Two Approaches of Substance Flow Analysis —An Inspiration from Fluid Mechanics

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Abstract: That flow is the common feature of substance flow and fluid flow is the viewpoint emphasized in the paper. Some notes on fluid mechanics, including the two approaches of fluid flow description, were given. The concepts of the chain and the chain group of product life cycles, which are essential for understanding the specific features of substance flow, were advanced. Taking the specific feature of substance flow into consideration, on the analogy of the two approaches in fluid mechanics, two approaches of substance flow analysis, i. e. L method and E model, were formulated. Illustrative models of steady and unsteady substance flow were sketched by both methods, and comparison between them was made in general.

Key words: Lagran gian and Eulerian approaches of fluid flow description; the chain of product life cycles; the chain group of product life cycles; the L approach of substance flow analysis; the E approach of substance flow analysis; steady and unsteady substance flow

1 Introduction

Substance flow analysis (SFA) is an effective tool for studying the industrial metabolism of specific substances (e. g. aluminum, copper) on a certain spatial scale, for example, on the scale of a nation, a region or a firm. Industrial metabolism means the whole integrated collection of physical processes that convert raw materials and energy, plus labor, into finished products and wastes[1]. Therefore, the subject of SFA is to identify and quantify the material flows related to those physical processes and the relationship among them. The purpose of SFA is looking for the potentials and measures of resource conservation and environment protection, and encouraging industrial system to meet the requirement of sustainable development.

It seems as if SFA has nothing to do with fluid mechanics. However, it should be mentioned that flow is the common feature of substance flow and fluid flow. Therefore, there should be something in fluid mechanics which is referential and useful for SFA.

In this paper, two approaches of SFA are formulated on the analogy of two approaches in fluid mechanics, taking the specific feature of substance flow into consideration.

In addition, as fluid mechanics is a well-established discipline, a close connection to it should be helpful for the development of SFA as a whole.

For this reason, some notes on fluid mechanics will be given in this paper. The references used for the notes are books of Bober and Kenyon[2], Daugherty and Franzini[3], Munson et al.[4], Resnick and Halliday[5].

2 Some Notes on Fluid Mechanics

Fluid mechanics is the science of the mechanics of liquids and gases. It may be divided into three branches: fluid statics is the study of the mechanics of fluid at rest; fluid kinematics deals with velocities and streamlines without considering forces or energy; and fluid dynamics is concerned with the relations between velocities and accelerations and forces exerted by or upon fluids in motion.

In fluid mechanics, fluid is considered to be made up of fluid particles that interact with each other and with their surrounding. Each particle contains numerous molecules. The flow of a fluid is described in terms of the motion of fluid particles rather than individual molecules.

Fluid may be steady or unsteady with respect to time. A steady flow is one in which all conditions (velocity, density etc.) at any point in a stream remain constant with respect to time. However, the conditions may be different at different points. In reality, almost all flows are unsteady in some sense. That is, the conditions do vary with time. Unsteady flows are usually more difficult to analyze and to investigate experimentally than are steady flows. Hence, considerable sim-

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plicity often results if one can make the assumption of steady flow without compromising the usefulness of the results. Whether or not unsteadiness of a fluid must be included in an analysis is not always immediately obvious.

There are two approaches in analyzing fluid mechanics problems. One of them, developed by Joseph Louis Lagrange (1736 - 1813), is called the Lagrangian method. It involves following individual fluid particles as they move about and determining how the fluid parameters associated with these particles change as a function of time. That is, the fluid particles are "tagged" or identified, and their parameters are determined as they move.

Another method, developed by Leonhard Euler (1707 - 1783), is called the Eulerian method. In it we give up the attempt to specify the history of each fluid particle and instead the fluid motion is given by completely prescribing the necessary parameters as function of space and time. From this method we obtain the information about the flow in terms of what happens at fixed points in space as the fluid flows past those points.

The difference between the two methods of flow description can be seen in the following biological example[4]. Each year thousands of birds migrate between summer and winter habitats. Ornithologists study these migrations to obtain various types of important information. One type of information is obtained by "tagging" certain birds with radio transmitters and following their motion along the migration route. This corresponds to a Lagrangian description—"position" of a given particle as a function of time. Another type of information obtained is the rate at which birds pass a certain location on their migration route (birds per hour). This corresponding to an Eulerian description—"flow rate" at a given location as a function of time. Individual birds need not be followed to obtain this information.

If enough information in Eulerian form is available, Lagrangian information can be derived from Eulerian data and vice versa.

In fluid mechanics, it is usually easier to use the Eulerian method to describe a flow. There are, however, certain instances in which the Lagrangian method is more convenient. For example, some numerical fluid mechanics calculations are based on determining the motion of individual particles. Similarly, in some experiments, individual fluid particles are "tagged" and are followed throughout their motion, providing Lagrangian description. Oceanographic measurements obtained from devices that flow with ocean currents provide this information. And, by using X-ray opaque dyes it is possible to trace blood flow in arteries and to obtain a Lagrangian description of the fluid motion.

3 Specific Feature of Substance Flow

Generally speaking, the specific feature of substance flow, in comparison with fluid flow, is that the track of flowing substance is its product life cycle (PLC).

PLC is the consecutive and interlinked stages of a product system, from raw material acquisition or generation of natural resources to the final disposal[6]. A PLC usually consists of four stages, i. e. production, manufacture, use and waste recovery, see Fig. 1, in which substance flows are indicated by arrows.

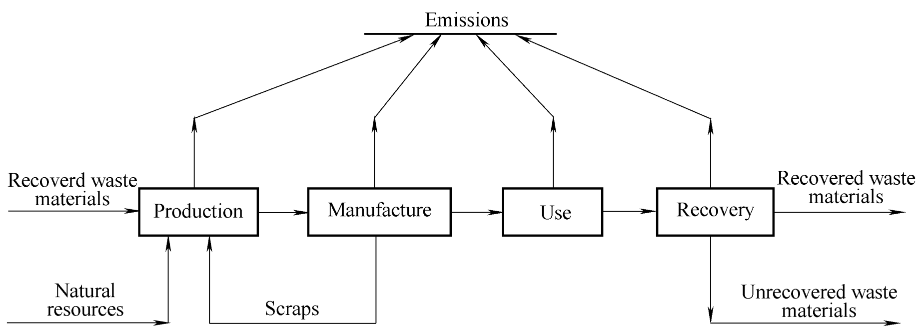


Fig. 1 Scheme of a product life cycle

Usually, a PLC lasts several years, or even longer. Therefore, in order to obtain enough information of the flow, the time-span of observation is fairly large.

In addition, the state, chemical composition and physical properties of flowing materials change from time to time in the period of a PLC. So, substance flow analysis will be feasible, only if it is aimed at a specific substance(element or stable chemical compound). All the flow rates appeared in SFA are not that of materials in kind, instead they are the flow rates of the specific substance.

In the following text more detail exposition of the specific feature of substance flow will be given on the basis of PLC. The concepts of "the chain of PLCs" and "the chain group of PLCs" will be advanced for the exposition. In order to explain them clearly and simply, we assume that each PLC lasts 5 years, in which the 1st year is the stage of production and manufacture, the 2nd, 3rd and 4th years—the stage of use, and 5th year—the stage of waste recovery.

3.1 The Chain of Product Life Cycles

At the end of a PLC, it is the stage of waste recovery, from which recovered waste substance goes to next PLC. Thus, from a long-term point of view, a number of PLCs of a specific substance will stand in a row, to which we refer as the chain of PLCs.

Fig. 2 shows the diagram of a chain of PLCs under the assumption that each life cycle lasts 5 years, as just mentioned(notes: 1). The chain could be much longer, if it is traced back to many years ago. In Fig. 2, only two successive complete life cycles with the ordinal numbers of n and $(n+1)$ are shown.

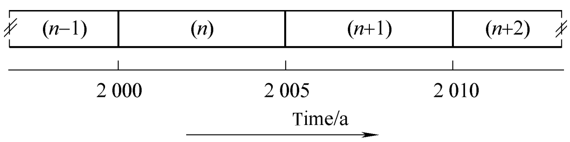


Fig. 2 Conceptual diagram of the chain of product life cycles

There is no doubt that the information of substance flow which can be obtained on a chain of PLCs is much more than on a single PLC. But please note, the information on a single chain of PLCs is still limited. For example, on the chain shown in Fig. 2, information is limited to the products, which are produced every 5 years, including the products produced in the years 2000 and 2005. It has nothing to do with the substance flows related to the products of other intermediate years, say the years 2001 – 2004.

3.2 The Chain Group of Product Life Cycles

A chain group of PLCs is the integration of all chains of PLCs of a specific substance; it describes the flow of the substance completely in a certain area.

Fig. 3 is the conceptual diagram of the chain group of PLCs under the assumptions stated for Fig. 2. It consists of five chains. Each life cycle within the chain group are numbered, e. g. the ordinal number of the n^{th} life cycle on the 3rd chain is $(3, n)$.

On the top of Fig. 3, the chain No. 1 is the one which has been shown in Fig. 2, on which the stage of production and manufacture of life cycle No. $(1, n)$ is in the year 2000. And on the chain No. 2, the same stage of life cycle No. $(2, n)$ is in the year 2001. It

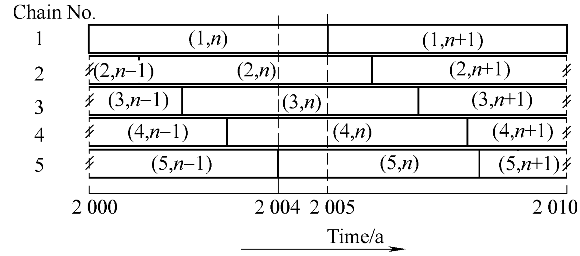


Fig. 3 Conceptual diagram of the chain group of product life cycles

may be deduced by analogy for the rest. Thus, product made in each year in the period of 2000-2004 has its own chain, along which the substance flows. For the rest of year, say 2005-2010, the state of affairs is the same.

It should be noticed that the maximum number of the chains in Fig. 3 is five, because we assumed that the time-span of a life cycle is 5 years. If the 6th chain were drawn, it would be the duplication of the chain No. 1.

In general, the number of chains in a chain group is equal to the number of years which a life cycle lasts (notes: 2).

The diagram of the chain group of PLCs can be read horizontally or vertically. When we read it horizontally, the product made in each year and its PLC can be found on one of the chains. When we read it vertically, one of the stages of the PLC associated with the product made in each year can be found on one of the chains.

The concept of the chain group of PLCs is essential for the exposition of the main topic of this paper, i. e. the two approaches of SFA.

4 The L Approach of Substance Flow Analysis

The L method of SFA is on the analogy of the Lagrangian method in fluid mechanics. It involves following the annual output of products of a specific substance, produced in a nation or a region, as they move along the chain of its PLCs, and determining how the substance flows change as a function of time.

That is, the products are "tagged" or identified and their changes, including the changes of substance flows associated with them are to be specified as they move.

As Fig. 3 indicates, if the "tagged" products are made in the year 2000 or 2005, they will be followed along the chain No. 1 for at least 5 years. In short, the L method of SFA is to be carried out along the horizontal lines in Fig. 3.

The model corresponding to L method is the L model of substance flow. The exposition of the L models of unsteady and steady substance flow (notes: 3) will be given below.

4.1 The L Model of Unsteady Substance Flow

Taking the life cycle No. (5, n) in Fig. 3 as an example, and assuming that there are no emissions and trades of the substance in any stage of the PLC, an illustrative example of the L model of unsteady substance flow (notes: 4) is given in Fig. 4.

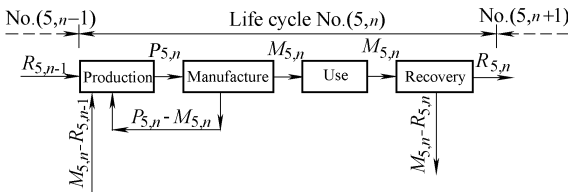


Fig. 4 The L model of unsteady substance flow (illustrative example)

In Fig. 4, the annual output of products in the stages of production and manufacture are $P_{5,n}$ and $M_{5,n}$ t/a, respectively.

The flow rate of waste materials from the stage of manufacture back to the stage of production is ($P_{5,n} - M_{5,n}$) t/a. In the stage of use, it is assumed that there are no losses of substance. In the stage of recovery, $R_{5,n}$ t/a of recovered materials will go to next life cycle as secondary resource, and the rest ($M_{5,n} - R_{5,n}$) t/a is not recovered.

The stage of production in life cycle No. (5, n) receives $R_{5,n-1}$ t/a of recovered materials from life cycle No. (5, $n-1$).

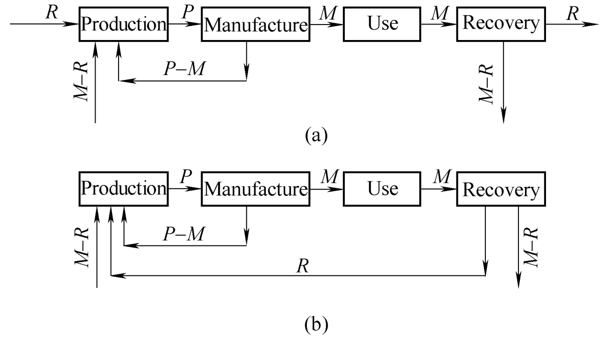
According to mass balance calculation, ($M_{5,n} - R_{5,n-1}$) t/a of the substance is needed from natural resources for production in life cycle No. (5, n).

Please note, $R_{5,n-1} \neq R_{5,n}$ for unsteady substance flow. In case of increasing annual output of products, $R_{5,n-1} < R_{5,n}$; and in case of decreasing output, $R_{5,n-1} > R_{5,n}$. And, the bigger the variation of output, the larger is the difference between them.

4.2 The L Model of Steady Substance Flow

From the L model of unsteady substance flow, the L model of steady substance flow can be obtained simply by assuming $R_{5,n} = R_{5,n-1}$, $P_{5,n} = P_{5,n-1}$ and $M_{5,n} = M_{5,n-1}$. That is, in case of steady flow no suffixes are needed for all flow rates in the model. Fig. 5. (a) shows the L model of steady substance flow.

Sometimes, Fig. 5. (a) is transformed into a circular form, as Fig. 5. (b) shows. It should be all right, nonetheless do not forget that R does not come from the same life cycle of production stage, instead it comes from the previous one.



(a)—original model (b)—circular model

Fig. 5 The L model of steady substance flow (illustrative example)

5 The E Approach of Substance Flow Analysis

The E method of SFA is on the analogy of the Eulerian method in fluid mechanics. In this method we give up the attempt to specify the history of a certain amount of products and instead specify the substance flows at each point in space and each instant of time. From this method we obtain the information about the substance flow in terms of flow rate at each stage of the PLC in a nation or a region as a function of time.

For example, in order to specify the substance flows in the year 2004, we should deal with those segments on five chains between the two dotted vertical lines in Fig. 3. The stages of production and manufacture is on the chain No. 5, the stage of use-on the chain No. 4, 3, 2, and the stage of recovery-on the chain No. 1. By the way, please note that the products in use stage were made in the years 2001 – 2003, and the retired products in the recovery stage were made in the year 2000.

In short, the E method of SFA is to be carried out along the vertical lines in Fig. 3.

The model corresponding to E method is the E model of substance flow. The exposition of the E model of unsteady and steady substance flow will be given below.

5.1 The E Model of Unsteady Substance Flow

Taking the year 2004 in Fig. 3 as an example, and assuming that there are no emission and trades of the substance in any stage of each PLC, the E model of unsteady substance flow is given in Fig. 6.

In the year 2004, the stages of production and manufacture are on the chain No. 5. The annual outputs of the two stages are $P_{5,n}$ and $M_{5,n}$ t/a, respectively. The substance inputs and outputs of the stages of use on the chain No. 4, 3, 2 are equal to $M_{4,n}$, $M_{3,n}$, $M_{2,n}$ t/a, respectively. The substance input of the stage of waste recovery on the chain No. 1 is $M_{1,n}$ t/a, of which $R_{1,n}$ t/a is recovered and the rest ($M_{1,n}$ –

$R_{1,n}$) t/a is not recovered.

The stage of production in life cycle No. ($5, n$) receives $R_{5,n-1}$ t/a of recovered materials from life cycle No. ($5, n-1$).

According to mass balance calculation, ($M_{5,n} - R_{5,n-1}$) t/a of the substance is needed from natural resources for production stage in life cycle No. ($5, n$).

It is a pity that the model in Fig. 6 is divided into five isolated parts. So this model is not applicable. However, if the concept of substance "reservoir"[7-9] is introduced, the model can be restructured into a practical form, as Fig. 7 shows (notes: 4).

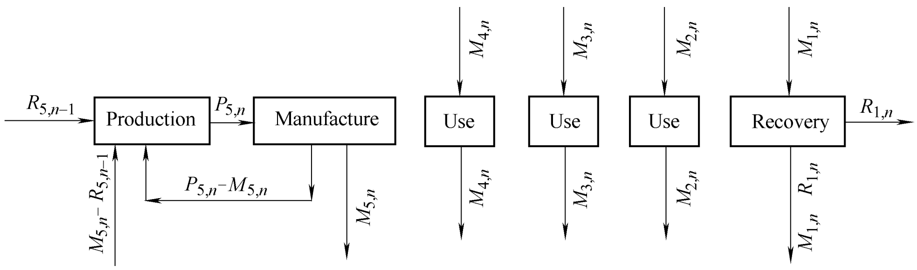


Fig. 6 The E model of unsteady substance flow (illustrative example)

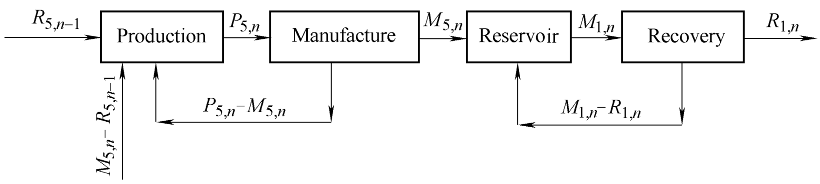


Fig. 7 Practical E model of unsteady substance flow (illustrative example)

Reservoir is a conceptual storehouse, and each substance, which is able to be recycled, has its own reservoir; for instance, copper is in the reservoir of copper. The reserved substance in it consists of three parts: a. products in use; b. retired products not yet dismantled; c. unrecovered waste materials. The stock magnitude of a specific substance in its reservoir is large and difficult to estimate. Usually, only the net increase of the substance stock is calculated in a SFA.

The E model in Fig. 7 will be used for explaining the calculation of the net increase of substance stock in its reservoir in the year 2004. In this year, $M_{5,n}$ t/a substance flows into the reservoir along the chain No. 5, and $M_{1,n}$ t/a flows out of it along the chain No. 1 to the stage of waste recovery, from which $R_{1,n}$ t/a is recovered, and the rest ($M_{1,n} - R_{1,n}$) t/a returns to the reservoir. So the net increase of the substance stock in this year is equal to ($M_{5,n} - M_{1,n}$) + ($M_{1,n} - R_{1,n}$) = $M_{5,n} - R_{1,n}$ t/a.

Please note that $R_{5,n-1} \neq R_{1,n}$ for unsteady substance flow. In case of increasing annual output of products $R_{5,n-1} < R_{1,n}$; in case of decreasing output of products $R_{5,n-1} > R_{1,n}$. And, the bigger the output variation, the larger is the difference between them.

Besides, it should be supplemented that $M_{4,n}$, $M_{3,n}$ and $M_{2,n}$ are a part of the stock in the reservoir, as they are the products in use in the year 2004.

5.2 The E Model of Steady Substance Flow

As stated earlier, in case of steady substance flow, no suffixes are needed for all flow rates in the model. The E model of steady substance flow can be obtained by eliminating them all from the E model of unsteady substance flow. Fig. 8 shows the E model of steady substance flow.

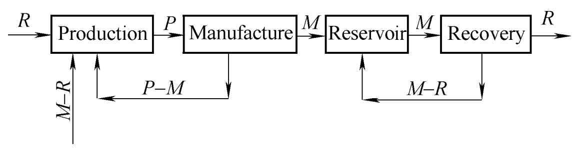


Fig. 8 The E model of steady substance flow (illustrative example)

Sometimes, Fig. 8 is to be transformed into circular form, as it is shown in Fig. 5. b, but it is rather grudgingly, as mentioned above.

6 Discussion

The two methods of SFA are complementary each other, and each of them has its own features.

1) If complete and accurate SFA is carried out each year in a rather long period of time for a nation or a region according to E method, all the data needed for

L method will definitely be found in the database obtained during the analysis and vice versa.

Taking Fig. 3 as an example, if complete and accurate SFA is carried out each year in the period of 2000–2009 according to E method, the data obtained will cover all the flows of substance on the five chains without any omission. The L model can be derived from the data obtained by E method and vice versa.

2) The distinction between steady and unsteady flow is the problem to which attention should be paid in prior. If the annual output of products in concern is basically stable, it will be allowable to choose the model of steady flow. However, the model of unsteady flow should be chosen in case of notable variation of the annual output of products, otherwise the usefulness of the results may be compromised.

In Fig. 7, the stage of recovery is the link which reflect the characteristics of unsteady flow. Attention should be paid to it during the application of E model.

L method is more suitable in dealing with unsteady substance flow, because it is carried out on a single chain of PLC, the history of the substance flow is clear. The fundamental characteristics of unsteady substance flow, e. g. the influence of product output on the availability of secondary resources for production stage, can be identified by L method[10,11].

3) L model needs more historical data, which is more or less difficult to obtain, particularly when statistical function is not healthy enough. On the contrary, E model needs only the data of one year, which is comparatively easy to collect.

7 Conclusion

1) Flow is the common feature of substance flow and fluid flow. The two approaches of substance flow analysis, mentioned in this paper, are formulated on the analogy of the two approaches in fluid mechanics, taking the specific feature of substance flow into consideration.

2) The chain group of product life cycles is the essential concept for understanding the intension of substance flow and structuring the L model and E model of substance flow.

3) In comparison with the models of unsteady substance flow, the models of steady flow are simple; however, it can be used only if the annual output of products in concern keeps or basically keeps constant.

4) L method and E method are complementary each other and each of them has its own features. L method can display the unsteadiness of substance flow clearly.

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Notes

1. If each life cycle lasts $\Delta\tau$ years, the diagram of the chain of PLCs will take the form as Fig. N1 shows.

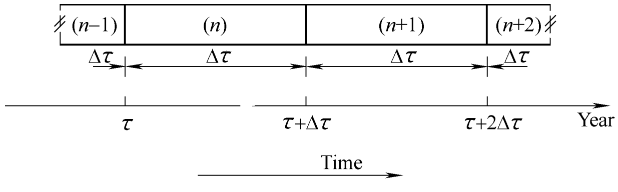

Fig. N1 Conceptual diagram of the chain of product life cycles

2. If each life cycle lasts $\Delta\tau$ years, the diagram of the chain group of PLCs will take the form as Fig. N2 shows. That is, the number of chains will be $\Delta\tau$; the starting point of each PLC will be staggered behind the upper one for one year. Thus, the starting point of the chain No. $\Delta\tau$ will be staggered behind the chain No. 1 for $(\Delta\tau - 1)$ years.

3. Silimar to fluid flow, substance flow may be steady or unsteady with respect to time. As to the difference between them, please refer to the paragraph "Some notes on fluid mechanics" of this paper.

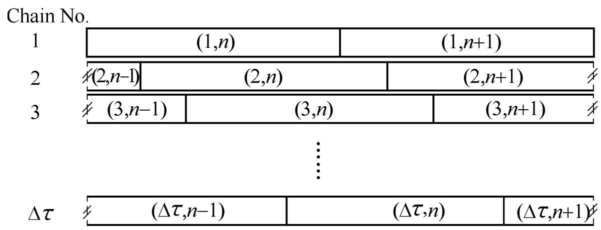

Fig. N2 Conceptual diagram of the chain of product life cycles

4. If each life cycle lasts $\Delta\tau$ years, both the L model and the practical E model of unsteady substance flow will be obtained only by using the number $\Delta\tau$ instead of the number 5 in the suffixes of each flow rate concerned; the rest of both models remain unchanged.

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