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Sustainable Management Model of Construction Minerals Mine Using a System Dynamics Approach

Aryanti Virtanti Anas[1*], Rini Novrianti Sutardjo Tui[1], Rizki Amalia[1], Hijir Ismail Adnin Rasyad[2], Angelie Santosa[1]

[1] Department of Mining Engineering, Engineering Faculty, Universitas Hasanuddin, Gowa 92172, Indonesia
[2] Bureau of Economics and Development Administration of Regional Secretariat, Makassar 90231, Indonesia

Corresponding Author Email: aryantiv@unhas.ac.id

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ABSTRACT

Construction minerals are vital to the supply of raw materials, especially for the construction industry, one of the world's most essential and oldest industries. However, construction minerals mines pose challenges to sustainable development due to their impacts on the sustainable development principle, including four pillars: social, economic, environmental, and institutional. Unmanaged mines will affect sustainability, so a systemic approach is needed to analyze and evaluate sustainability using indicators or attributes of each dimension. This research sought to construct the relationship between social, economic, environmental, and institutional leverage attributes and dimension sustainability. Therefore, we developed system dynamics models to describe the dynamism of dimension sustainability in the case of the construction minerals mine in Jeneberang River in three scenarios based on actual sustainability conditions. The simulation results show that the sustainability index value of Scenario 3 is the worst, which means all dimensions will be less and unsustainable. Meanwhile, Scenario 2 is the best scenario, where all dimensions of sustainability index values will increase and become relatively sustainable and sustainable.

1. INTRODUCTION

Construction minerals are raw materials the construction industry needs, which use the most construction minerals and are the most significant cause of the depletion of mineral resources. The industry uses a variety of materials, including non-metallic mineral-based products (concrete, asphalt, bricks, stone, and aggregate) [1], and the most significant are construction minerals, namely sand, stone, gravel, and crushed stone (crushed stoned). Construction minerals are critical materials for fill material, mortar, sub-base, et cetera, and are essential for buildings and infrastructures such as housing, hospitals, offices, roads, railways, and bridges. Construction activities of buildings and other much-needed infrastructures influence fluctuating demand for construction minerals [2, 3].

Construction minerals mining consists of excavation or dredging activities of sand, gravel, rocks, blocks, and other sediment deposits from river channels, glacial deposits, floodplains [4], processing, and transportation activities. Construction mineral processing and extraction activities are generally low-tech and labor-intensive [5], located near end-use markets where construction and other development activities drive demand for these commodities [6, 7]. The demand for construction minerals increases by an average of 2-5%/year, which raises questions about the continuity of supply [3], as well as increasing environmental impacts due to exploitation, such as water quality, road damage, dust, and noise [8, 9]. Attention to the social, economic, and environmental pillars, which are sustainable development's main goals, is vital in mining activities [10]. The sustainable development of mining is a significant challenge for today's world. Therefore, the first guiding principle must be the reasonable and economical acquisition and use of mineral resources [11]. The issue of managing mineral resources is increasingly significant because of their finite and non-renewability [12].

Construction minerals exploitation and processing activities face several challenges related to sustainable development because they significantly impact the environment and local communities. This condition requires mining operations to comply with sustainable development principles while still meeting demand [7] but minimizing negative impacts. The study of sustainable development aims to balance the economic, social, and environmental aspects of mining. Although mining has negative environmental impacts, it also provides financial and social benefits [13]. On the one hand, it is an opportunity to generate sustainable wealth for all stakeholders, but on the other hand, it directly impacts environmental and social life quality [14]. Mining has created social and economic activities in some regions, improved social and financial infrastructure, increased workforce skills, mainly local employees, and developed sustainable wealth [15].

Mining's positive contribution to regional development includes multiple benefits related to the company's existence and direct contributions from the company as part of corporate social responsibility to the community, such as employment, infrastructure improvements, and market growth due to increased business opportunities. The negative impacts that arise apart from physical changes are changes in social and cultural life [16].

Sustainable mine development is the key to the availability of mineral resources, leading to this industry's positive and negative impacts on three main dimensions: social, economic, and environmental [14]. These dimensions focus on various efforts to minimize environmental damage. They are applied in various mining project cycles to be economically profitable, environmentally clean, and socially responsible to maximize mining's contribution to development [11, 17]. The social dimension describes the increase in economic welfare in the community through caring for employees and community development in the mining environment. The economic dimension describes the desire to improve economic well-being and is the fundamental motivation behind every organization. The environmental dimension describes increased economic welfare but does not reduce environmental quality [17, 18]. Mining can become sustainable by adopting and integrating the three main social, environmental, and economic dimensions with the institutional (government) dimension. The institutional dimension describes the relationships between society and mining regulations [7]. Economic development, environmental impact, and social responsibility must be appropriately managed through productive relationships between companies and the government, non-governmental organizations, industry, and stakeholders. Companies are primarily responsible for developing a sustainable mining industry and partnering with the government. The government ensures the comprehensive impact assessment process, effective monitoring, and reporting system to ensure the mine management plan is performed [19, 20].

There are various sustainability assessments, such as the Global Reporting Initiative (GRI), the Sustainability Accounting Standards Board (SASB), the Task Force on Climate-related Financial Disclosures (TCFD), and the Carbon Disclosure Project (CDP) [21]. The Analytical Hierarchy Process (AHP) and Multi-Criteria decision-making (MCDM) sustainability assessment frameworks have been developed in the mining sector. MCDM is considered the best method for sustainability assessment [22], such as the Fuzzy Best Worst Method, used to analyze sustainability challenges in the Turkish mining sector [23]. The study uses the Life Cycle Sustainability Assessment (LCSA) to assess the three pillars of sustainable development in gold production [24]. Life Cycle Assessment (LCA), Life Cycle Costing (LCC), and Social Life Cycle Assessment (SLCA) construct the LCSA. The three principles of sustainability should be simultaneously applied during the mining life cycle (MLC), for example, the Data Envelopment Analysis (DEA) approach as a tool to model exploration sustainability [14]. Another tool is Partial Least Squares Structural Equation Modeling (PLS-SEM) to investigate the interrelationship between green mining policies and sustainable resource management [25].

Many stakeholders have highlighted the importance of measuring the mining sustainability performance. Based on the authors' knowledge, there is only a handful of research on sustainable management of construction minerals mining in Indonesia. Several technical and managerial studies evaluated the sustainability dimensions separately; meanwhile, sustainable development is holistic and encompasses all sustainability aspects [14]. The sustainable development of a system is based on the lack of sustainability in subsystems. Sustainable development comprises six systems: individual development, social system, governance, infrastructure, economic system, resources, and environment [26]. Therefore, sustainable systems assessment can be complex, so a new technique is needed to perform interactions among systems and subsystems, such as system dynamics modeling.

Considering the many interests and mining as a system, management should be evaluated through a holistic approach (multi-criteria analysis) and a systemic approach. A holistic approach uses indicators to measure the level of mining sustainability based on assessing the attributes of the social, economic, and environmental dimensions as the three main pillars of sustainable development and the role of related institutions (institutional dimensions) as policymakers and implementers. Previous research on the evaluation of mine sustainable development by a study used 95 indicators of environmental sustainability in copper mining [21], a study used three indicators on several aspects of mineral resource management [26], and a study used three attributes (safety, efficiency, and environment), nine criteria, and 35 indicators [27]. Moreover, a study set 31 indicators (nine social, 14 environmental, and eight economic) in the context of mine closure and repurposing [28], and a study used 18 leveraging indicators on mining management strategies of construction material in the Jeneberang River [29].

A comprehensive systemic approach is needed to make effective decisions because social, economic, environmental, and institutional responsibility are broad development characteristics that shape the sustainability of a system. Dynamic system modeling differs from other sustainability assessment tools by adopting a systematic perspective and analytical approaches to describe a complex system's behavior and dynamic interactions [30, 31]. System dynamics, categorized as integrated assessment, allows the integration of economic, environmental, social, and governmental policies as required by sustainable development, usually focusing on policy change or project implementation [31, 32].

In recent years, much research on mining sustainability implemented system dynamics as a tool because the system dynamics approach can address various problems, including integrated planning and designing strategies, demonstrating the capability and level of trust. This approach has been used in the mining engineering and project management analysis. Some previous research is as follows: The study uses system dynamics to model interactions between environmental and economic policies governing the long-term behavior of mineral investment funds [32]; Some used to evaluate the effectiveness of mining green strategy in a large-scale copper mine [10]; Some provide a comprehensive review and analysis of the sustainable management of water resources in the mining industry [12]; Some captures the dynamism of mining fiscal regimes by analyzing technical and economic variables over time [33]; and others introduce a system dynamics model at diversifying the global supply chain of rare earth elements (REEs) and reducing reliance on China [34]. Moreover, a study [35] combined the LCA and system dynamics approach to establish the value chains for both minerals and water in the beneficiation process; meanwhile, a study combined system dynamics and balanced scorecards method to be used in the industrial safety management in the metallurgical mining sector [36].

Various issues related to sustainable construction minerals mining arise due to limitations and ineffective regulatory controls, which have social, economic, and environmental impacts. A management approach that ignores aspects of sustainable development will affect the mining industry's sustainability level. A system dynamic model is built using key indicators or leverage attributes to formulate a policy based on mine management scenarios of construction minerals as a recommendation for formulating sustainable mine management policies.

2. RESEARCH METHOD

The research reviews the management sustainability of construction minerals (sand, gravel, and crushed stone) mines in the Jeneberang River, Gowa Regency, from a literature study (previous research) as a case study by the dynamism of indicators or attributes we say in this research [30]. The assessment has been developed using indicators because the indicators can provide information for policymakers in decision-making. The indicator-based approach is acknowledged as a helpful tool in communicating simplified, concise, and scientifically reliable information on problems of sustainable development [18, 22].

The attributes of Jeneberang River mining sustainability, including social, economic, environmental, and institutional dimensions, consist of 43 attributes. There were 15 attributes of social dimension, seven attributes of economic dimension, ten attributes of environmental dimension, and 11 attributes of institutional dimension. The attributes represent the common indicators of construction minerals mining in the research area. The assessment was gathered from various related stakeholders through a questionnaire to the mining companies' management, the Department of Mines and Energy, the Head and staff of the Environmental Agency, and the Heads of Districts and Villages in Gowa Regency. Attribute leveraging analysis shows the effect of removing one attribute at a time on the ordination of mining sustainability. Leverage (sensitivity) analysis is roughly the average radius of the leveraging scatter for dimension status [29]. Leverage analysis of all attributes obtains eighteen key attributes as leveraging factors [30], namely:

1) Social dimension: guidelines for occupational health and safety, community participation in mining management, availability of safety equipment, changes in the quality of inhabitants' lives, changes in socio-cultural values, and frequency of conflict.
2) Economic dimension: the mining sector's contribution to the Gross Regional Domestic Product (GRDP), employees' income, economic conditions of inhabitants due to the mining companies, and the amount of construction materials demanded.
3) Environmental dimension: impact of mining on water quality of the river, impact of trucks on road damage, nuisance of dust from trucks and crushers, and nuisance of noise from trucks and crushers.
4) Institutional dimension: availability of labor unions, availability of river mining guidelines, mining land use zoning, and availability of regulations and guidelines of occupational health and safety.

The research method combines sustainability assessment tools: indicators/attributes and system dynamics. The dynamic management system model is built based on the leverage attributes of each dimension. The changes in management index values can affect the sustainability of the mine management system. The system was analyzed using a flow chart based on a box-arrow symbol and a causal loop diagram using STELLA 10.0.4 software in Mine Planning and Valuation Laboratory, Universitas Hasanuddin.

The system dynamics approach is used for modeling and simulating the dynamic behavior of complex systems over time [33, 37]. System dynamics are the best way to understand complex systems so they can be used to solve various kinds of problems. This approach was developed by Jay W. Forrester in 1961 and has been used in various fields where interactions between humans and systems occur, including global environmental analysis in the world system, regional and international sustainable development issues, environmental management, water resource management and planning, and environmental modeling. In mining, system dynamics modeling has found wide applications, including public policy analysis, engineering systems evaluation, analysis of environmental factors, business planning, Artisanal and Small-scale Mining (ASM), and hydrogeological assessments. Interrelationships capture systems interdependencies and holistic understanding, internal causal loops (feedback loops), time delays, stocks, and flows, and facilitate long-term projection [33, 34, 37].

Table 1. The initial score of each dimension attribute [29, 30]

Dimension and Attributes	Score
Social	
Guidelines of occupational health and safety (LS_1)	1
Community participation in mining management (LS_2)	1
Changes in the quality of inhabitants' lives (LS_3)	1
Availability of safety equipment (LS_4)	1
Changes in socio-cultural values (LS_5)	1
Frequency of conflict (LS_6)	1
Economic	
Mining sector's contribution to the Gross Regional Domestic Product (GRDP) (LEc_1)	0
Employees' income (LEc_2)	1
Economic conditions of inhabitants due to the mining companies (LEc_3)	2
Amount of construction materials demanded (LEc_4)	1
Environmental	
Impact of mining on water quality of the river (LEn_1)	1
Impact of trucks on road damage (LEn_2)	1
Nuisance of dust from trucks and crushers (LEn_3)	1
Nuisance of noise from trucks and crushers (LEn_4)	1
Institutional	
Availability of labor union (LI_1)	0
Availability of river mining guidelines (LI_2)	1
Mining land use zoning (LI_3)	1
Availability of regulations and guidelines of occupational health and safety (LI_4)	1

A causal loop diagram expresses cause and effect events in pictorial language as interlocking arrows expressing the cause and the effect. Cause and effect must refer to measurable conditions, both qualitatively for perceived conditions and quantitatively for actual conditions. Stock and flow structures are fundamental to the dynamics of complex systems. Stocks represent both non-physical and physical accumulations left by an activity. In dynamic systems, this cause-and-effect diagram is used as a basis for constructing stock and flow diagrams, which are then simulated. Flows represent activities that draw from or infuse into a stock instantaneously or over time and are divided into inflows and outflows. These models can be quantitative or qualitative, using relationships among processes or sub-systems to simulate a complex system [33, 38].

In this research, the system dynamic model was developed using an initial score of the leverage attributes of each dimension. All attributes are scored based on stakeholders' assessment in the 0 (bad) to 2 (good) range, as seen in Table 1. The lousy score reflects the most unfavorable conditions for sustainable mining and vice versa [29].

The sustainability index scale used in the previous research comprises four categories, namely 0-25% means unsustainable, 25.01-50% means less sustainable, 50.01-75% means relatively sustainable, and 75.01-100% means sustainable. The value of the sustainability index of mine management in Jeneberang River obtained: social dimension was 44.95% (less sustainable), economic dimension was 45.77% (less sustainable), environmental dimension was 66.02% (relatively sustainable), and institutional dimension was 53.59% (relatively sustainable). The index value was 54.28%, categorized as relatively sustainable [30].

3. RESULTS AND DISCUSSION

The Jeneberang River is one of the main rivers in South Sulawesi, Indonesia. It is located in the Gowa District and flows east to west across the province to Makassar City, which is 85.5 km long with a catchment area of 762.01 km^2, originating from Mt. Bawakaraeng (2,833 m). A large amount of sediment is mined conveniently and economically to fulfill the needs mainly of Gowa District and Makassar City [29, 30]. Sustainable development is a primary issue for the construction minerals mining industry due to various negative environmental and social consequences based on three fundamental principles: society, economy, and environment [11, 39, 40].

The mine management sustainability system in Jeneberang River is divided into four dimensions sub-models: social, economic, environmental, and institutional [30]. The whole causal loop diagram of the sub-model is shown in Figure 1, and then the system dynamics models develop by using the initial score or the actual condition (Table 1), as seen in Figure 2.

The system was set to run using the Eulerian method. It fixed the numerical time-step of 1 year and simulated for the next 30 years by using the dimensions sustainability index as the initial value. The simulation results of the actual (Table 1) can be seen in Table 2.

The relative sustainability status is analyzed using multidimensional scaling (MDS), namely Rapmines (Rapid appraisal of mining management sustainability), an ordination method, and analysis is done following the Rapfish analysis procedure [29, 30]. The social dimension index value in actual condition was 44.95% and decreased to 27.97% (less sustainable) in the 30th year. The economic dimension index value was 45.77%, decreasing to 36.03% (less sustainable). The environmental dimension index value was 66.02%, which became 51.24% (relatively sustainable), and the institutional dimension became 46.99% (less sustainable). The sustainability index values predicted will worsen if no improvement is made in the mine management. All dimension's index values will decrease, and only the sustainability of the institutional dimension will change to the lower category status.

Table 2. Simulation results of mine sustainability based on initial attributes scores

Year	Dimension			
	Social	Economic	Environmental	Institutional
0	44.95	45.77	66.02	53.59
1	40.67	41.41	65.31	65.40
2	36.80	37.93	65.08	65.35
3	33.30	36.68	64.94	64.50
4	30.24	36.25	64.54	64.36
5	28.75	36.10	63.81	63.62
6	28.24	36.05	63.07	63.35
7	28.07	36.04	62.81	62.43
8	28.00	36.03	62.08	62.26
9	27.98	36.03	61.41	61.88
10	27.98	36.03	60.48	60.91
11	27.97	36.03	59.52	60.16
12	27.97	36.03	58.96	60.13
13	27.97	36.03	58.65	59.22
14	27.97	36.03	58.55	58.65
15	27.97	36.03	58.11	57.91
16	27.97	36.03	57.25	56.92
17	27.97	36.03	56.45	56.46
18	27.97	36.03	56.15	56.35
19	27.97	36.03	55.68	55.48
20	27.97	36.03	55.35	55.24
21	27.97	36.03	55.26	54.40
22	27.97	36.03	55.04	53.52
23	27.97	36.03	54.89	52.99
24	27.97	36.03	54.85	52.10
25	27.97	36.03	54.09	51.99
26	27.97	36.03	53.30	51.82
27	27.97	36.03	52.55	50.96
28	27.97	36.03	51.61	50.28
29	27.97	36.03	51.30	49.47
30	27.97	36.03	51.24	46.99

Three scenarios are arranged in this research by accommodating all possible changes in attribute scores from bad to good to analyze and evaluate management sustainability in the future. The scenarios can be seen in Table 3 consists of:

1) Scenario 1: If an improvement effort is made only on a bad (0) score.
2) Scenario 2: If the value of each attribute is good (2).
3) Scenario 3: If the value of each attribute value is terrible (0).

Scenario 1 is better than the actual condition because it assumes that there is an improvement in leverage attributes that have a 0 (bad) score, which becomes one as follows:

1) The mining sector's contribution to the Gross Regional Domestic Product (GRDP) increases (economic dimension) from low (0) to moderate (1).
2) There are already labor unions for mining employees (institutional dimension), but not active (1) from none (0).

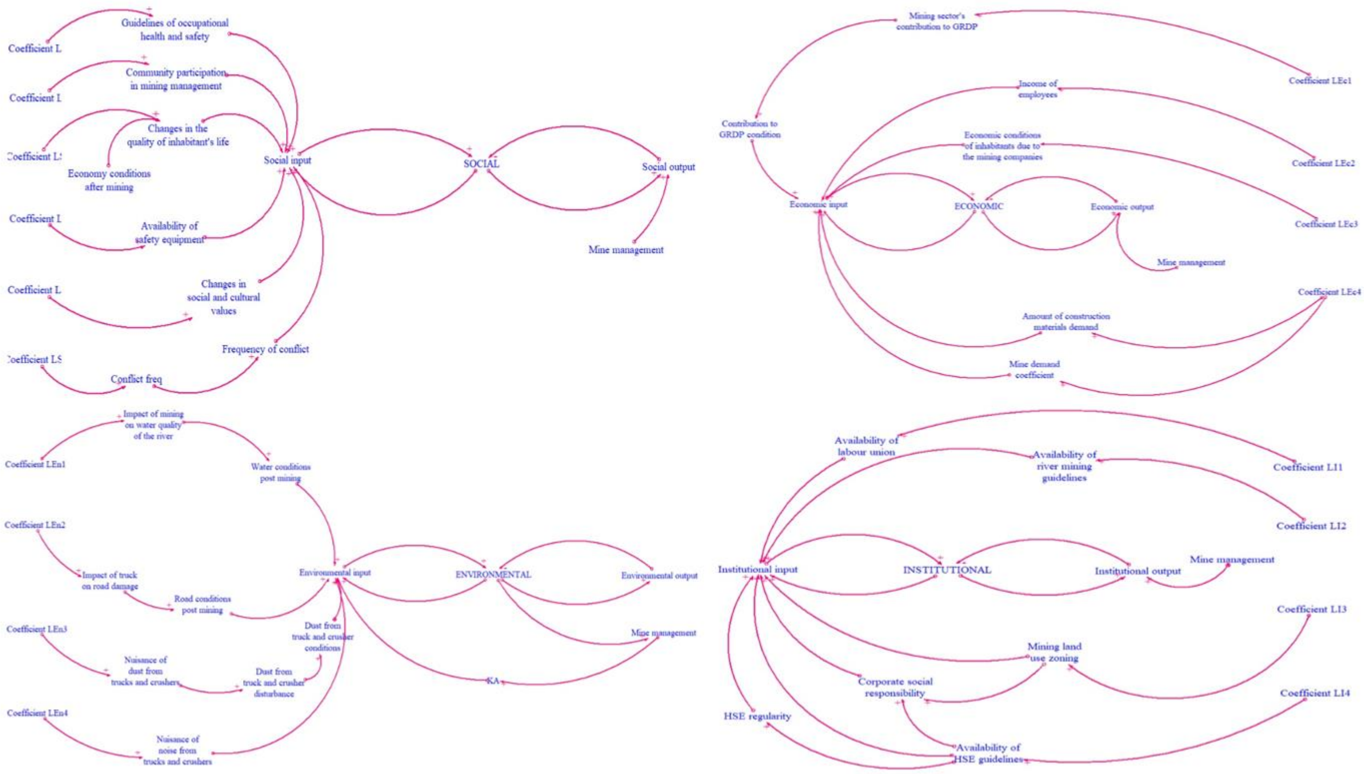

Figure 1. Causal loop diagram of four sustainability dimensions

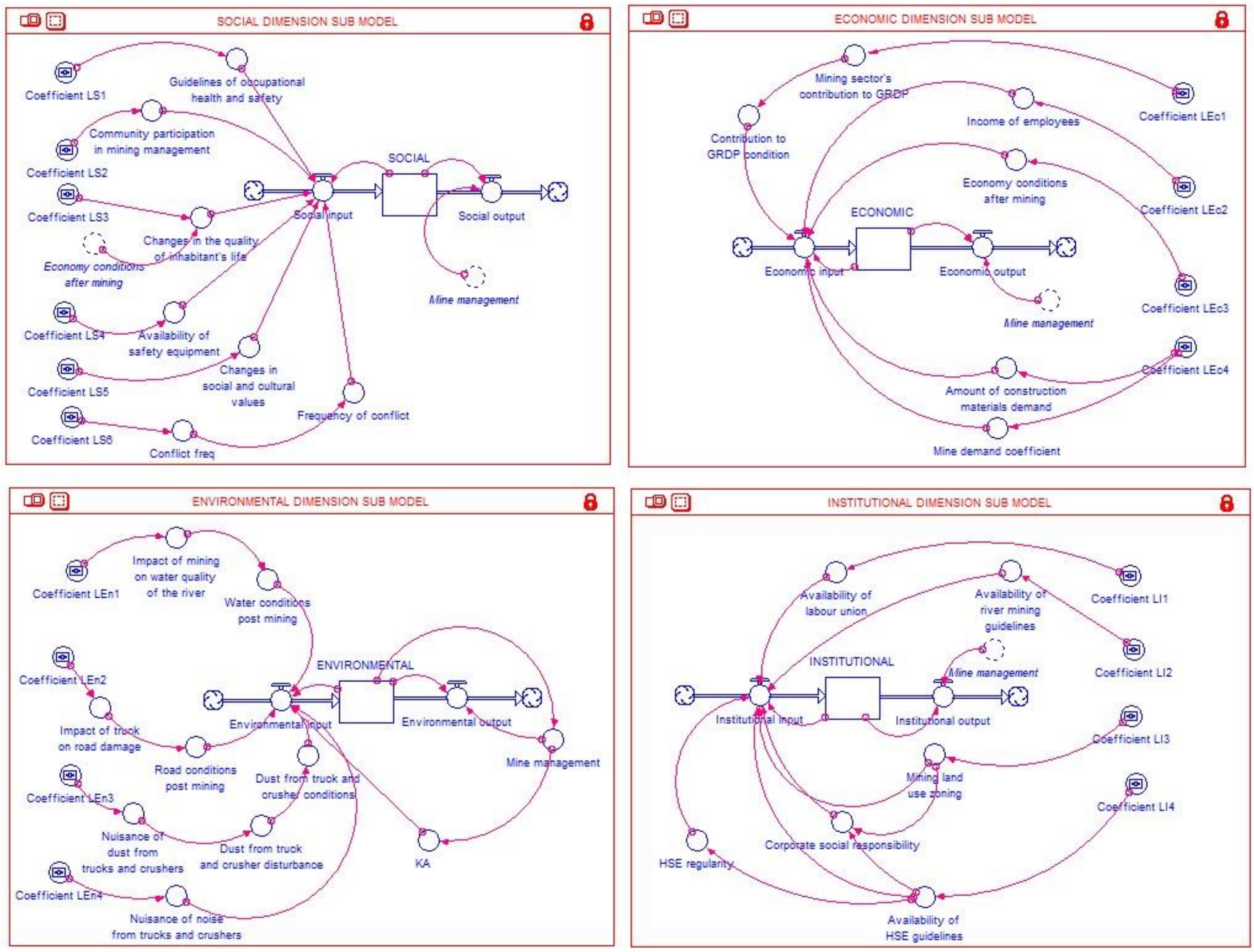

Figure 2. System dynamics model of construction minerals mine management

Table 3. Attributes score of each scenario

Dimension and Attributes	Scenario		
	1	2	3
Social			
LS_1	1	2	0
LS_2	1	2	0
LS_3	1	2	0
LS_4	1	2	0
LS_5	1	2	0
LS_6	1	2	0
Economic			
LEc_1	1	2	0
LEc_2	1	2	0
LEc_3	2	2	0
LEc_4	1	2	0
Environmental			
LEn_1	1	2	0
LEn_2	1	2	0
LEn_3	1	2	0
LEn_4	1	2	0
Institutional			
LI_1	1	2	0
LI_2	1	2	0
LI_3	1	2	0
LI_4	1	2	0

Scenario 1 has the simulation results indicated in Table 4.

Table 4. Simulation results of Scenario 1

Year	Dimension			
	Social	Economic	Environmental	Institutional
0	44.95	45.77	66.02	53.59
1	40.67	48.41	65.31	59.36
2	36.80	49.31	65.08	61.34
3	33.30	49.63	64.94	62.02
4	30.24	49.73	64.54	62.26
5	28.75	49.77	63.81	62.34
6	28.24	49.78	63.07	62.37
7	28.07	49.79	62.81	62.38
8	28.00	49.79	62.08	62.38
9	27.98	49.79	61.41	62.38
10	27.98	49.79	60.48	62.38
11	27.97	49.79	59.52	62.38
12	27.97	49.79	58.96	62.38
13	27.97	49.79	58.65	62.38
14	27.97	49.79	58.55	62.38
15	27.97	49.79	58.11	62.38
16	27.97	49.79	57.25	62.38
17	27.97	49.79	56.45	62.38
18	27.97	49.79	56.15	62.38
19	27.97	49.79	55.68	62.38
20	27.97	49.79	55.35	62.38
21	27.97	49.79	55.26	62.38
22	27.97	49.79	55.04	62.38
23	27.97	49.79	54.89	62.38
24	27.97	49.79	54.85	62.38
25	27.97	49.79	54.09	62.38
26	27.97	49.79	53.30	62.38
27	27.97	49.79	52.55	62.38
28	27.97	49.79	51.61	62.38
29	27.97	49.79	51.30	62.38
30	27.97	49.79	51.24	62.38

Suppose each attribute in all dimensions has a good (2) score (Scenario 2). In that case, it can be said that mine management can provide benefits that need to be preserved so the future generation can also enjoy them (intergenerational welfare). Scenario 2 is the ideal scenario as the ultimate goal of mine management. Sustainability will be maintained so that mining resources can become the foundation of society's hopes for improving their standard of living. The model simulation results can be seen in Table 5.

Table 5. Simulation results of Scenario 2

Year	Dimension			
	Social	Economic	Environmental	Institutional
0	44.95	45.77	66.02	53.59
1	49.67	50.83	87.28	59.26
2	51.30	52.57	94.89	62.59
3	51.86	53.17	97.63	64.27
4	52.05	53.37	98.82	62.82
5	52.12	53.44	99.30	64.49
6	52.14	53.47	99.82	64.12
7	52.15	53.48	99.63	65.03
8	52.15	53.48	99.62	64.38
9	52.15	53.48	99.65	64.91
10	52.15	53.48	99.92	63.81
11	52.15	53.48	99.63	64.13
12	52.15	53.48	99.86	64.32
13	52.15	53.48	99.74	64.81
14	52.15	53.48	99.42	63.64
15	52.15	53.48	99.49	63.22
16	52.15	53.48	99.84	64.54
17	52.15	53.48	99.72	63.12
18	52.15	53.48	99.95	63.13
19	52.15	53.48	99.53	62.39
20	52.15	53.48	99.84	64.33
21	52.15	53.48	99.48	64.93
22	52.15	53.48	99.38	63.96
23	52.15	53.48	99.66	63.50
24	52.15	53.48	99.64	64.93
25	52.15	53.48	99.67	63.44
26	52.15	53.48	99.88	64.75
27	52.15	53.48	100.01	64.81
28	52.15	53.48	100.03	63.65
29	52.15	53.48	99.74	62.68
30	52.15	53.48	99.98	64.82

Scenario 3 is the worse condition of mine management than the other scenarios. All scores of the attributes are assumed to have a bad score or 0 value. The results of a simulation model of Scenario 3 can be seen in Table 6.

Sustainable mine management depends on the management of social, economic, environmental, and institutional attributes. The sustainability mine management index value of the economic dimension of Scenario 1 increases from 45.77% to 49.79% (less sustainable) until the 30th year, or the sustainability status of the economic dimension will not change. The government can extract revenue from the minerals sector by designing fiscal regimes for mining that integrate tax and non-tax elements, including area charges, mining license fees, property taxes, business license fees, mineral royalties, Corporate Income Tax (CIT), withholding tax, etc. [33]. Although implementing this is difficult, mining revenue is essential to support government programs through the budget process. Over the last five years (2019-2023), the economic structure in Gowa Regency has been dominated by three business fields: agriculture, forestry, and fisheries [41]. This means the revenue obtained from mining has not significantly impacted the GRDP, although it is assumed in this scenario there is an improvement in mining income management. Similarly, with the economic dimension, the institutional dimension status will not change (relatively sustainable), although the index value increases from 53.59% to 62.38%. The change in the score of the availability of labor unions influenced the index value. The existence of labor unions can actively fight for workers' rights and support institutional sustainability. Previous research shows that about 34% of 67 mine workers observed in Jeneberang Rivers mines generate a monthly income between IDR0.5-0.75 million, 49% between IDR0.751-1.2 million, and only 17% more than IDR1.2 million. 83% of the mine workers get payment below the government monthly minimum wage [42]. Meanwhile, the index value of sustainability of social and environmental dimensions will remain the same as the actual condition because, in this scenario, there are no changes in the attribute value made for these two dimensions.

Table 6. Simulation results of Scenario 3

Year	Dimension			
	Social	Economic	Environmental	Institutional
0	44.95	45.77	66.02	53.59
1	40.67	41.41	65.85	48.49
2	36.80	37.47	65.25	43.88
3	33.30	33.91	64.62	39.70
4	30.13	30.68	64.30	35.92
5	27.26	27.76	63.57	32.50
6	24.67	25.12	63.39	29.41
7	22.32	22.73	63.28	26.61
8	20.20	20.57	62.84	24.08
9	18.28	18.61	62.67	21.79
10	16.54	16.84	61.87	19.71
11	14.96	15.24	61.00	17.84
12	13.54	13.79	60.26	16.14
13	12.25	12.47	59.36	14.60
14	11.08	11.29	58.38	13.22
15	10.03	10.21	57.47	11.96
16	9.08	9.24	56.66	10.82
17	8.21	8.36	55.70	9.79
18	7.43	7.57	55.23	8.86
19	6.72	6.85	54.74	8.02
20	6.08	6.19	54.10	7.25
21	5.50	5.60	53.85	6.56
22	4.98	5.07	53.26	5.94
23	4.51	4.59	52.44	5.37
24	4.08	4.15	51.89	4.86
25	3.69	3.76	51.23	4.40
26	3.34	3.40	50.74	3.98
27	3.07	3.13	49.75	3.66
28	3.07	3.13	47.32	3.66
29	3.07	3.13	45.01	3.66
30	3.07	3.13	42.82	3.66

The simulation results of Scenario 2 show that the index value of sustainability mine management will increase until the 30th year. The social dimension index value in actual conditions was 44.95%, which will increase to 52.15% (relatively sustainable). The economic dimension index value was 45.77%, increasing to 53.48% (relatively sustainable). The environmental dimension index value was 66.02%, becoming 99.98 (sustainable), and the institutional dimension became 64.82% (relatively sustainable). Scenario 2 is the best because the sustainability index value of all dimensions will increase in two categories: relatively sustainable and sustainable. There are no less sustainable dimensions than in the actual condition. This achievement can occur if all stakeholders work together to improve the condition of all attributes so the value becomes good. For example, there is no conflict, employees' income is above the regional minimum wage, there is no nuisance of dust from trucks and crushers, and there is an active labor union for mine workers.

Contrary to Scenario 2, in Scenario 3, the social, economic, and institutional dimensions have the lowest index values (unsustainable). The results show that the sustainability of the mine management index value will significantly decrease. The social dimension index value in actual conditions was 44.95%; in the 10th year, falls to 16.54%; in the 20th year became 6.08%; and in the 30th year decreased again to 3.07% (unsustainable). The economic dimension index value was 45.77%, whereas in the 10th year, it will fall to 16.48%; in the 20th year, it will become 6.19% and 3.13% (unsustainable). The environmental dimension index value for actual conditions was 66.02%, becoming 61.87% in the 10th year, decreased to 54.10% in the 20th year until 42.82% (less sustainable) in the 30th year. The institutional dimension index's initial value was 53.59%; in the 10th year, it decreased to 19.71%, and in the 20th year, it became 7.25% and continuously decreased to 3.66% (unsustainable). This is the worst scenario, where all dimension indexes decrease to less and are unsustainable. It will happen if there is no good management of mining, so all attributes have a lousy score (0), such as changes in the quality of inhabitants' lives and economic conditions of inhabitants due to the mining companies getting worse than the actual condition, the impact of trucks on road damage is high, and there are no river mining guidelines available.

The level of sustainability index value in the future can be increased by trying to improve each dimension's leverage attributes. Leverage attributes will become critical information in formulating mine management policies for construction minerals. Strategies and policies can be implemented by prioritizing leverage attributes in each scenario. Several strategies can be used, such as entitling the community to give inputs in the rulemaking of local regulations, law enforcement against illegal mining, and optimization of institutional performance [29]. For the ideal implementation and integration of sustainable development, the sustainability principles should be applied simultaneously and not sequentially to maximize the opportunities in the mining industry to contribute to comprehensive development.

Management of the sustainability performance of the construction minerals mines can be improved through commitment and cooperation to improve and enhance all relevant stakeholders' main tasks and functions. Collaboration built between institutions must encourage the achievement of common goals carried out in an integrated and continuous manner based on their respective commitments and responsibilities. Therefore, socialization of regulations needs to be carried out to increase understanding of applicable regulations and implemented policies. This is determined by the institutional role in routine monitoring, supervision, and control over the implementation of established regulations and policies. The sustainability index evaluation should be carried out regularly by the responsible institutions.

4. CONCLUSIONS

The system dynamics model can be used to analyze and evaluate the sustainability of construction minerals mine management regularly and continuously. Based on the scenarios arranged, changes in attribute values can be immediately input into the model to find out and predict all possibilities regarding changes in index values and sustainability status. The analysis results can improve attributes with low sustainability index values by implementing or strengthening strategies or policies. The best scenario is in ideal conditions where all attributes score 2 (good). However, the results still depend on the actual condition of each dimension's initial index value.

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