 2018, Govindan vd., 2019, Dubey vd., 2020; Haryani and Subriadi, 2021), but studies on the recycling of industrial solid wastes generated during the production process are very limited.

Businesses often experience a tradeoff with solid waste generated in the production process: they can sell the solid waste as scrap and purchase new raw materials, or they can recycle and reuse it. Since the difference between these two options is not clear and the latter requires more complex operations, in practice, most of the companies prefer to sell their waste as scrap and buy new raw materials (Agarwall et al., 2018). This paper proposed a system dynamics framework to address this waste recycling with the responsibility of the manufacturer and analyze the economic and environmental effects of recycling the industrial solid wastes. Another aim of the study is to determine the effects of recycling plastic, glass, steel and aluminum solid wastes in terms of economic and environmental sustainability and compare the cases through the proposed model.

The simulation model considers the scrap value of the wastes, the selling price of the recycled material, the purchase cost of the new raw material, the energy, gas, and water consumptions, and operating costs incurred in the recycling process. Thus, the model compared the recycling/reusing wastes versus selling waste/buying new raw materials, and analyzed the economical and environmental impacts of recycling with a temporal perspective. The system dynamics model was calibrated by applying to four different industries: plastic, glass, steel, and aluminum.

In summary, the study makes three contributions to the literature: *i)* a model was proposed to measure the impact of the recycling of industrial solid wastes generated during the production process on sustainability performance, ii) sell waste/buy new and recycle/reuse tradeoff was addressed, and *iii)* contribution of solid waste recycling to the sustainable performances of different industries was compared.

There were some limitations to the preparation and completion of this study. First of all, the fact that many of the recycling facilities couldn’t be managed with a 'professionalism' made the research process difficult both in model setup and data collection. In this process, sufficient data on environmental variables could not be obtained directly from the sector. For this reason, the data on environmental criteria were supported by the data of some sources in the literature. On the other hand, the validity and reliability of the proposed system dynamics model could not be fully tested in this study. The accuracy of the relationships between the variables and the model map were qualitatively tested and found valid by the experts. However, quantitative testing was not performed for the model. Because the simulation outputs of the model, which were reached through four different cases, have not been compared since there is no reference data set in reality.

2. Literature Review

2.1. Waste Management in Sustainable Supply Chain Management (SSCM)

Today, the importance of the economic benefits and environmental impacts provided by the recycling of waste has led many companies to design a closed-loop supply chain network (Farrokh et al., 2018). In the literature, the effects of supply chain network design on overall performance have been studied with different applications. Ali et al. (2020) aimed to design a multi-stage reverse logistics network for the recycling of returned products in an industrial air conditioning company in India, Jafari et al. (2017) aimed to design the recycling network in the textile industry, taking into account many environmental and social factors. Studies investigating the number of warehouses, vehicles, containers, the locations of recycling centers or vehicle routes for waste management in the sustainable supply chain have been examined by many researchers (Ramos et al., 2014; Jafari et al., 2017 ; Feitó-Cespón et al., 2017; Ali et al., 2020).

In a successful sustainable supply chain performance management, it is necessary to regularly evaluate the effects of recycling activities on the performance of businesses. Feitó-Cespón et al. (2017) aimed to create performance indicators that consider environmental and economic targets to redesign the recycling supply chain network. In the study, recycling capacity, demand, energy consumption, water consumption, space usage, distances between units and logistics costs between units were used. Yu and Solvang (2018) proposed a model that reveals the effects of wood waste recycling on SSC performance under quality and quantity uncertainty. In the model, operational costs, recovery costs, CO2 emissions, capacity, recycling rates, energy recovery and quality level indicators were used.

Some researchers aimed to develop a performance measurement system directly for the sustainable supply chain (Olugu and Wong, 2012; Wei et al., 2014; Wu et al.,2018; Avsec and Kaucic (2018). Olugu and Wong (2012), which aimed to design a high-performance closed-loop supply chain in the automotive industry, used the variables of recycling cost, recycling efficiency and waste generation level in their study. On the other hand, Avsec and Kaucic (2018) proposed a comprehensive performance measurement system by developing eco-efficiency indicators to evaluate the recycling system performance of end-of-life solid wastes. Parameters such as total waste amount, recycled waste, recycling rate, production inputs, production costs, parameters associated with technology and quality, fixed costs, net asset value were used in the model.

Sarkis and Dijkshoorn (2007) were interested in the efficiency of both environmental and economic dimensions to determine the sustainability performance of SMEs adopting waste management practices. While Suttibak and Nitivattananon (2008) focused specifically on economic indicators to explore the factors affecting sustainable supply chain performance regarding solid waste recycling; Das and Dutta (2013) focused on indicators such as secondary product inventory, order quantity, demand for secondary products, retailer inventory, retailer sales, average revenue and average cost. Cucchiella et al. (2014) applied life cycle analysis to evaluate the sustainable supply chain performance of battery recycling facilities from an environmental and economic perspective. Theyel and Hoffman (2015) also focused on product designs, energy use indicators, competitiveness, efficiency and total cost to determine the effects of waste recycling on SSC performance.

For similar purposes, Haghighi et al. (2016) were interested in recycling plastics, Ding et al. (2016) and Rinsatitnon et al. (2018) conducted to examine the effects of reusing or recycling construction waste on SSC performance. Ding et al. (2016) focused only on environmental performance in their study, while Rinsatitnon et al. (2018) examined through both environmental and economic dimensions such as labor and equipment maintenance. Nidhi and Pillai (2019) addressed sustainable supply chain performance, aiming to develop a sustainable index by taking into account the economic, environmental and social impacts of material recovery. In order to determine the performance of the supply chain, emissions during production, recycling and disposal were evaluated. In the same year, Lagarda-Leyva et al. examined the effects of packaging recycling on performance. When we look at the studies after 2020, mostly studies to determine the SSC performance of recycling have been carried out on economic, environmental and social dimensions. Alamerew and Brissaud (2020) investigated the effects of including electric vehicle batteries in the end-of-life recycling process, Chaudhary and Vrat (2020) environmentally friendly recycling of mobile phone waste, and Beiler et al. (2020) recycling of glass bottles on SSC performance.

According to the studies examining the effects of recycling on sustainable supply chain performance in the existing literature, it can be stated that the subject attracts increasing attention among both academic circles and practitioners (Govindan et al., 2015). However, the literature on sustainable supply chain management in recycling industries shows that research studies are limited and no comprehensive framework has been found for models that reflect performance (Haghighi et al., 2016). It can be mentioned that there is a lack of comprehensive studies on studies that directly examine the effects of waste management and especially recycling activities on SSC performance. Published studies also mostly included wastes such as municipal waste, glass, construction waste, end-of-life batteries, mobile phones or electric vehicle batteries. However, as far as is known, there are no studies examining the effects of recycling of industrial waste generated in the production facility on SSC performance. The gap in the literature has been influential in the preparation and conduct of this study.

2.2. System Dynamics in Waste Management

It is important to consider and evaluate many different dimensions in sustainable supply chain management. In the management of supply chains with uncertain parameters, mostly stochastic, fuzzy, robust and constrained modeling approaches used (Nidhi and Pillai, 2019). Based on existing studies, there is a lot of incompleteness in the metrics used in studies designed to demonstrate closed-loop supply chain performance (Olugu and Wong, 2012; Nidhi and Pillai, 2019). An important point noticed as a result of the literature review is that multi-purpose complex integer linear/non-linear modeling methods are preferred in many of the studies prepared for similar purposes.

Yu and Solvang (2018) proposed a two-stage, stochastic and mixed integer programming model in their study to determine sustainable supply chain performance in waste management. Jafari et al. (2017) suggested Multi-Purpose Vibration Damping Optimization and NSGA-II (Non-Dominant Sequence Genetic Algorithm) algorithms, Feitó-Cespón et al. (2017) proposed Stochastic Multi-Purpose Mixed Integer Nonlinear programming methods, Nidhi and Pillai (2019) proposed a five-stage mixed integer linear programming model, Ali et al. (2020) proposed a multi-objective mixed integer linear programming model in their studies in which a recycling logistics network was designed considering a number of performance dimensions.

The system dynamics approach is a powerful technique for understanding feedback behaviors and relationships in sustainable systems (Nabavi et al., 2017; Beiler et al., 2020; Ulku et al., 2020). Because system dynamics has started to be seen as a more useful tool for analyzing reverse logistics. (Beiler et al., 2020). However, system dynamics applications in sustainable operations is quite limited compared to other methods such as linear programming and multi-criteria decision-making techniques (Rebs et al., 2019). System dynamics has been applied to waste management in the last few years and mainly focused on public practices. This approach was applied to demonstrate the municipal solid waste management performance (Pinha and Sagawa, 2020), estimate municipal and industrial recyclable waste streams that can be recovered as energy (Chaves et al., 2021), and evaluate greenhouse gas emissions from recycling facilities and landfills (Chen and Liu, 2021). Also the system dynamics approach has been used to determine the environmental and economic impacts of recycling materials in line with government policies (Tian et al., 2021) and to evaluate investment and incentive scenarios for waste recycling (Wang et al. 2020; Zhou et al. 2021).

On the other hand, in recent years, system dynamics has been used for modeling approaches that measure recycling to sustainable supply chain performance. Ding et al. (2016) proposed a system dynamics model showing the effects of recycling construction waste on SSC performance. Avsec and Kaucic (2018) proposed a performance measurement system by developing eco-efficiency indicators to evaluate the performance of the waste recycling system. Rinsatitnon et al. (2018) proposed a model that shows the effects of solid waste recycling on SSC performance and run the model with system dynamics under various scenarios. In the study, it was decided at least how many years the recycling programs should be implemented and how many more years should be run in order for businesses to achieve positive net profit.

Alamerew and Brissaud (2020) applied system dynamics to evaluate the effects of vehicle batteries, Chaudhary and Vrat (2020) applied system dynamics to evaluate the effects of mobile phone waste, Beiler et al. (2020) applied system dynamics to evaluate the effects of glass waste recycling on the sustainable supply chain performance of the business in terms of various dimensions. Despite these studies in recent years, there are major research gaps in analyzing waste management studies with system dynamics (Micky, 2019; Maqsoom et al., 2019; Chen and Liu, 2021). In this study, a system dynamics approach is proposed for the model that shows the effect of recycling industrial wastes on performance. It is important that many criteria can be evaluated simultaneously in the system dynamics model.

3. Methodology

In cases where the same or similar of a real system is designed, the importance of modeling tools that reveal real relationships increases. The system dynamics method was developed by W. Forrester in the 1950s in order to easily model complex systems, to show the relationships between variables, to establish feedback systems and to analyze the whole system. The system dynamics approach focuses on analyzing the actual system behavior in detail. The complex interplay of variables in feedback loops with nonlinear relationships in system behavior is characteristic for systems dynamics models (Forrester, 1994). Many concepts and tools that support the understanding of relationships in complex systems are used in the application of the method (Reynoso-Campos et al., 2004).

In this study, which examines the effects of waste recycling on sustainable supply chain performance, it is suggested to use the system dynamics approach in order to reveal the changes of the variables depending on time and to clearly define the relationships between the variables. The method was recognized as one of the best responders in determining the effect of a change in any variable on system behavior. Because the system dynamics approach provides important tools for modeling the complexity inherent in the recycling system. It is also important that the method allows the evaluation of more than one case in the study. From this point of view, system dynamics method was needed in this study in order to test product groups in different sectors under various uncertainties.

System dynamics approach basically consists of 6 steps. These steps in order:

a. Problem Identification: The first step of the system dynamics approach begins with the definition of the problem. At this point, it is important for researchers/practitioners to decide what they really want to research and examine, and to define it clearly and precisely.
b. Dynamic Hypotheses and Model Conceptualization: There are many different subcomponents or units in the system that the problem to be investigated belongs to. The relationships between these units can be linear as well as include nonlinear situations. The complex interaction of variables in feedback loops with nonlinear relationships that lead to uncertainties in system behavior are characteristic for systems dynamics models (Forrester, 1994). System dynamics models are established to examine and manage the feedback of complex systems in which causal loop diagrams are created (Yuan andWang, 2014). Feedback loops form the basis of system dynamics models and evaluate the relationships between system components.
c. Setting up the Model: Model Setup: After the causal loop diagram is established, the system is modeled using flow maps. The units in the system are divided into two as stock and flow variables. Establishing a model is achieved by developing stock flow diagrams. Stocks, on the other hand, help to make the status of the system understandable, that is, give information about how the system is. Flows are variables that show an increase or decrease in stock, filling or emptying them. In the literature, stocks at time t are shown as $X(t)$, flows $f(t)$. The relationship between stock and flow is shown as $X(t+1)=f(t)+X(t)$, t= 0,1,2,3..
d. Model Validity/Reliability Test: Validation of the model is generally seen as an evaluation of its suitability for the purpose to be achieved. The validity of tests used in system dynamics is divided into two

as structural and behavioral (Forrester, 1961). It should be accepted that the model has sufficient structural accuracy and that the model behaves reasonably (Mclucas and Ryan, 2012). Researchers first check the structural validity to determine that the required parameters are included in the model and that all relationships reflect reality. After the structural validity is completed, as a second step, it is examined whether the model outputs reflect the reality for behavioral validity. Here, by changing the parameters, it is observed whether the model exhibits abnormal behavior.

e. Model Analysis: It is the stage where the model is examined in a certain time period and under the desired conditions and how it will behave. In the analysis of the model, the results are followed by using mostly mathematical or analytical methods.

f. Design Improvement: An important issue in system dynamics is that the results of the model can be observed under various scenarios. These are expressed as scenario tests, and model results are followed under different optimistic or pessimistic scenarios. It is possible for practitioners to take action against possible situations that may be encountered in real life by trying various possibilities.

4. Model Development

4.1. Causal Loop Diagrams (CLD)

Causal loop diagrams (CLD) are necessary to present the relationships between variables in complex systems (Yuan andWang, 2014). A detailed literature review was first conducted to define the main sustainability dimensions and their interactions, and the initial CLDs were constructed. These CLDs were then validated by fifteen engineers working in the recycling industry. Necessary changes were made in CLD structures in line with expert opinions and final CLDs were created.

At this stage, three environmental (water consumption, energy consumption, and gas emission) and two economic (total cost and profitability) closed-loop models were designed and visualized with the VENSIM PLE x64 program. Direction signs in the model show whether the variables have a reinforcing (+) or balancing (-) impact on the other variables. Please note that these CLDs handle the sell waste/buy new and recycle/reuse tradeoff.

Figure 1 presents the environmental CLDs. In these cycles, the amount of water, energy, and gas consumed in the recycling of solid wastes were compared to the consumption in the primary production. An increase in recycling rate refers more recycled materials and less primary materials, and vice versa. Hence, "water consumption gain/loss" variable compares the amount of water consumed in the industrial solid waste recycling to the amount of water required in primary production. This also implies for energy and gas consumption models.

Figure 1.a: Water Consumption CLD

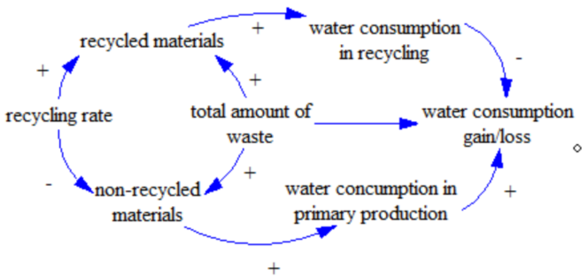


Figure 1.b: Energy Consumption CLD

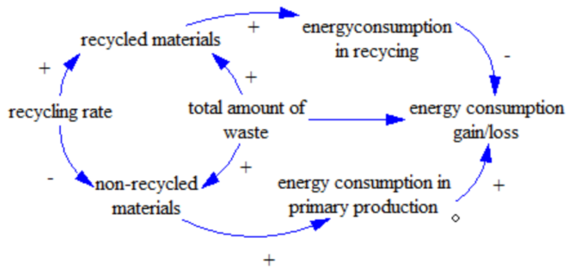


Figure 1.c: Gas Emission (CO2) CLD

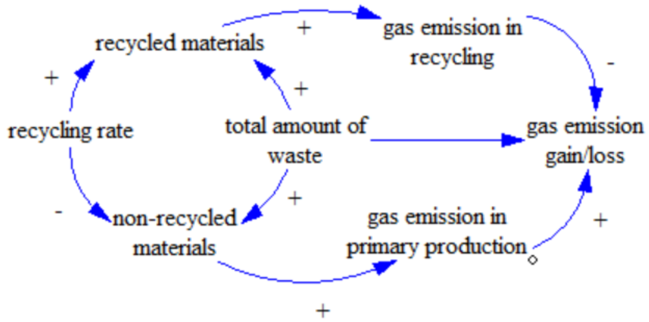


Figure 2 presents the CLD for the total cost, which is a sub-criterion of the economic dimension. This compares the total cost of acquiring the same material with recycling and primary production. Here, the cost of recycling includes energy, water, and gas consumption costs, and other production costs related to the recycling process. Primary production cost was defined as a function of material sales price. Again, higher recycling rate implies more recycled materials and less primary materials. Hence, the total cost gain/loss variable reveals the difference between primary production and recycling costs.

Figure 2: Causal Loop Diagram for Total Costs

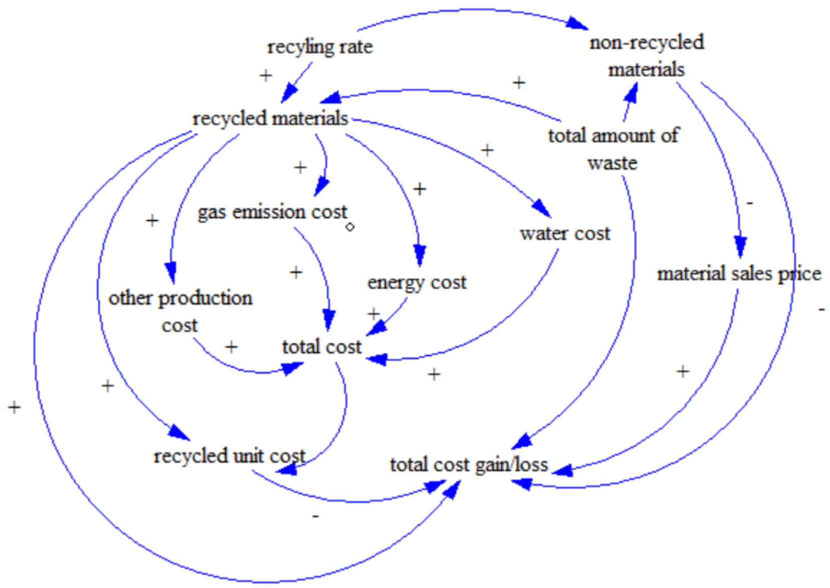
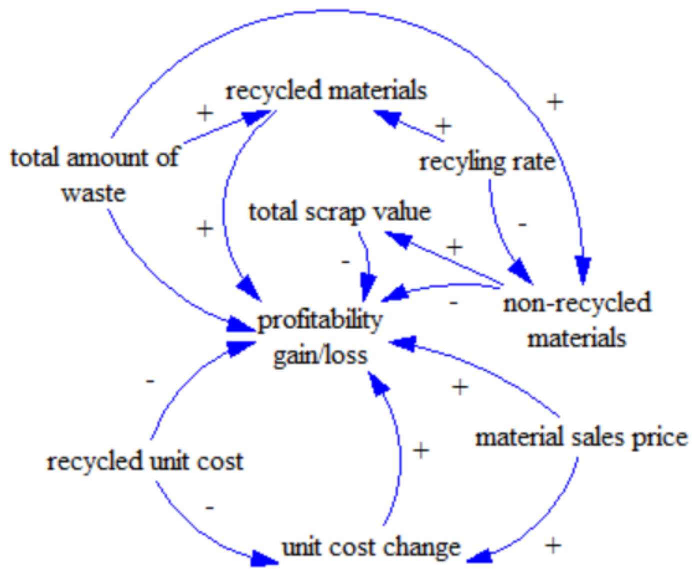


Figure 3 is the final CLD and compares the contributions of recycling and primary production to the profit. Here, two new variables were introduced. The scrap sales value of non-recycled materials negatively affects the profitability of recycling. Because if the scrap value is high, it may be more profitable to sell the waste and buy primary materials than to recycle it. Contrarily, the price of primary materials positively affects profitability because the high cost of materials makes recycling more advantageous and makes managers more willing to recycle.

Figure 3: Causal Loop Diagram for Profitability



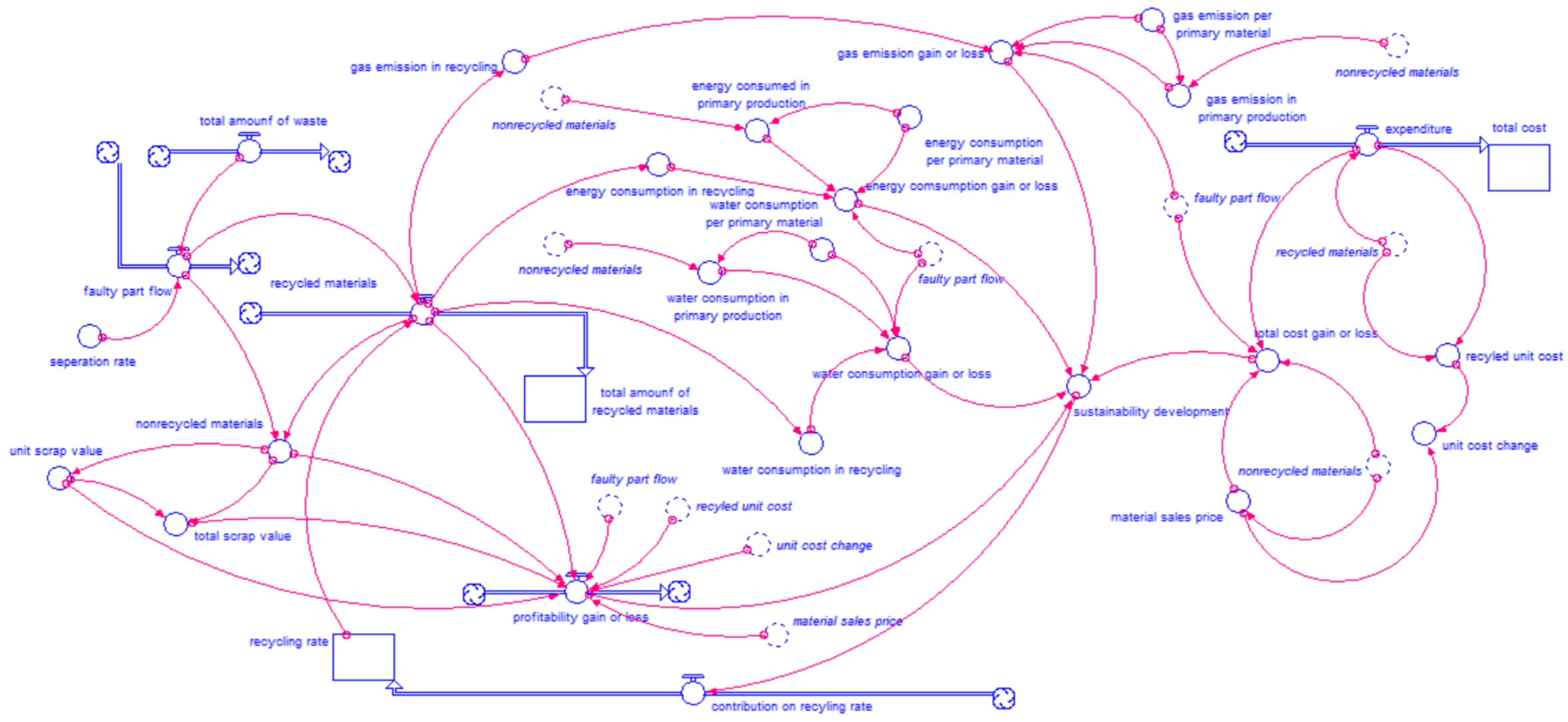
4.2. Model Map

After the stock and flow diagrams including all the variables and cycles of the model were completed, the model map was created (Figure 4). Please note that the model map includes all CLDs.

The model was designed similar to a real system for businesses to recycle their waste through recycling companies. The designed recycling model allows the system to show different behaviors by changing the variables over time. The change of many variables depending on time affects the dynamic feature of the system and the results can be followed separately for each period. The process starts with the accumulation of industrial solid wastes formed in the production facility and the materials that can be processed are separated. Then, it continues with the recycling of materials with a certain recycling rate by recycling companies.

The designed recycling model allows the system to show different behaviors by changing the variables over time. The change of many variables depending on time affects the dynamic feature of the system and the results can be followed separately for each period. In the model, three environmental causal cycle diagrams, namely water consumption, energy consumption and gas emission, and two economic causal cycle diagrams, namely cost and profitability, are combined with the variable named "sustainability development". Because the function prepared for the sustainability development variable includes both economic and environmental sustainability variables. At the same time, the positive status of this variable, which expresses the sustainability performance, shows that recycling is in an advantageous position. The fact that recycling creates an environmental and economic advantage may create a situation that encourages businesses to recycle more waste every period. In this way, sustainability development has an impact on the amount of recycled waste. In such a design, a closed supply chain has been created in the system. A highly eco-friendly and sustainable production system based on the reuse and recovery of resources in closed-loop supply chains is already aimed (Angelis-Dimakis et al., 2016). In line with the aims of the study, the effects of resource recovery on the sustainable supply chain coincide with this closed-loop model proposal.

Figure 4: Model Map in STELLA Program



The model map presented in Figure 4 were constructed for four types of wastes. The variables in the model are explained in Table 1.

Table 1: Model Variable

Variable	**Description**
Total amount of waste (x_1)	Total amount of waste generated in the production facility.
Separation rate (x_2)	The ratio shows the amount of material to be recycled.
Defective part flow (x_3)	Amount of waste that can be recycled: $x_3 = x_1 \times x_2$
Recycling rate (x_4)	Material recycling rate
Recycled materials (x_5)	The amount of the waste that will be directly recycled: $x_5 = IF(x_4 > 1) THEN\ 1 \times x_3\ ELSE\ [IF(x_4 < 0)\ THEN\ 0\ ELSE\ x_4 \times x_3]$
Total amount of recycled material (x_6)	The cumulative sum of the amount of waste to be recycled.
Non-recycled materials (x_7)	The amount of waste that cannot be recycled.
Gas emission in recycling (x_8)	The total amount of CO2 emitted in recycling: $x_8 = x_5 \times average\ CO2\ released\ in\ recycling$
Gas emission per primary material (x_9)	The average CO2 emitted in the primary production per unit.
Gas emission in primary production (x_{10})	The total amount of CO2 emitted in primary production: $x_{10} = x_7 \times x_9$
Gas emission gain/loss (x_{11})	Gas emission in recycling compared to primary production: $x_{11} = IF(x_3 = 0)\ THEN\ 0\ ELSE\ 1 - [(x_8 + x_{10})/(x_3 \times x_9)]$
Energy consumption in recycling (x_{12})	The total amount of energy consumed in recycling: $x_{12} = x_5 \times average\ energy\ consumed\ in\ recycling$
Energy consumption per primary material (x_{13})	The average energy consumed in the primary production per unit.
Energy consumption in primary production (x_{14})	The total amount of energy consumed in primary production: $x_{14} = x_7 \times x_{13}$
Energy consumption gain/loss (x_{15})	Energy consumption in recycling compared to primary production: $x_{15} = IF(x_3 = 0)\ THEN\ 0\ ELSE\ 1 - [(x_{12} + x_{14})/(x_3 \times x_{13})]$
Water consumption in recycling (x_{16})	The total amount of water consumed in recycling: $x_{14} = x_5 \times average\ water\ used\ in\ recycling\ (l/kg)$
Water consumption per primary material (x_{17})	The average water consumed in the primary production per unit.
Water consumption in primary production (x_{18})	The total amount of water consumed in primary production: $x_{18} = x_{17} \times x_7$
Water consumption gain/loss (x_{19})	Water consumption in recycling compared to primary production: $x_{19} = IF(x_3 = 0)\ THEN\ 0\ ELSE\ 1 - [(x_{18} + x_{16})/(x_3 \times x_{17})]$
Expenditure (x_{20})	Total expenditure of recycling: $x_{20} = (a \times x_5 + B) \times x_5$ where a refers fixed value and B refers regression coefficient of regression equation. The x_{20} variable is the expenditure made by the firm for recycling in the relevant period.
Total cost (x_{21})	The total cumulative expenditure of recycling. The difference of x_{21} from x_{20} is that it is equal to the sum of the total costs spent in all periods. In other words, one shows the periodical expenditure and one shows the total expenditure.
Recycled unit cost (x_{22})	The unit cost of the recycled material per unit: $x_{22} = IF(x_5 = 0) THEN\ 0\ ELSE\ (x_{20}/x_5)$
Material sales price (x_{23})	The sales price of the primary material.
Total cost gain/loss (x_{24})	The cost gain/loss of recycling instead of purchasing primary material: $x_{24} = IF(x_3 = 0)\ THEN\ 0\ ELSE\ 1 - [(x_7 \times x_{23}) + x_{20})/(x_3 \times x_{23})]$

Unit cost change (x_{25})	It is the difference between the unit sales price of the primary production material in the market and the cost of the unit material obtained in recycling.
Unit scrap value (x_{26})	The unit scrap value of non-recyclable wastes.
Total scrap value (x_{27})	The total scrap value of non-recyclable waste: $x_{27} = x_7 \times x_{26}$
Profitability gain/loss (x_{28})	The profit gain/loss of recycling instead of purchasing primary material: $x_{28} = 1 - \frac{(x_7 \times x_{23}) + (x_7 \times x_{25}) - x_{27} + (x_5 \times x_{22})}{(x_3 \times x_{23}) + (x_3 \times x_{25}) - (x_{26} \times x_3)}$
Sustainability development (x_{29})	The sustainability performance of recycle/reuse compared to the sell waste/buy primary material. Combines the five casual loop diagrams: $x_{29} = (x_{11} + x_{15} + x_{19} + x_{24} + x_{28})/5$
Contribution on recycling rate (x_{30})	Impact of sustainability performance on recycling rate in the next period.

4.3. Data

Data on model variables in Table 1 are compiled from both industry and literature. Industry was used as the primary data source and these data were supported by the literature. Here, a three-stage process was followed. First, the required data were collected through interviews from 16 companies in Bursa, Istanbul, Tekirdağ, Kocaeli, Ankara and Eskisehir, which recycle plastic, glass, steel, and aluminum. Second, the data provided in the literature were collected to complete the missing data and to test the reliability of the data provided by the companies. Finally, the arithmetic mean was calculated by considering the normal distribution of the data around a certain mean.

Table 2 presents the data on environmental variables for each waste group (plastic, glass, steel, and aluminum). These values are the arithmetic mean of industry data and the literature.

For energy consumption data;

The studies of Raadal et al. (2008), Ren (2012), Liljenström and Finnveden (2015), Gu et al. (2017) and data of four different plastic recycling companies were used for energy consumption data in the recycling of plastic industrial solid waste. The energy consumption data spent in primary production was also used by making use of the The Association of Plastic Recyclers (2020) report and the data referenced by the same plastic recycling companies.

The study of Leblanc (2019) and the data of three different glass recycling companies were used for the energy consumption data in the recycling of glass industrial solid waste and the energy consumption data in primary production.

The studies of Mohsen and Akash (1998), Yellishetty et al. (2011), Martelaro (2016) and five different steel recycling companies' data were used for energy consumption data in the recycling of steel metal solid waste. the data in Yellishetty et al. (2011)'s study and the data accepted as reference by four different recycling companies separately were used.for the energy consumption data spent in primary production.

Finally the studies of Norgate and Haque (2010), Global Aluminum Cycle from World Aluminum (2017), Assan Alüminyum (2021) and data provided by 4 different aluminum recycling companies were used for the energy consumption data in the recycling of aluminum metal solid wastes and the energy consumption data in the production of the same material as primary production.

For gas emission data;

Benner et al. (2007), Gradus et al. (2017), Storm (2017), The Association of Plastic Recyclers (2018), Khoo (2019) and The Association of Plastic Recyclers Report (2020) studies were used for data needed on gas emissions in the recycling of plastic industrial solid waste and the primary production of the same materials.

British Glass Recycling (2003), Larsen et al. (2009), Hilmann et al. (2015) studies and data of four different glass recycling companies were used for data needed on gas emissions in the recycling of glass solid waste and the primary production of the same materials.

Yellishetty et al. (2011) and World Steel Association (2020) studies and data of four different steel recycling companies were used for data needed on gas emissions in the recycling of glass solid waste and the primary production of the same materials. On the other hand, the data from the study of World Steel Association (2020) and the data taken as reference by the same recycling companies were used for the gas amount data released in the case of producing the same materials with primary production.

Hilmann et al. (2015), Peng et al. (2019), Weresch (2021) studies and data given by four aluminum recycling companies were used for gas emissions from recycling aluminum metal solid waste and gas emissions from primary production.

For water consumption data;

The studies of The Association of Plastic Recyclers (2018, 2020) and Benavides et al. (2018) were used for the water consumption data in the recycling of plastic industrial solid wastes. On the other hand, the Association of Plastic Recyclers (2018, 2020) studies and the data referenced by a recycling company were used for the data on the amount of water needed in primary production.

The study of Landi et al. (2019) and the data referenced by four recycling companies were used for water consumption data in the recycling of glass solid waste and the amount of water needed in primary production.

The reports of the European Commission (2008) and the World Steel Association (2018) and the data of four steel recycling companies were used for the water consumption data in the recycling of steel metal solid waste. On the other hand, the World Steel Association (2020) report and the data referenced by four steel recycling companies were used for the amount of water needed in the primary production of steel materials.

The study of Liljenström and Finnveden (2015) and data of two different aluminum waste recycling companies were used for the water consumption data in the recycling of aluminum metal solid waste. On the other hand, the same recycling companies were used for the amount of water needed in the primary production of the same aluminum materials.

Table 2: Data on Environmental Variables

	Energy Consumption		Water Consumption		CO_2 Emission	
	Recycling	Primary Prd.	Recycling	Primary Prd.	Recycling	Primary Prd.
Plastic	0.361 kwh/kg	1.040 kwh/kg	0.945 l/kg	1.360 l/kg	0.380 kg/kg	1.70 kg/kg
Glass	0.445 kwh/kg	0.600 kwh/kg	0.225 l/kg	0.450 l/kg	0.55 kg/kg	0.79 kg/kg
Steel	0.688 kwh/kg	1.725 kwh/kg	3.65 l/kg	6.40 l/kg	0.682 kg/kg	4.3 kg/kg
Aluminum	3.20 kwh/kg	46 kwh/kg	0.28 l/kg	0.50 l/kg	0.53 kg/kg	12 kg/kg

On the other hand, after expert interviews the data for the variable "separation rate" were accepted as 85% for plastics, 95% for glass, 90% for steels and aluminum. The scrap value of wastes and the sales price of primary material were provided by companies and based on the industry price index of the last six months. The data of the related variables were obtained from the database depending on the amount. Regression equations were established for the data needed due to the dynamic nature of the system dynamics models and the change in the waste amount flow (Table 3). The equations show the selling prices of scrap and primary materials, which vary depending on the amount of waste. In the model, different equations were used depending on different data for each product group.

Looking at the data, it is seen that the scrap value of aluminum waste is quite high compared to other material groups. The scrap value of glass waste is very low. When the current scrap sector is evaluated, it can be stated that the metal scrap sector is more developed. When the sales prices of the materials produced with primary production are evaluated, it is seen that aluminum metal has a high price with a significant difference. It can be stated that the sale price of metal materials produced with primary production is high due to both the access to raw material sources and the processes they undergo in the production processes. The product group with the lowest selling price is glass. When these two criteria are evaluated together, it is seen that the results are quite parallel to each other. Product groups with high sales prices also have high scrap values.

Another variable "expenditure" criterion in the model was the amount of payment made by waste owners to recycling companies Recycling companies can apply different price policies depending on the amount to be recycled. For this reason, a regression equation was established for the expenditure variable by considering the amount of recycled material and the cost.

Table 3: Data on Economic Variables

	Scrap value of wastes	Sales price of primary material	Expenditure of recycling
Plastic	$y = 0.0001x + 4.2502$	$y = -0.0009x + 24.801$	$y = -0.0005x + 11.586$
Glass	$y = 0.0001x + 1.2712$	$y = -0.0003x + 11.917$	$y = -0.0006x + 7.0808$
Steel	$y = 0.0007x + 8.4992$	$y = -0.0017x + 43.8$	$y = -0.0014x + 22.296$
Aluminum	$y = 0.001x + 20.336$	$y = -0.0026x + 60.904$	$y = -0.0024x + 32.718$

The "separation rate", which refers to the rate of material to be recycled, differs for each product group. These rates was decided with expert interviews working in recycling companies: 85% for plastics, 95% for glass, 90% for steels and aluminum. Based on the expert opinions, the recycling rate of glass is the highest and plastic is the lowest.

Finally, the material recycling rate and the impact of sustainability performance on recycling rate in the next period (Contribution on recycling rate) were obtained from the various reports. At the beginning of the simulation model, the current recycling rate was accepted as 30%. This assumption was based on the average accepted recycling rates of industrial solid waste in Turkey (Döngüsel Ekonomi ve Atık Yönetimi Dairesi Başkanlığı, 2022). It was assumed that the recycling rates will increase by 4% in the next period if it has a positive impact on business performance. Because sustainability reports published by companies show that recycling rates increase by 20-24% on avarege each year (Asaş, 2020; Kordsa,, 2020; Henkel, 2020). Since the annual cumulative rate was 24% and the program was run in 2-month periods, 4% increase rate was calculated for each period. This ratio was accepted as the same for four different product groups. Because one of the important aims of the study was to reveal the economic and environmental performances of recycling in four different product groups, it was important to consider the data of some variables as equal.

4.4. Model Assumptions

The overall assumptions in the system dynamics model are as follows:

- In order to compare different product groups, defective product flow was considered in kilograms and all data were calculated per kilogram.
- Only CO^2 was considered out of the six gas types defined in the Kyoto Protocol.
- The total amount of waste (x_1) was assumed to be 100 kg for each product group at the beginning of the simulation model.

The following conditions are assumed for the plastics:

- Model includes only PP (Polypropylene) and ABS (Acrylonitrile Butadiene Styrene) thermoplastics because they most widely used in industry.
- The mechanical recycling method is based on the recovery of thermoplastics. Because with mechanical recycling, materials are recovered in high quantities and almost without loss of quality.

The following conditions are assumed for the glasses:

- Only transparent and laminated glasses are included to the model. Transparent colored glasses are the most widely used in industrial products (Khazhiakhmetova et al., 2020) and has the most application area. Laminated glasses are preferred because they have easy recycling properties (Farel et al., 2013).
- Glass products to be recycled are small glasses with an average thickness of 10-30 mm and do not contain pollution.

The following conditions are assumed for the steels:

- Only "New Scrap" and low carbon and high strength steels are included to the model.

- Electric arc furnace is used in the recycling of steel metal waste. It is known that the technique has great application in the steel recycling industry and accepts all steel (Kovacic et al., 2019).
- Steel materials produced as a result of recycling activities consist of flat plates with an average thickness of 1-5 mm and a width of 600-1250 mm.

The following conditions are assumed for the aluminums:

- Only "New Scrap" and A5xxx (like A5083) and A6xxx aluminum sheet alloys steels are included to the model.
- Induction furnaces are used due to the use of small and clean scraps in the melting step.
- Aluminum materials produced as a result of recycling activities consist of flat sheets with an average thickness of 0.5-10 mm and a width of 1000-2000 mm.

5. Findings

In this study, the program was run for 2 years. For the findings in the table, each time "t" represents the 2-month period. In the study, the criteria weights for the four product groups were considered equal and the results were examined. The model was designed to have a total weight value of 0.50 for environmental sustainability criteria and 0.50 for a total weight value for economic sustainability criteria.

5.1. Findings for The Plastic Product Group

Table 4: Program Outcomes for Plastic Waste

t	Sustainability development	Energy consumption amount	Gas emission amount	Water consumption amount	Total cost	Profitability
1	0.16	0.20	0.23	0.09	0.12	0.15
2	0.18	0.22	0.26	0.10	0.14	0.17
3	0.20	0.25	0.30	0.12	0.16	0.19
4	0.22	0.27	0.33	0.13	0.17	0.21
5	0.24	0.30	0.36	0.14	0.19	0.23
6	0.26	0.33	0.39	0.15	0.21	0.25
7	0.28	0.35	0.42	0.16	0.22	0.27
8	0.30	0.38	0.45	0.18	0.24	0.29
9	0.32	0.40	0.48	0.19	0.26	0.31
10	0.34	0.43	0.51	0.20	0.27	0.34
11	0.36	0.46	0.54	0.21	0.29	0.36
Final	0.38	0.48	0.57	0.23	0.31	0.38

The potential results of plastic waste recycling with the program running for two years are shown in Table 4. In general, it is an important result of the study that plastic recycling creates advantages for businesses in terms of relevant economic and environmental factors. In terms of environmental sustainability performance, the contribution rate of plastic solid waste recycling in terms of water consumption, which is 9.2% at the beginning, will reach 22.6%. The contribution rate, which is 19.6% in terms of energy consumption, will reach 48% and the contribution rate of 23% in terms of gas emissions will reach 57.5%. These data also show that the recycling of plastic industrial wastes can be prevented by 23.3% in terms of water consumption, 48% in terms of energy consumption and 58% in terms of gas emissions, compared to primary production.

In terms of economic sustainability performance, plastic recycling is very advantageous on both total cost and profitability. The effect of recycling plastic waste on the total cost of the business decreases by 12.3% at the beginning and will reach 30.5% at the end of the period according to effect on the total cost of purchasing the same source produced with primary production. These rates can be interpreted as the cost of recycling activities can be reduced by 12-31% compared to the purchase of the product produced with primary production. It is seen that the profitability variable calculated by adding the opportunity cost and the scrap value of the wastes will increase from 15.2% to 38% within the two-year working period. This ratio of up to 38% shows the positive effect on the profitability of the business of recycling rather than purchasing new material to replace plastic waste. Looking at the sustainability development, which shows the final result of the study, it is expected that the sustainability performance will increase by 39% at the end of two years if businesses recycle their existing waste.

5.2. Findings for the Glass Product Group

Table 5: Program Outcomes for Glass Waste

t	Sustainability development	Energy consumption amount	Gas emission amount	Water consumption amount	Total cost	Profitability
1	0.12	0.08	0.09	0.15	0.12	0.16
2	0.14	0.09	0.10	0.17	0.14	0.18
3	0.16	0.10	0.12	0.19	0.15	0.21
4	0.17	0.11	0.13	0.21	0.17	0.23
5	0.19	0.12	0.14	0.23	0.19	0.25
6	0.21	0.13	0.15	0.25	0.20	0.27
7	0.22	0.14	0.16	0.27	0.22	0.29
8	0.24	0.15	0.18	0.29	0.24	0.32
9	0.26	0.16	0.19	0.31	0.25	0.34
10	0.27	0.17	0.20	0.33	0.27	0.36
11	0.29	0.18	0.21	0.35	0.29	0.38
Final	0.31	0.19	0.22	0.37	0.30	0.40

The potential results of glass waste recycling with the program running for two years are shown in Table 5. Glass recycling is advantageous in terms of relevant economic and environmental factors. In terms of environmental sustainability performance, the contribution rate of glass waste recycling in terms of water consumption, which is 15% at the beginning, will reach 37%. At the same time, the contribution rate, which is 7.7% in terms of energy consumption, will reach 19.1% and the contribution rate of 9.1% in terms of gas emissions will reach 22.5%. These data also show that the negative effects of glass waste recycling on the environment can be prevented at the rates of 37% in terms of water consumption, 19% in terms of energy consumption and 23% in terms of gas emissions, compared to primary production.

In terms of economic sustainability performance, glass recycling is very advantageous on both total cost and profitability. The effect of recycling glass waste on the total cost of the business decreases by 12.2% at the beginning and will reach 30.2% at the end of the period according to effect on the total cost of purchasing the same source produced with primary production. These rates can be interpreted as the economic burden of recycling activities on the business can be reduced by 12-30% compared to the purchase of the product produced with primary production. The 31% contribution rate is the effect size of the recycling of glass material instead of purchasing it on the profitability of the business. Looking at the sustainability development, which shows the final result of the study, it is expected that the sustainability performance will increase by 31% at the end of two years if businesses recycle their existing waste.

5.3. Findings for the Steel Product Group

Table 6: Program Outcomes for Steel Waste

t	Sustainability development	Energy consumption amount	Gas emission amount	Water consumption amount	Total cost	Profitability
1	0.18	0.18	0.25	0.13	0.15	0.18
2	0.20	0.20	0.29	0.15	0.17	0.21
3	0.22	0.23	0.32	0.16	0.19	0.23
4	0.25	0.25	0.35	0.18	0.21	0.26
5	0.27	0.28	0.39	0.20	0.23	0.28
6	0.29	0.30	0.42	0.21	0.25	0.30
7	0.32	0.32	0.45	0.23	0.27	0.33
8	0.34	0.35	0.49	0.25	0.29	0.35
9	0.36	0.37	0.52	0.27	0.31	0.38
10	0.39	0.40	0.56	0.28	0.32	0.40
11	0.41	0.42	0.59	0.30	0.34	0.43
Final	0.44	0.44	0.62	0.32	0.36	0.45

According to Table 6, steel recycling is quite advantageous in terms of economic and environmental factors compared to primary production. In terms of environmental sustainability performance, the contribution rate of steel waste recycling in terms of water consumption, which is 12.9% at the beginning, will reach 31.8% at the end of the 2-year working period. At the same time, the contribution rate, which is 18% in terms of energy consumption, will reach 44.5% and the contribution rate of 25.2% in terms of gas emissions will reach 62.3%. These data also show that the negative effect of steel waste recycling on the environment can be prevented at the rates of 32% in terms of water consumption, 45% in terms of energy consumption and 62% in terms of gas emissions, compared to primary production.

In terms of economic sustainability performance, steel recycling is very advantageous on both total cost and profitability. The effect of recycling steel waste on the total cost of the business decreases by 14.7% at the beginning and will reach 36% at the end of the period according to effect on the total cost of purchasing the same source produced with primary production. These rates show that the economic burden of recycling activities on the business can be reduced by 15-36% compared to the purchase of the product produced with primary production. The 45% contribution rate is the effect size of the recycling of steel material instead of purchasing it on the profitability of the business. Looking at the sustainability development, which shows the final result of the study, it is expected that the sustainability performance will increase by 44% at the end of two years if businesses recycle their existing steel waste.

5.4. Findings for the Aluminum Product Group

Table 7: Program Outcomes for Aluminum Waste

t	Sustainability development	Energy consumption amount	Gas emission amount	Water consumption amount	Total cost	Profitability
1	0.19	0.28	0.29	0.13	0.14	0.16
2	0.22	0.32	0.32	0.15	0.16	0.18
3	0.24	0.35	0.36	0.17	0.18	0.20
4	0.27	0.39	0.40	0.18	0.19	0.22
5	0.29	0.43	0.44	0.20	0.21	0.24
6	0.32	0.47	0.48	0.22	0.23	0.26
7	0.34	0.50	0.52	0.24	0.25	0.28
8	0.37	0.54	0.55	0.26	0.27	0.30
9	0.39	0.58	0.59	0.27	0.29	0.33
10	0.42	0.61	0.63	0.29	0.31	0.35
11	0.45	0.65	0.67	0.31	0.33	0.37
Final	0.47	0.69	0.71	0.33	0.34	0.39

According to Table 7, aluminum recycling has a significant advantage over primary production in terms of economic and environmental factors. The contribution rate of aluminum waste recycling in terms of water consumption, which is 13.2% at the beginning, will reach 32.6% at the end of the 2-year working period. At the same time, the contribution rate of 27.9% in terms of energy consumption will reach 68.9% and the contribution rate of 28.7% in terms of gas emissions will reach 70.7%. These data also show that the negative effects of aluminum waste recycling on the environment can be prevented at the rates of 33% in terms of water consumption, 69% in terms of energy consumption and 71% in terms of gas emissions, compared to primary production.

Aluminum recycling can provide very important opportunities in terms of economic sustainability performance. The effect of recycling aluminum waste on the total cost of the business decreases by 13.9% at the beginning and will reach 34.4% at the end of the period according to effect on the total cost of purchasing the same source produced with primary production. These rates show that the economic burden of recycling activities on the business can be reduced by 14-34% compared to the purchase of the product produced with primary production. The rate of 39% in the profitability variable shows the contribution of the recycling of aluminum materials to the profitability of the business instead of purchasing them. Looking at the sustainability development, which shows the final result of the study, it is expected that the sustainability performance will increase by 47% at the end of two years if businesses recycle their existing aluminum waste.

All the results for the economic and environmental performance of the four different product groups in the study are shown in Table 8. The table shows the min-max values of the criteria showing economic and environmental sustainability performances.

Table 8: Combined Table of Results for Four Different Product Groups

	Aluminum	Steel	Plastic	Glass
Sustainability development	0.190-0.471	0.186-0.435	0.156-0.385	0.124-0.308
Total cost	0.139-0.344	0.147-0.365	0.123-0.305	0.122-0.303
Profitability	0.157-0.390	0.182-0.451	0.152-0.376	0.162-0.404
Water consumption	0.132-0.326	0.129-0.318	0.092-0.226	0.150-0.370
Energy consumption	0.279-0.689	0.180-0.445	0.196-0.483	0.077-0.191
Gas emission	0.287-0.707	0.252-0.623	0.233-0.575	0.091-0.225

Table 8 contains answers to the following question: "How does the impact of different types of (plastic, glass, steel and aluminum) industrial solid waste recycling on economic and environmental sustainability performance change?"

The potential impact of recycling on energy consumption is mostly in aluminum metal with a rate of 69%, and the least impact is in the glass product group with a rate of 19.1%. Secondly, compared to primary production, the environmental contribution of recycling in terms of gas emission is the highest in aluminum metal with a rate of 71%, and the second highest contribution is in steel metal with a rate of 62.3%. On the other hand, glass products provide the lowest benefit of industrial waste recycling in terms of gas emissions, with a rate of 22.5%. Glass product group provide the biggest advantage of recycling in terms of water consumption compared to primary production with a rate of 37%.

In terms of economic sustainability performance, the biggest contribution of recycling products instead of purchasing products produced with primary production on the total cost of the enterprise is realized in steels with 36.5%, followed by aluminum materials with 34.4%. Similar to this ranking, steel materials give the highest contribution rate (45%) on the profitability variable, which includes scrap value and opportunity cost.

As a result of the study, the biggest contribution to the sustainability performance of the use of recycling instead of purchasing new materials to replace the wastes is aluminum with 47%, followed by steel with 44%.

6. Conclusion and Discussion

In this study, a model has been proposed that shows the economic and environmental effects on the supply chain performance by recycling the solid wastes of the business. In addition, it is aimed to compare the effects of recycling four different types of industrial solid wastes, namely plastic, glass, steel and aluminum, on sustainability performance and to reveal possible causes. It is expected that the study will contribute to the existing literature, since both the proposed model and the effects in different product groups are revealed. As far as is known, this model, which reveals the effect of recycling of wastes on the sustainability performance, is thought to be the first in the current literature.

In order to achieve the main objectives of the study, the recycling system behaviors of the businesses that can recycle their wastes under the responsibility of the producer were examined with the system dynamics approach and the changes depending on the time were estimated. The findings obtained by running the program are evaluated for different purposes. The common finding for all product groups is that recycling of waste by businesses has significant effects on sustainability performances compared to purchasing new materials. However, recycling in different product groups has different effects on the economic and environmental sustainability performance of businesses. This situation affects the sustainability performance of businesses at different levels.

It is stated that the recycling of aluminum waste made the highest contribution in terms of energy consumption. This situation is probably caused by the fact that the amount of energy needed in the primary production of aluminum materials is higher than that of other product groups. This finding supports the finding in the study of Dahlström and Ekins (2007) that "aluminum metal is potentially the most widely applicable in terms of energy consumption rates". On the other hand, it is stated that the least contribution of recycling in terms of energy consumption is in the glass product group. This is the possible result of the low amount of energy required in the primary production of glass materials compared to other product groups.

Similarly, it is stated that the recycling of aluminum waste was the product group that made the highest contribution in terms of gas emissions. In this case, it supports the results of Dahlström and Ekins (2007), which discuss the recycling of aluminum waste in terms of different material categories along the value chain. The situation with the second highest contribution in terms of gas emission is stated as the recycling of steel waste. Accordingly, it can be stated that the environmental gain of the recycling of metal wastes in terms of gas emission is higher than the others. The lowest contribution of recycling in terms of gas emission is expressed in glass product groups. In this case, the amount of gas emission in the primary production of glasses is likely to be more environmentally friendly than other product groups.

It is seen that recycling of glass waste had the highest contribution rate in terms of water consumption. This finding is supported by the study of Zarrinpoor (2021), in which he designed the supply chain network for glass recycling. However, it should be stated that the results are not in terms of the total amount of water consumed, but in terms of the effect ratio. Despite the significant environmental benefits in terms of water consumption in the recycling of aluminum and steel metals, these effects are not observed in plastic product groups. In this case, the relatively high amount of water needed for the recycling of plastic industrial wastes is probably effective.

When the findings are evaluated in terms of cost-benefit ratio, it is seen that steel metal recycling is more advantageous. However, when evaluated in terms of total cost, it is seen that aluminum recycling provides the greatest advantage. Because the selling price of aluminum materials is on average 1.3-2 times higher than steel materials. According to these findings, aluminum and steel recycling have a greater impact on the total cost of businesses compared to other product groups. The high contribution of metal recycling to the total cost compared to many other materials is similar to the study results of Seshappa and Prasad (2020). The lowest contribution rate on the total cost rate of recycling is in the glass product group. It can be stated that the recycling of glass waste is not economical enough compared to other product groups. In terms of profitability, which includes the scrap values and opportunity costs of wastes, the highest contribution is seen in metal recycling, while glass materials give the lowest contribution rate. The uneconomical scrap value of glass is likely to increase the opportunity cost.

Aluminum materials provide the biggest contribution to sustainability performance in industrial solid waste recycling. Businesses with aluminum waste can improve their sustainability performance by almost half if they incorporate recycling into their supply chain instead of purchasing new materials directly. The second biggest contribution of recycling to the sustainability performance is seen in the steel product group. By looking at the data of the two metals, recycling of metals provides a higher contribution in terms of sustainability performance than recycling of waste with glass and plastic materials.

On the other hand, the study was carried out under some constraints. The first of these constraints was experienced during the data collection process. The study was greatly hampered by the fact that most companies in the industry were not keeping data on environmental performance. Especially for the data of environmental dimensions in the model, the data of similar studies in the literature were used. These collected data were analyzed for use in the document. The second limitation was that the validity of the model was not fully determined and its reliability was not tested. Expert opinions were consulted for the structural accuracy of the relations between the variables and the model map, and the current structure was found to be valid. The data obtained as a result of the document could not be compared because there was no real reference data set.

Another issue that needs to be emphasized is that the collected data reflect this period. However, periodic differences can be expected in the results obtained separately for the four product groups, especially in the economic performance results. Energy costs, water consumption costs may have different seasonal effects for businesses, which may affect the total cost. However, this will affect both the recycling cost and the primary production cost. It is expected that the results will not be affected much by examining the performance criteria in the document from a proportional perspective. For this reason, it is thought that the results can be generalized.

Finally, the proposed system dynamics model to determine the effect of industrial solid waste recycling on sustainability performance can be used by both researchers and practitioners with similar working areas. The dynamic structure of this model has been designed in such a way that it can easily allow new data entry of model variables. This situation may provide an opportunity for businesses to use existing system data in a way that can support real decision processes according to their goals. In the next period, researchers can easily carry out their own studies by reflecting the differences (technology level, level of development, etc.) to the model. In addition, although the research is examined for cases for four different product groups, the study can be repeated with a broad perspective by including wastes with different materials. In addition, all the results in the study were obtained when the companies recycle their industrial wastes through the recycling company. Different cost items can be added to the work, as the company establishes its own recycling structuring. The investment needed first will constitute the largest share of the cost. The logistics cost from transport will also need to be excluded. While there will be no change in its environmental performance dimensions, its economic performance will change drastically. Under these conditions, the study may give ideas to future researchers.

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