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A System Dynamics Simulation Approach for Describing How Carbon Emissions Produced from a Production System

Petrus S. Murdapa[1], Theresia L. Widyaningrum[1,*], and Lorensius A. S. Waloyo[1]
[1]PSDKU Rekayasa Industri Universitas Katolik Widya Mandala Surabaya
Corresponding Author's E-mail: theresialiris@ukwms.ac.id

***Abstract*— This paper discusses how a production system will produce carbon emissions when the system carries out its activities. This mainly due to the use of energy obtained from fossil fuels. The use of electricity will also produce emissions if it comes from burning coal, natural gas or other fossil fuels. For a particular production system prototype, a model in the form of a mathematical formula taken from natural phenomena occurring in the system, under the influence of the environmental conditions of the system, can be constructed. However, mathematical models involving multiple differential equations cannot be described or understood easily. For this reason, the formulation can be expressed in the language of system dynamics. The language is actually a generalization of a system of differential equations expressed in the formulation of stock and flow diagrams. The diagram represents the differential rate quantities of the transfer processes involved, and the integration of their accumulative quantities. Several special software related to system dynamics language are now widely known, one of which is Vensim PLE (by Ventana Systems, Inc.) which can be used for academic purposes. With this software, the emission process in the production system can be easily displayed and completed. A prototype of what-if analysis can be carried out in the learning classroom to understand the behavior of the modeled system and to derive the best activity control decision setting of the system. For simplicity, the scope of the research is limited to a hypothetical factory which is a single process and then followed by a single distribution stage.**

Keywords*— Carbon Emission, Single Stage Production System/ Model, Prototype, System Dynamics

I. INTRODUCTION

Industry in general consists of supply chain units. Certain products are created through a long series of processes from raw materials to finished products. In a supply chain there is at least one factory that acts as the heart of the system. The factory determines the rhythm of the flow of goods from raw materials to the community. The factory pulls materials from the upstream side, processes them, and then pushes downstream. On the upstream side there are supply companies, and on the downstream side there are distribution companies. The scope can be local, national, or global. The useful products that are created play an important role in growing an economy that is useful for the welfare of the community.

Unfortunately there are side effects from the industry, one of which is carbon emissions. Industry is the main source of carbon emissions because the unity of the supply chain requires the existence of several factors, especially the three most important, namely: electricity, transportation and factories. According to [1], these three factors are the main sources of carbon emissions, followed by agriculture, commercial, and residency. As long as the energy used is sourced from fossil fuels, the emission process will continue to occur ([2]).

The content of carbon dioxide in the atmosphere is increasing, causing global warming and climate change on earth. For one unit of product produced by industry, it can be traced the amount of carbon emissions that have been raised from the beginning, to become a product to consumers. The amount of carbon per unit of product is called the carbon footprint of that product. Carbon footprint is a marker of the amount of carbon emissions that accumulate directly or indirectly, and are attached to a product ([3]). Furthermore, [3] categorizes the origin of the carbon footprint into the following types: indirect carbon footprint (which is brought from suppliers) and direct (from production activities in factories). Both types are accumulated and integrated in the carbon footprint of a product. A high value on the carbon footprint indicates that a lot of emissions have been produced to create the product. So the carbon tax must be high too, which eventually forces the price of the product to be high.

Carbon footprint analysis includes identification of emission sources, composition and quantity of Green House Gases arising from them. Normally, the analysis uses the life-cycle assessment method ([4]). With this method, the accumulated carbon footprint of a product can be traced back to all stages of the activity it has undergone, such as processing, transportation, and storage, and others (See Fig. 1).

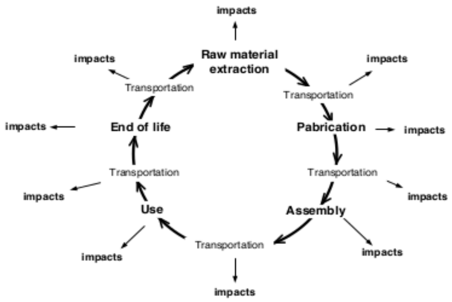

Fig 1. *Life-Cycle Assesment* (adapted from [5])

In [5], the number of emissions that occurs along the closed-loop supply chain is calculated using the concept of mass transfer phenomena. Carbon emissions in each stage of the supply chain are modeled as the process of mass transfer of gas from the emission source to the environment, among others by taking into account differences in concentration, the influence of wind, and dry or wet precipitation. The total emissions released by the supply chain come from suppliers, factories, warehouses, and non-stationary sources. As an illustration, a simple four-echelon automotive supply chain located in China consisting of suppliers, manufacturers, warehouses, and logistics service providers provides the emission distribution as shown in Table 1.

Table 1. Distribution of emission quantities in each echelon in a sample supply chain (analyzed from [6])

Supply chain echelon	Supplier	Logistic	Plant	Warehouse	Total
Relative emission (calculated)	25.2%	21.9%	39.6%	13.4%	100%

To limit carbon emissions, each organization is required to comply with the maximum allowable emission limits. Two of the four emission limiting mechanisms ([6]) are cap and trade and tax policy. In the cap and trade system (or carbon trading, [7] calls it quantity based), there is cost consequences if the quota (cap) is violated. However, the rest of the quota can also be sold, meaning that in the cap and trade system, emission quotas can be traded ([8],[9],[10]. Meanwhile, in the tax system, companies producing carbon emissions bear the tax per unit ton of emissions issued ([10]).

II.PROBLEM

A product exists to meet the needs of society. The product is created by a supply chain system, which starts from the process of extracting materials from nature by, for example, a mining company (echelon-1). The extracted material is then sent by a certain transportation vehicle, to a processing company (echelon-2) to become a material with certain specifications, which are needed as raw materials by the factory (echelon-3, focal echelon). In factories, raw materials are processed, along with other raw materials, to become a product.

Controlling the quantity of carbon emissions should start from the operational planning stage in the entire supply chain. It is important to find the right operational settings to ensure the carbon footprint per unit of product is below the value set by the regulator. The supply chain operational controller can do this if there is a "forward" calculation tool, starting from the creation of raw materials, transportation and others, until the product is created and distributed. Calculations in the life-cycle assessment are technically "backward". So a calculation model that is forward (in the direction of the product metamorphosis) can provide a prediction of the carbon footprint of each product unit if the operational conditions are set on certain decisions.

In this paper, an example of a simple modeling with a very simplified scope is presented. The system is limited to the factory (which is reviewed globally, so it is a single process) followed by a single distribution stage. Provision processes along the upstream, and along the subsequent downstream, are not covered so that the discussion is not too broad. The emission quantity is simply calculated based on the emission factor. Emission factors must be identified in each emission activity that takes place, based on empirical or observational data. The basic definition of emission factor is the quantity of emission that arises per unit of process activity ([1]).

The model is then expressed in the form of a VENSIM PLE diagram (academic version). Some important instructions are obtained from the user manual, and small modules called "molecules", which are provided in the software ([11]). The modeling is directed at the activities of production, storage and delivery, as well as the emissions that arise in a single production system (because the factory is viewed as a single process unit) with one distribution center (DC). Two objectives to be achieved with the model are (1) to describe simply how emissions occur, and (2) to estimate the quantity of emissions per unit product for a particular operational decision setting.

III. SYSTEM DESCRIPTION

The system to be discussed is a factory with one process stage, followed by one distribution channel. The upstream and downstream sides are excluded from the discussion, without intending to eliminate them (see [12] for comparison).

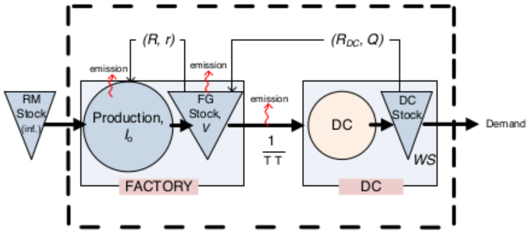

Fig 1. System Under Study

The behavior of the system is assumed to follow the following conditions:

1. The stock of raw materials is sufficient so that there is never a shortage (the effect on the system can be ignored).
2. The amount of carbon footprint per unit of raw material when it leaves the raw material warehouse is certain (C_0 kg carbon per unit of raw material), which is not calculated in this paper.
3. The factory controls the finished product stock (FG) with the (R, r) mechanism.
4. There is only one distribution center (DC), where the inter-arrival time of demand from the DC is represented by its inventory cycle time.
5. Emissions arise from production activities, FG storage, and delivery to DC.
6. Emission factors are identified as much as possible from secondary data (general data), which is processed by taking into account the suitability of the unit for each emission activity that is considered.

IV. RESEARCH METHOD

The research was conducted by means of simple modeling and simulation. Fig 1 gives the framework of the research. While [12] solved the model using numerical discrte Markovian approach, in this paper the model was conducted using continuous system dynamics approach.

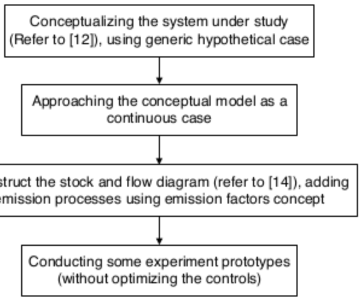

Fig 1. The research framework

A. Raw material preparation

To limit the scope of the problem, raw materials are considered to be always available when needed. It is considered that only one type of raw material is processed to become one unit of product. This raw material certainly already contains a carbon footprint of a certain value caused by the processes of processing, storage, transportation, etc., which are experienced before arriving at the raw material warehouse at the factory. As already mentioned, the carbon footprint, for example, is C_0 kg carbon per unit of raw material.

B. Production

Production run on a stop and went on the basis using a mechanism (R,r) which was approached as a process for continuous materials ([13]). Production activities in factories were viewed in terms of aggregates so that these activities were a one-stage process, where the production leadtime was assumed to be exponentially distributed.

Suppose the electricity demand for production, on average, was 100 kwh/unit/day, then the value of the production emission factor, ϵ_p, for example was estimated as follows ([13]):

$$\begin{aligned}\epsilon_{\mathrm{p}} &= 0.875 \frac{\text{kg carbon}}{\text{kwh}} \\ &= \left(0.875 \frac{\text{kg carbon}}{\text{kwh}}\right)\left(\frac{50 \text{ kwh}}{1 \text{ unit}}\right) \\ &= 43.75 \frac{\text{kg carbon}}{\text{unit}}\end{aligned} \tag{1}$$

The production emission, E_p, was calculated based on the production emission factor and the production rate, I, according to the following manner:

$$E_{\mathrm{p}} = \epsilon_{\mathrm{p}} \left(\frac{\text{kg carbon}}{\text{unit}}\right) . \, I \left(\frac{\text{unit}}{\text{day}}\right) . T_{\mathrm{p}}(\text{day}) \tag{2}$$

C. Finished product warehouse

Products were sent to the finished product warehouse in the same quantity as the lots of production each time they arrive at the warehouse. The mechanism (R, r) assumed the lotsize was one unit. However, it could then be multiplied by another number, if desired, the lot size of the production was more than one. The finished product warehouse accommodated the production before it was finally sent to distribution, with the lotsize of shipments being equal to the lotsize of the demand..

If, for example, the average electricity requirement to store one unit of product for one day was 1 kwh, then the value of the storage emission factor, ϵ_h, was estimated as follows ([13]):

$$\begin{aligned}\epsilon_{\mathrm{h}} &= 0,875 \frac{\text{kg carbon}}{\text{kwh}} \\ &= \left(0,875 \frac{\text{kg carbon}}{\text{kwh}}\right)\left(\frac{1 \text{ kwh}}{\text{unit.day}}\right) \\ &= 0,875 \frac{\text{kg carbon}}{\text{unit.day}}\end{aligned} \tag{3}$$

Storage emissions, E_h, were calculated by multiplying the storage emission factor, inventory level, V, in warehouse, and storage time, T_h, according to the following equation:

$$E_{\mathrm{h}} = \epsilon_{\mathrm{h}} \left(\frac{\text{kg carbon}}{\text{unit.day}}\right) . \, V \, (\text{unit}) . \, T_{\mathrm{h}}(\text{day}) \tag{4}$$

D. Shipment

There was only one distribution channel. The amount sent follows the specified lotsize. This meant that the quantity of each demand was equal to the lotsize. The time between arrivals of demand was determined by the amount of inventory cycle time in the distribution center warehouse.

Shipping emissions were calculated based on the shipping emission factor and the number of shipments and delivery times according to the following:

$$E_{\mathrm{s}} = \epsilon_{\mathrm{s}} \left(\frac{\text{kg carbon}}{\text{shipment}}\right) . \, F \left(\frac{\text{shipment}}{\text{day}}\right) . T_{\mathrm{s}}(\text{day}) \tag{5}$$

To estimate the value of ϵ_s for example it was estimated as follows ([13]):

$$\begin{aligned}\epsilon_{\mathrm{s}} &= \left(74{,}100 \frac{\text{kg carbon}}{\text{TJ}}\right)\left(\frac{1\text{L}}{7 \text{ km}}\right)\left(\frac{36 \text{ x } 10^{-6}\text{TJ}}{\text{L}}\right) \\ &= 0.381 \frac{\text{kg carbon}}{\text{km}} \\ &= \left(0.381 \frac{\text{kg carbon}}{\text{km}}\right)\left(\frac{60\text{km}}{\text{hour}}\right)\left(\frac{16 \text{ hour}}{\text{day}}\right) \\ &= 365.8 \frac{\text{kg CO}_2}{\text{day.shipment}}\end{aligned} \tag{6}$$

E. The continuous model

With a continuous approach, the change in stock in the finished product warehouse, FG Stock, was expressed as the volume of liquid V that got input I, and gave output D as shown in Fig. 2 ([13], [14],[15]).

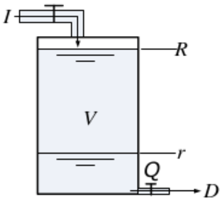

Fig 2. The system is described as a continuous process

The system of equations related to the process in Fig. 1 was expressed as follows:

$$\frac{dV}{dt}=I-D \qquad (7)$$

Where mechanism (R,r) means:

$$I=\begin{cases} I_0 & \text{if} \quad V\le r \ \text{ to } \ V=R \\ 0 & \text{if} \quad V>R \ \text{ to } \ V<r \end{cases} \qquad (8)$$

The production cycle time was exponentially distributed with an average of $1/I_0$, and the demand interarrival time was exponentially distributed with the mean WS, where:

$$D=\begin{cases} Q & \text{if} \quad \text{demand comes} \\ 0 & \text{if} \quad \text{demand not comes} \end{cases} \qquad (9)$$

The continuous system in Fig. 1 was written in a system dynamics model using Vensim PLE software (Fig. 3). The complete quantification of variables is provided upon request.

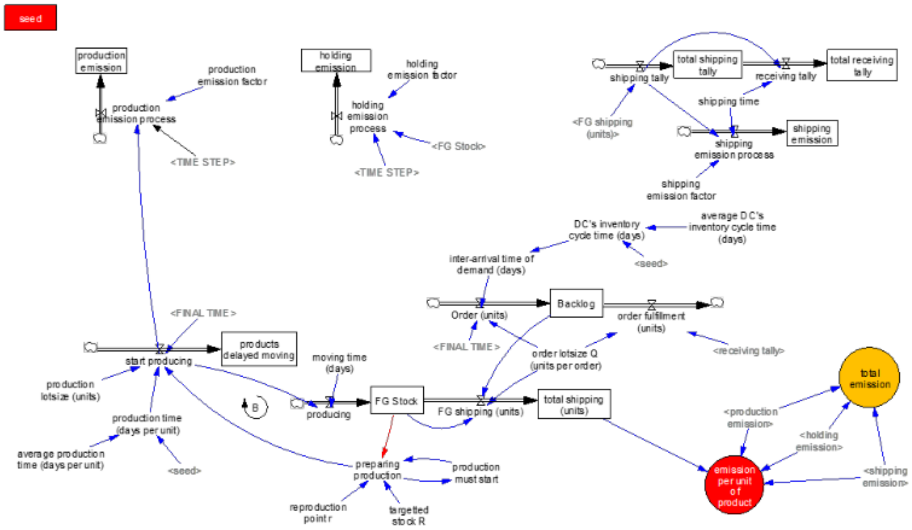

Fig 3. System dynamics model in Vensim PLE for the system in question (the equations used can be seen in the attachment)

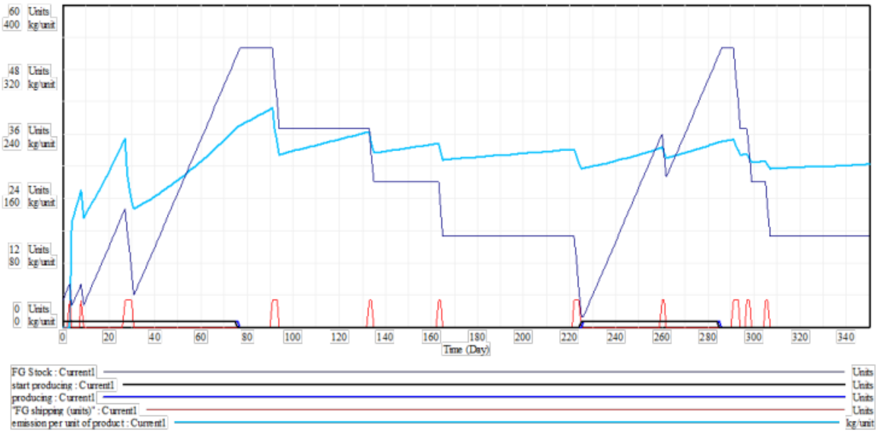

Fig 4. Profile of the inventory level in the FG warehouse, and the amount of emission per unit of product (up to 200 kg/unit) in the case example

F. Numerical example

As a simple example, we discuss a hypothetical case with the following conditions. The factory produced with the mechanism (R, r), where R = 50 and $r = 10$. Production time was exponentially distributed with an average of 1/24 days. The inter-arrival time was exponentially distributed with an average of 300/24 days. Demand was always $Q = 5$ units. Delivery time was 30/24 days. Assuming the production, storage, and shipping emission factors had the magnitude as written on the previous pages, the run is shown in Fig 4. The amount of inventory in the FG warehouse is dynamic, which changes when there is production and/or delivery. In this simple example, the delivery is done at the same time the request arrives. Emissions per unit of product, where the average per product is 202.16 kg of carbon, since leaving the raw material warehouse.

V. RESULT AND DISCUSSION

This paper provides a simple example of emissions arising when the system performs production, storage, and product delivery activities. The amount of emissions produced depend on several operational decisions in the system, namely reproduction point r, targeting stock R, production lotsize, and delivery lotsize Q. A sensitivity analysis in the example case is carried out by looking at the effect of changes in these variables on the emission quantity for each product unit. The change range, for example, is as follows: r between 5 and 50, R between 10 and 200, shipping lotsize between 5 and 20, and production lotsize between 1 and 10 units.

Fig 5 shows the effect of changes in r and R simultaneously on the emission quantity. Fig 6 shows the same thing if the shipping lotsize variable is added, and in Fig 7 if lotsize production is also added. Production increases inventory, so emissions are high because of production emissions and inventory emissions. It can be seen that the larger the value of r, R, and production lotsize, especially when in their combination, the larger the emissions will arise. It is also seen that the high emissions have occurred earlier (Fig 7).

Sometimes at that time there is also a delivery activity. Delivery activities cause inventory in the FG warehouse decreases, storage emissions decrease, and shipping emissions arise. From the pattern that occurs, it can be seen which activities provide the most emissions. An optimum setting of those controls can be found, however, it is beyond the scope of this paper.

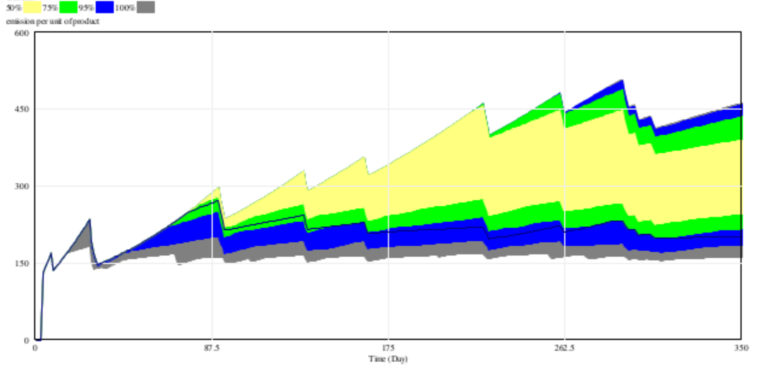

Fig 5. An overview of the emission range that arises (can reach 450 kg/unit) if a variation of the r and R decisions is made

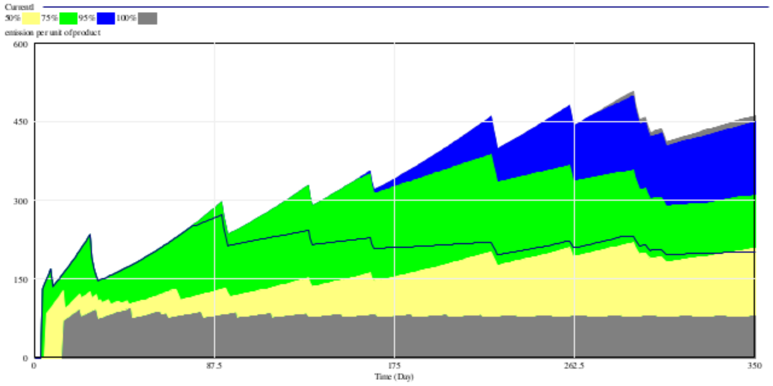

Fig 6. An overview of the emission ranges that arise (can reach 470 kg/unit) if a variation of the r, R and order lotsize decisions is made

VI. CONCLUSIONS

Industry is needed to increase welfare. However, there are side effects, namely carbon emissions that cause global warming and climate change if fossil fuels are used as the source. A simple model based on system dynamics can be used to reveal the emission when the system is operating. A system of differential equations will be obtained if the dynamics of the system is modeled with a continuous approach. The solution will be quite complicated because there are some limitations in the system of equations.

However, with the concept of system dynamics using Vensim PLE software, for example, the system of differential equations can be solved relatively easily. The model obtained may be used as a means for simulating and predicting the quantity of emissions that will arise if a certain decision scenario is chosen. However, it is still a simple prototypes. Some next improvements should be conducted. It is recommended for future research to examine in more detail how the system can be set, not in combination, such that the emission is under control. Also, an example of a real supply chain system, which is generally multi-echelon, needs to be examined to give a more specific picture of the concept that has been built.

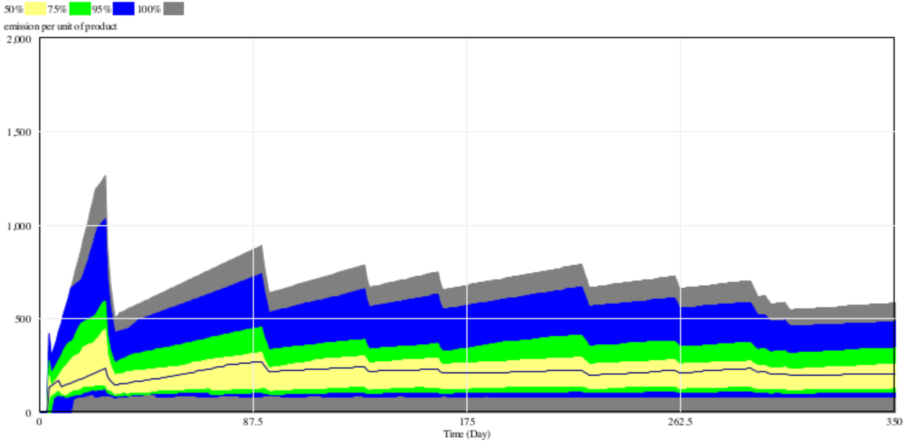

Fig 7. An overview of the emission range that arises (can reach 750 kg/unit) if variations are made to r, R, order lotsize, and production lotsize

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