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SUSTAINABLE MANUFACTURING SYSTEMS - COST, ENERGY AND CO_2 EMISSION APPROACH

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Abstract: *The sustainability of manufacturing systems plays a major role in the insurance of the competitive power of enterprises. To describe a manufacturing system as sustainable, the LEAN approach must be complemented by environmental considerations. In the present paper, the authors describe a Sustainable Manufacturing Systems (SMS) in terms of costs, energy consumption and carbon dioxide emissions. The mathematical optimization model describes the objective minimization functions, the decision making variables and the conditions on the three components. The proposed theoretical model is implemented by means of the standard function block of specialized simulation and optimization environment.*

Key words: *sustainable manufacturing system, cost-energy-emission optimization.*

1. Introduction

In order to increase the competitiveness of an organization in conditions of sustainability, integrating the LEAN principles with other methodologies becomes necessary. The LEAN manufacturing concept does not include environmental considerations, namely energy consumption and carbon dioxide emissions. For the development of a sustainable manufacturing system (SMS) these environmental factors will also be taken into account. In this context, it is required a multi-object modeling of an SMS approach, the assessment of energy consumption and CO_2 emissions in relation to the total cost, respectively [5], [9].

One of the integration options, due to its possibility of addressing product costs, is the Material Flow Cost Accounting (MFCA). The results of research on this topic show the integration of MFCA with productivity enhancing techniques, namely TPM [1], the design of the quality inspection system [1] and simulation [4]. The optimization of operations and activities in terms of efficiency and compliance with environmental conditions represents the framework in which the integration of MFCA with LEAN is used.

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The LEAN methodology provides systems analysis tools that allow the application of MFCA in order to enhance productivity.

The present paper is structured as follows: after a brief presentation of the theoretical aspects of the MFCA, the authors will discuss the development of an SMS, considering the following variables: suppliers *s*, the factory *f* and the warehouse *w*. The model aims to determine the optimal solution taking into account the three objective functions, namely the investment cost required to configure the manufacturing system, the total energy consumption of the manufacturing system and the total CO_2 emissions. The following chapter presents the solving methodology using the Anylogic environment. The last chapter describes the conclusions related to the simulation model and possible further developments.

2. Literature Review

Material Flow Cost Accounting (MFCA) is a tool aimed at improving resource efficiency by determining the costs of products and waste based on flow management [4].

In calculating the costs, the MFCA (ISO 14051) reduces the structure to four items: material cost, energy cost, waste management cost and system cost. These costs are further divided into the costs of positive products (associated with the finished product) and negative costs (associated with a residual product).

ISO 14051 defines the three objectives of MFCA [10]:

- increasing the transparency of the materials flow and that of the energy used, the associated costs and environmental aspects;
- decision support for the organization in respect to areas such as process engineering, production planning, quality control and supply chain management are concerned;
- improving coordination and communication on material and energy flows within the organization.

The MFCA includes an approach based on material cost, system costs, electricity costs, waste costs and quantity centers [7].

In the classical approach, the costs will be allocated to the product as a unit of cost [7].

In the MFCA the material costs are divided between the product and the residual materials, depending on the place where the flow ends [7], [8]. In addition, there are system costs allocated for storage, processing or transportation. These are also divided between products and residual materials, based on a few appropriate key indicators. This allocation may be made on the basis of physical quantities.

Material loss costs may also indicate directions for improvement measures. The MFCA focuses on the materials flow and the associated costs within the systems.

The materials, as physical units, will be tracked and quantified. As a next step, this information will be used to calculate costs. The aforementioned cost structures will provide data on opportunities of improving processes and reducing environmental effects. The MFCA supports the process engineer in identifying both the material and energy losses from both the quantity and their location point of view [1], [6]. For an effective and systematic identification of thee sources of losses, the MFCA must be applied along the production flow in the system, from the receipt of the raw material to the delivery of the finished product. This tool allows the company to identify the inefficient use of materials, energy and other resources throughout the entire process and system. The activity and the process are the basic notions that allow the global and generic representation of the development process. The activities are at the heart of information, physical and decision-making flows.

3. Mathematical Cost Model from the SMS Perspective

The SMS cost approach will be presented as a multi-objective optimization [3], [6]. For the development of the optimization model, the construction of the total cost of the product (Z_1) will be taken into consideration in Eq. (1), based on the following elements:

$$Z_1 = C_s^{es} + C_f^{es} + C_{ws}^{es} + C_s^{ma} + C_f^{ma} + C_s^{ir} + C_f^{ir} + C_w^{ir} + C_s^{il} + C_f^{il} + C_w^{il} + \\ + C_{sf}^{r} + C_{sfw}^{mp} + C_{sf}^{t} + C_{fw}^{t} + C_l^{t}, \quad (1)$$

from which:

C_s^{es} - the costs generated by the choice of suppliers;
C_f^{es} - the costs generated by the choice of factories;
C_{ws}^{es} - the costs generated by the choice of warehouses;
C_s^{ma} - the cost of machines in the process *j* to the supplier *s;*
C_f^{ma} - the cost of machines in the process and at the factory *f;*
C_f^{ir} - the cost of cooling / heating in the process and at the factory *f;*
C_s^{ir} - the cost of electricity in the process and to the supplier *s;*
C_w^{ir} - the cost of electricity in the process *i* at the warehouse *w;*
C_f^{il} - the cost of electricity in the process *i* at the factory *f;*
C_s^{il} - the cost of electricity in the process and to the supplier *s;*
C_w^{il} - the cost of electricity in the process *i* at the warehouse *w;*
C_{sf}^{r} - the total cost of raw materials to the supplier *s;*
C_{sfw}^{mp}- total manufacturing cost in the factory *f;*
C_{sf}^{t} - the total transportation cost of the raw material, per km, between *s* and *f;*
C_{fw}^{t}- the total transportation cost of the finished products, per km, defining the resource as depending on *f* and *w;*
C_l^{t} - the total transportation cost of the products, per km, defining resource *l* as depending on *s, f* and *w.*

For the development of the Eq. (1) [6], we consider the formulas regarding the costs involved for establishing suppliers, *s*, factories *f* and warehouses *w*, respectively C_s^{es}, C_f^{es} *and* C_{ws}^{es} , as follows (Eqs. 2, 3 and 4):

$$C_s^{es} = C_s^{land} + C_s^{buildings} + C_s^{equipments} + C_s^{services} + C_s^{salaries}, \quad (2)$$

$$C_f^{es} = C_f^{land} + C_f^{buildings} + C_f^{equipments} + C_f^{services} + C_f^{salaries}, \quad (3)$$

$$C_w^{es} = C_w^{land} + C_w^{buildings} + C_w^{equipments} + C_w^{services} + C_w^{salaries}. \tag{4}$$

The cost of the machines, C_s^{ma} $şi$ C_f^{ma} involved in the process *j* at the supplier *s*, within the process *i* at the factory *f* and at the warehouse *w* is defined as follows:

$$C_s^{ma} = \sum_{j=1}^{\prod s} C_{sj}^{ma} n_{sj}^{machine}, \tag{5}$$

$$C_f^{ma} = \sum_{i=1}^{\prod f} C_{fi}^{ma} n_{fi}^{machine}. \tag{6}$$

The costs C_s^{ir} , C_f^{ir} and C_w^{ir} (Eqs. 7, 8, 9) required for heating / cooling involved in the process *j* at the supplier *s*, within the process *i* at the factory *f* and at warehouse *w* are:

$$C_s^{ir} = \sum_{j=1}^{\prod s} C_{sj}^{ir} n_{sj}^{ir}, \tag{7}$$

$$C_f^{ir} = \sum_{i=1}^{\prod f} C_{fi}^{ir} n_{fi}^{ir}, \tag{8}$$

$$C_w^{ir} = \sum_{w=1}^{W} C_w^{ir} n_w^{ir}. \tag{9}$$

The costs C_s^{il} , C_f^{il} and C_w^{il} required for electricity involved in the process *j* at the supplier *s*, within the process *i* at the factory *f* and at the warehouse *w* are:

$$C_s^{il} = \sum_{j=1}^{\prod s} C_{sj}^{bulp} n_{sj}^{bulp}, \tag{10}$$

$$C_f^{il} = \sum_{i=1}^{\prod f} C_{fj}^{bulp} n_{fj}^{bulp}, \tag{11}$$

$$C_w^{il} = \sum_{w=1}^{W} C_w^{bulp} n_w^{bulp}. \tag{12}$$

The total cost of raw materials at the supplier *s*, C_{sf}^{r} will be calculated as follows:

$$C_{sf}^{r} = \sum_{s=1}^{S} \sum_{j=1}^{F} C_s^{r} q_{sf}^{r}. \tag{13}$$

The Eq. (14) describes the total manufacturing cost in the factory f, C_{fw}^{mp}:

$$C_{fw}^{mp} = \sum_{f=1}^{F} \sum_{w=1}^{W} C_j^{mp} q_{fw}^{mp}. \tag{14}$$

The total transportation cost of the raw material, C_{sf}^{t} per km, between *s* and *f* is described in Eq. (15):

$$C_{sf}^{t} = \sum_{s=1}^{S} \sum_{f=1}^{F} C_{sf}^{t} \frac{q_{sf}^{r}}{V} T_{sf}. \tag{15}$$

Total transportation cost of finished products, per km, C_{fw}^{t}, defining the resource as depending on f and w is calculated using Eq. (16):

$$C_{fw}^{t} = \sum_{f=1}^{F} \sum_{w=1}^{W} C_{fw}^{t} \frac{q_{fw}^{mp}}{V} T_{fw} \,. \tag{16}$$

Total transportation cost of the products per km, C_{l}^{t}, defining the resource *l* as depending on s, f and w is calculated using Eq. (17), in which $l \in \{s, f, w\}$:

$$C_{l}^{t} = \sum_{s=1}^{S} \sum_{f=1}^{F} C_{sf}^{t} \frac{q_{sf}^{r}}{V} T_{sf} + \sum_{f=1}^{F} \sum_{w=1}^{W} C_{fw}^{t} \frac{q_{fw}^{mp}}{V} T_{fw}. \tag{17}$$

The total cost of stocks, (Eq. 18), C_{fw}^{l} , in the warehouse *w* is determined as follows:

$$C_{fw}^{l} = \sum_{f=1}^{F} \sum_{w=1}^{W} C_{w}^{l} q_{fw}^{mp} \,. \tag{18}$$

4. The Development of the Optimization Model for Costs, Energy and Carbon Dioxide Emissions

The linear programming problem will be defined expressing the objective function, the restrictions and the conditions of existence [3], [6], for each of the considered parameters.

Taking into account the mathematical model from Eq. (1), we will develop the optimization model containing the objective function (19) and the conditions (20):

$$\begin{aligned} Min\, Z_1 = {} & C_{s}^{land} + C_{s}^{buildings} + C_{s}^{equipments} + C_{s}^{services} + C_{s}^{salaries} + C_{f}^{land} + \\ & + C_{f}^{buildings} + C_{f}^{equipments} + C_{f}^{services} + C_{f}^{salaries} + C_{w}^{land} + C_{w}^{buildings} + \\ & + C_{w}^{equipments} + C_{w}^{services} + C_{w}^{salaries} C_{s}^{mach} + \sum_{j=1}^{\prod s} C_{sj}^{ma} n_{sj}^{machine} + \\ & + \sum_{i=1}^{\prod f} C_{fi}^{ma} n_{fi}^{machine} + \sum_{j=1}^{\prod s} C_{sj}^{ir} n_{sj}^{ir} + \sum_{i=1}^{\prod f} C_{fi}^{ir} n_{fi}^{ir} + \sum_{w=1}^{w} C_{w}^{ir} n_{w}^{ir}\, C_{s}^{il} + \\ & + \sum_{j=1}^{\prod s} C_{sj}^{il} n_{sj}^{il} + \sum_{i=1}^{\prod f} C_{fj}^{il} n_{fj}^{il} + \sum_{w=1}^{w} C_{w}^{il} n_{w}^{il} + \sum_{s=1}^{S} \sum_{j=1}^{F} C_{s}^{r} q_{sf}^{r} + \\ & + \sum_{f=1}^{F} \sum_{w=1}^{W} C_{j}^{mp} q_{fw}^{mp} + \sum_{s=1}^{S} \sum_{f=1}^{F} C_{sf}^{t} \frac{q_{sf}^{r}}{V} T_{sf} + \sum_{f=1}^{F} \sum_{w=1}^{W} C_{fw}^{t} \frac{q_{fw}^{mp}}{V} T_{fw}, \end{aligned} \tag{19}$$

within the conditions of the negativity of the quantities of materials *q* for the facility *l*:

$$\begin{cases} q_{sj}^{r} \geq 0 \\ q_{sf}^{r} \geq 0 \\ q_{fi}^{r} \geq 0 \\ q_{fw}^{mp} \geq 0 \end{cases} \tag{20}$$

Considering the analysis of the sustainability attribute of the production process, we propose the definition of the objective functions for minimizing the consumed energy, Z_2.

Defining the linear programming problem to optimize electricity consumption involves object function development, according to Eq. (21):

$$Min\, Z_2 = \sum_{j=1}^{\prod s} E_{sj}^{ma} + E_{sj}^{ir} + E_{sj}^{il} + E_{sj}^{comp} + \sum_{i=1}^{\prod sf} (E_{fi}^{mach} + E_{fi}^{ir} + E_{fi}^{il} + E_{fi}^{comp}) + \\ + E_{w}^{ir} + E_{w}^{il}. \tag{21}$$

The conditions under which the objective function will be solved, as a minimum, refers to the manufacturing rate *k* for operation *j* and *i* to the supplier *s* and factory *f* which must be greater than or equal to the quantity of material required for the next operation, (*j* + 1) and (*i* + 1) to the supplier s and the factory *f.*

These will be in the following form (Eq. 22):

$$\begin{cases} k_{sj} n_{sj}^{machine} \geq q_{s(i+1)}^{r} \\ k_{fj} n_{fj}^{machine} \geq q_{f(i+1)} \end{cases}, \tag{22}$$

where:

E_{sj}^{ma} - the energy consumed for the machines for the process *j* at the supplier *s;*

E_{sj}^{ir} - the energy consumed for heating / cooling for the process *j* at the supplier *s;*

E_{sj}^{il} - the energy consumed for the electricity for the process *j* at the supplier *s.*

The linear programming problem for optimizing the CO_2 emissions will be defined expressing the objective function, the restrictions and the conditions of existence [3], [6], according to Eqs. (23) and (24):

$$Min\, Z_3 = \sum_{j=1}^{\prod s} (e_{sj}^{ma} + e_{sj}^{ir} + e_{sj}^{il} + e_{sj}^{comp}) + e_{sf}^{l} + e_{fw}^{t} + \\ + \sum_{i=1}^{\prod f} (e_{fi}^{ma} + e_{fi}^{ir} + e_{fi}^{il} + e_{fi}^{comp}) + e_{w}, \tag{23}$$

under the following conditions:

$$\begin{cases} k_{sj} n_{sj}^{machine} \geq q_{s(i+1)}^{r} \\ k_{fj} n_{fj}^{machine} \geq q_{f(i+1)} \end{cases}, \tag{24}$$

where:

Z_3 - total carbon emissions;

e_{sj}^{ma} - the emissions determined by the operation of the machines for the process *j* at the supplier *s*;

e_{sj}^{ir} - the emissions determined by heating / cooling for the process *j* at the supplier *s;*

e_{sj}^{il} - the emissions determined by the electricity for the process *j* at the supplier *s;*

e_{sf}^{l} - the emissions caused by the transportation for the process *j* and the supplier *s;*

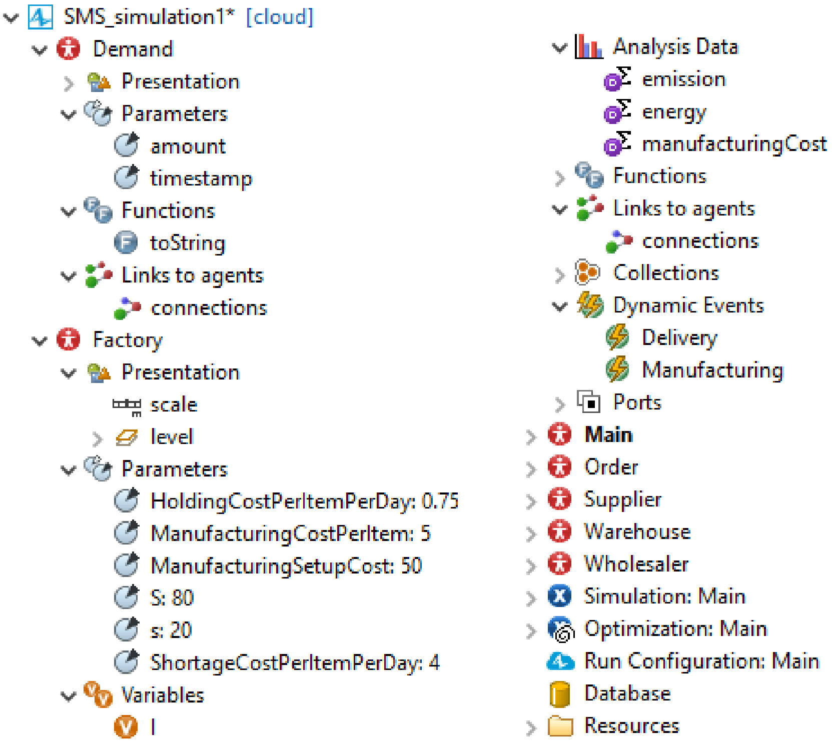
e_{fw}^{t} - the emissions caused by the transportation for the process *j* and the supplier *s.*

5. SMS Simulation

According to [11], AnyLogic is a ‘comprehensive and powerful tool that supports all of the most common simulation methodologies in place today: System Dynamics, Process-centric (AKA Discrete Event), and Agent Based modeling. AnyLogic’s graphical interface’.

The SMS simulation model is an activity based model with cost, energy, CO_2 emissions parameters [2], [11].

The simulation environment offers the facility of importing data from EXCEL or filling in datasets. Figure 1 describes the main components of our application in terms of agents, variables, functions and parameters.



- SMS_simulation1* [cloud]
  - Demand
    - Presentation
    - Parameters
      - amount
      - timestamp
    - Functions
      - toString
    - Links to agents
      - connections
  - Factory
    - Presentation
      - scale
      - level
    - Parameters
      - HoldingCostPerItemPerDay: 0.75
      - ManufacturingCostPerItem: 5
      - ManufacturingSetupCost: 50
      - S: 80
      - s: 20
      - ShortageCostPerItemPerDay: 4
    - Variables
      - I
    - Analysis Data
      - emission
      - energy
      - manufacturingCost
    - Functions
    - Links to agents
      - connections
    - Collections
    - Dynamic Events
      - Delivery
      - Manufacturing
    - Ports
  - **Main**
  - Order
  - Supplier
  - Warehouse
  - Wholesaler
  - Simulation: Main
  - Optimization: Main
  - Run Configuration: Main
  - Database
  - Resources

Fig. 1. *System structure*

Figure 2 shows the interface in design phase. The main agents Factory, Customers and Suppliers are presented with specific behaviors.

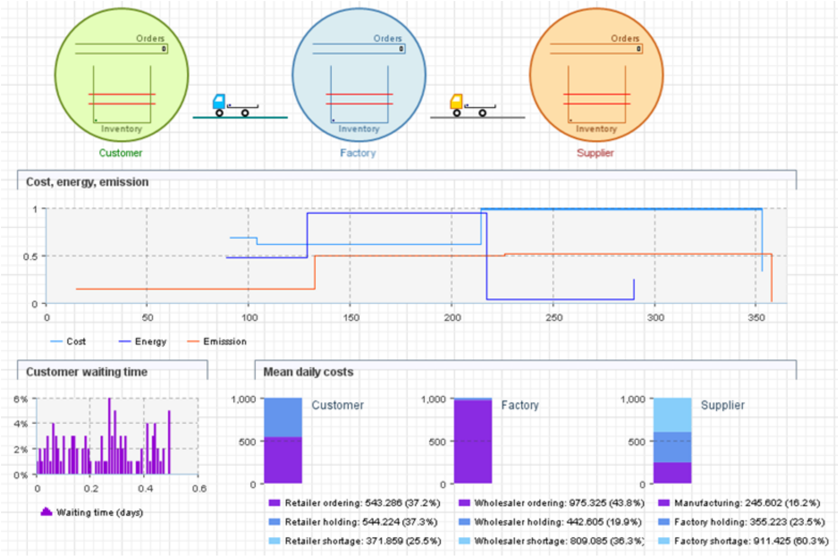


Fig. 2. *Design interface*

The expressions of the objective functions, restrictions and start values are generated by the programs parameters. A detailed agent description in presented in Figure 2.

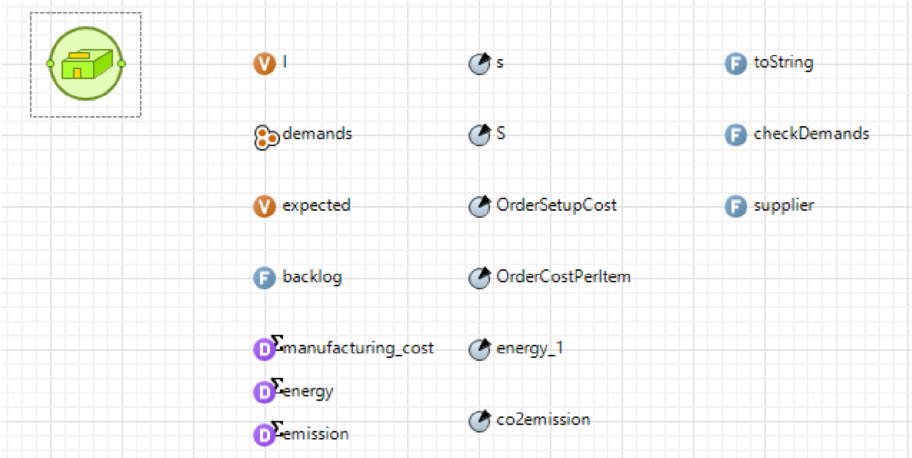


Fig. 3. *Simulation design - Factory agent*

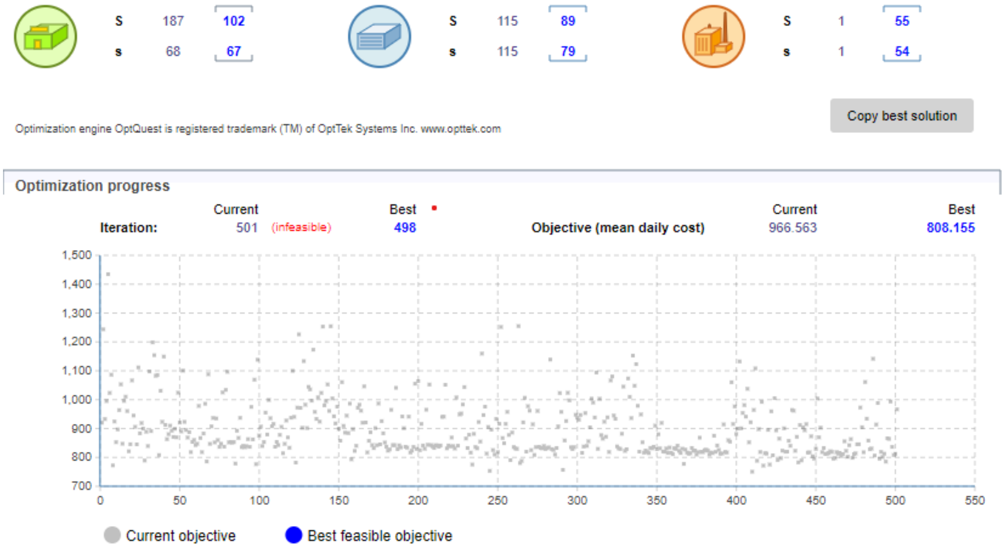
Parameters variation experiment performs several single model runs varying one or more parameters. Using this experiment one can compare the behavior of model with different cost, energy, emissions values (Figure 3).

Cost is associated with both waiting in the queue before the station, and with the processing.

Each minute of waiting and each processing operation have a unit cost. The system collects the values of cost, emissions and energy assigned to the parts that exit the system in a time series dataset. The simulation experiment runs the model with animation displayed (Figure 4) according to cost, energy and emission parameters.

Fig. 4. *Running simulation-process*

The optimization module is designed to offer visual information for the best solution (Figure 5).


S 187 102
s 68 67

S 115 89
s 115 79

S 1 55
s 1 54

Optimization progress

Iteration: Current 501 (infeasible) Best 498

Objective (mean daily cost) Current 966.563 Best 808.155

Fig. 5. *Running process optimization*

The solution given by the current simulation is described as follows: s [Supplier] 67; S [Supplier] 102; s [Factory] 79; S [Factory] 89; s [Customer] 54; S [Customer] 55.

6. Conclusion

By analyzing the proposed optimization model, we can conclude that, under the conditions of the designing of a sustainable manufacturing system, the solutions that can be obtained taking into account the total cost of the product, the energy consumption and CO_2 emissions [6] and determining the optimal flow of materials in the manufacturing system.

The mathematical and simulation model thus developed can be used to obtain an optimal configuration of SMS considering both economic criteria and environmental responsibilities, reflected in minimizing the total cost, total energy consumption and CO_2 emissions. As a future direction of development, the simulation model will be extended with a detailed manufacturing module in the Anylogic environment, so that the application of the optimization can be done quickly.

References

1. German, A.M.: *A Real Option Perspective for Industrial Enterprises in a Dynamic Environment*. In: Bulletin of the *Transilvania* University of Brașov, 10 (2017), p. 59. http://webbut.unitbv.ro/BU2017/Series%20I/2017/BULETIN%20I/German_A.M.pdf.
2. Ivanov, D.: *Supply Chain Simulation and Optimization with Anylogistix: Teaching Notes*. In: Berlin School of Economics and Law, 2019.
3. Lokeshgupta, B., Sivasubramani, S.: *Multi-Objective Dynamic Economic and Emission Dispatch with Demand Side Management*. In: International Journal of Electrical Power & Energy Systems **97** (2018), p. 384. https://doi.org/10.1016/j.ijepes.2017.11.020.
4. Mrugalska, B., Wyrwicka, M.K.: *Towards Lean Production in Industry 4.0*. In: Procedia Eng. **182** (2017), p. 466. https://doi.org/10.1016/j.proeng.2017.03.135.
5. Nakajima, M., Kimura, A., Wagner, B.: *Introduction of Material Flow Cost Accounting (MFCA) to the Supply Chain: A Questionnaire Study on the Challenges of Constructing A Low-Carbon Supply Chain To Promote Resource Efficiency*. In: Journal of Cleaner Production **108** (2015), p. 130. https://doi.org/10.1016/j.jclepro.2014.10.044.
6. Nujoom, R., Mohammed, A., Wang, Q.: *Drafting a Cost-Effective Approach towards a Sustainable Manufacturing System Design*. In: Computers &Industrial Engineering **133** (2019), p. 317. https://doi.org/10.1016/j.cie.2019.05.007.
7. Peruzzini, M., Grandi, F., Pellicciari, M.: *Benchmarking of Tools for User Experience Analysis in Industry 4.0*. In: Procedia Manuf. **11** (2017), p. 806.
8. Schmidt, M., Nakajima, M.: *Material Flow Cost Accounting as an Approach to Improve Resource Efficiency in Manufacturing Companies*. In: Resources **2** (2013), p. 358. DOI: 10.3390/resources2030358.
9. Yagia, M., Kokubub, K.: *Corporate Material Flow Management in Thailand: The Way to Material Flow Cost Accounting*. In: Journal of Cleaner Production **198** (2018), p. 763. https://doi.org/10.1016/j.jclepro.2018.07.007.
10. ISO 14051: *Environmental Management - Material Flow Cost Accounting - General Framework.* In: ISO (2011), Geneva.
11. www.anylogic.com. Accessed: 06.01.2020.