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Causal Loop Diagrams And Feedbacks: A Case Study In Flexible Manufacturing System

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Abstract

The causal loop diagrams, a simple way to map the interactive elements in feedback systems, were first proposed by Maruyama in 1963. The purpose of the causal loop diagrams is to demonstrate which element in the dynamic system causes a change in the other. Causal loop diagrams are used to map the system structure in order to try to understand system behavior. This study aims to show how to use causal loop diagrams to analyze lot size in flexible manufacturing systems. This provides a wide comprehension of factors that force production managers.

Keywords: Causal Loop Diagrams, Feedback Loops, Flexible Manufacturing System

Introduction

The dynamic behavior of the system consists of feedback mechanisms. The feedback loop is the basic building block of the system. Feedback corresponds to the interaction between cause and effect in systems theory. In system thinking, feedback is accepted as a proposition where each influence will be both cause and effect at the same time. Nothing is never influenced in only one direction. Feedback is a process where the initial reason ultimately influences itself by moving through a causal chain (Martin, 1997b: 6, Forrester, 1969: 13, Sterman, 2000, Senge, 2002).

Model components affect each other. Said interactions result in feedback processes. Feedbacks define the process. A component in the model causes a change in another component in the model, and these changes trigger further changes in other components in the model (Morecroft, 2015: 8). The feedback loop is a closed path that links action and the results surrounding it, and the consequences are fed back as information and affect subsequent actions (Forrester, 1973: 17).

A feedback loop must contain at least one rate and one level. If there is no rate and level in the loop, there will be no progress in time and a behavior could not be formed (Wolstenholme, 1990: 19).

1. Causal Loop Diagrams

The causal loop diagrams, a simple way to map the interactive elements in feedback systems, were first proposed by Maruyama in 1963. The purpose of the causal loop diagrams is to demonstrate which element in the dynamic system causes a change in the other. Causal loop diagrams are used to map the system structure in order to try to understand system behavior (Sezen and Günal, 2009: 302). These diagrams are also referred to as influence diagrams (Wolstenholme, 1990).

Initial system dynamics studies did not utilize causal loop diagrams. Loops were expressed by accumulation-flow diagrams and equations. Such representations are natural for engineers. Use of causal loop diagrams increasingly expanded and became popular to open the system dynamics approach to a wider population (Richardson, 1986: 158). Causal loop diagrams are a visual tool for feedback system designers (Morecroft, 2007: 39). Causal loop diagrams are used to understand the model in general, not in detail. Thus, they preserve their simple appearance (Pidd, 1996: 189). Figure 1 demonstrates causal cycle diagrams that reflect the correlations between population, birth and death, and between revenues and orders.

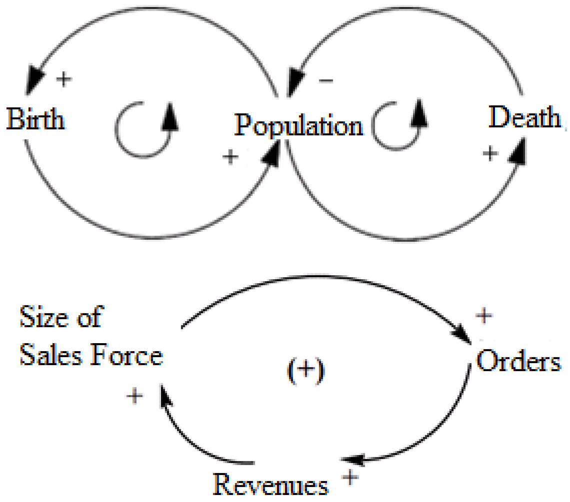

Figure 1: Causal Loop Diagram Examples

A feedback loop is the sequencing of causes and effects in a closed manner. Figure 2 could be examined as an example.

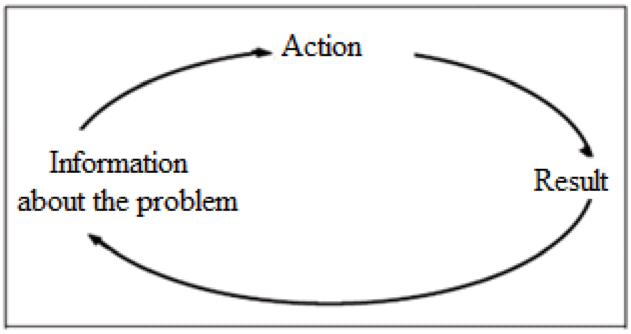

Figure 2: Closed Loop Structure of the Earth

(Resource: Morecroft and Sterman, 1994: 55)

The reason behind the significance of the feedbacks is the fact that feedback structures are the main causes of system behavior structures. A linear chain of causes and effects that do not cycle onto themselves is called an *open loop* (Kirkwood, 1998: 7). Figure 3 indicates the open loop structure.

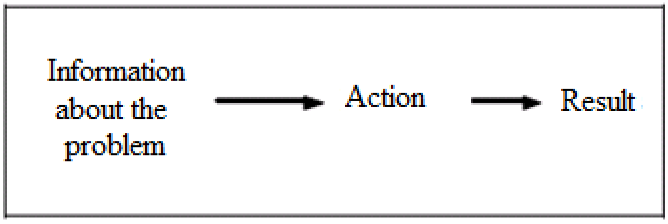

Figure 31: Earth’s Open Loop Structure

(Resource: Morecroft and Sterman, 1994: 55)

The closed loop is shown in Figure 4 using a simple example of filling a glass with water.

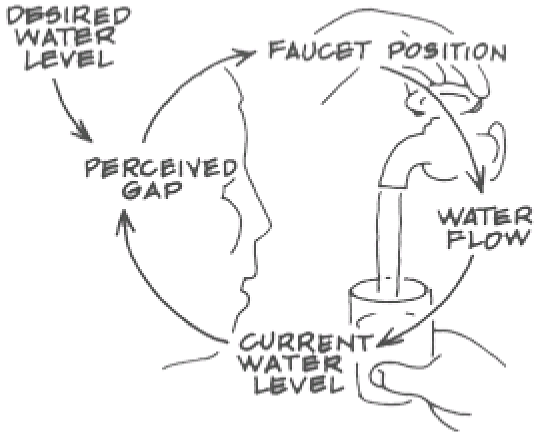

Figure 42: Visual Representation of the Glass Example

(Resource: Senge, 1994 : 60)

Causal links could be established by empirical research or official records (Weber, 2010: 10). In the diagram shown in Figure 1, there are causal links (elements and arrows). In addition, the + and - marks on these arrows could be observed. The meanings of these signs are as follows:

1) If a change in A results a change in B in the same direction, or if A is added to B, then the causal link (arrow) from an element A to element B is positive (+).
2) If a change in A results a change in B in the opposite direction or if A is subtracted from B, then the causal link (arrow) from an element A to element B is negative (-).
   Causal links are shown in Figure 5.

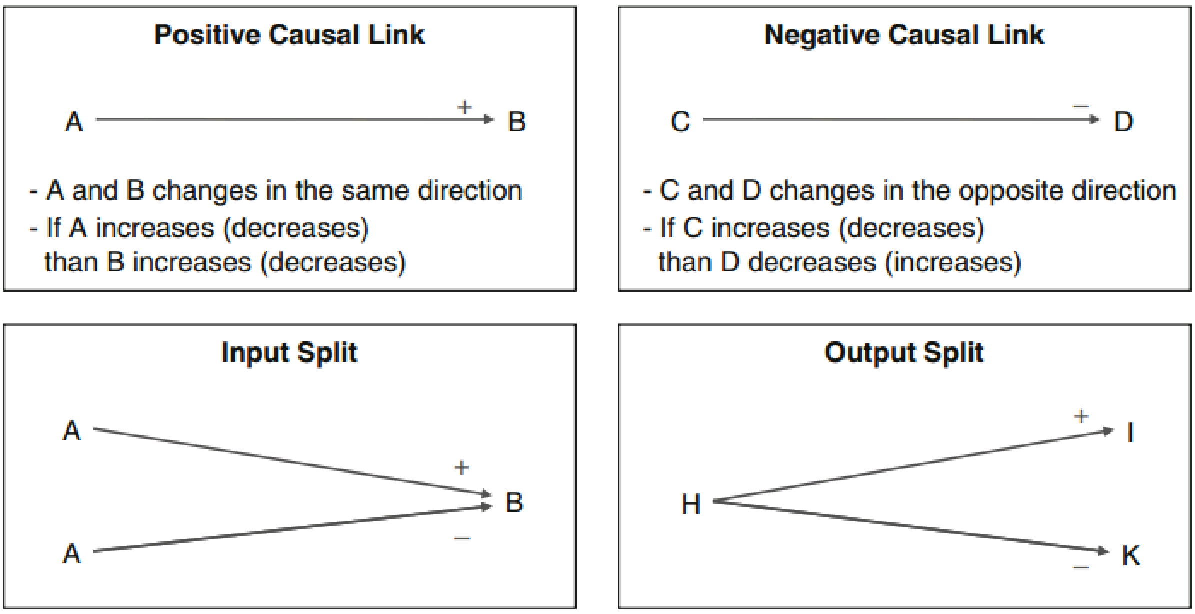

Figure 5: Causal Links

(Resource: Weber, 2010: 10)

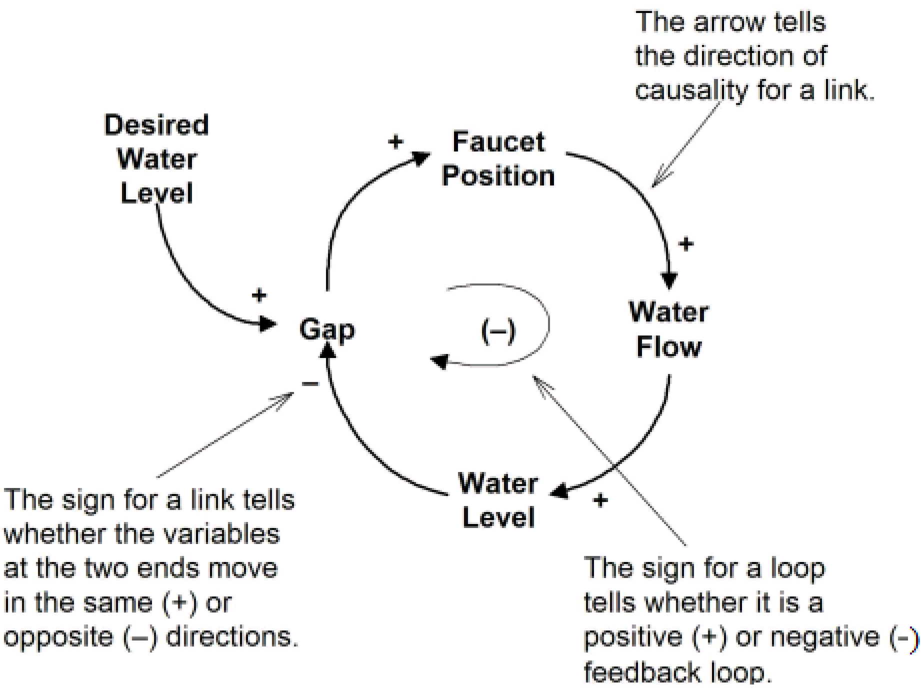

Figure 63: Causal Loop Diagram: Closed Loop

(Resource: Kirkwood, 1998:8)

Considering the example in Figure 6, the water flow will increase when the faucet position is raised (when the faucet opens more). Therefore, the water flow and the faucet position have a positive link. Similarly, the water level will increase when the water flow increases. The link between water flow and water level is therefore positive.

$$\text{Difference} = \text{Desired water level} - \text{Water level} \quad \textbf{(1)}$$

Per this definition, if the water level increases, the difference decreases, so the difference between them is negative. Finally, there is a positive relationship between the faucet position and the difference to close the loop. The greater the difference, the more we turn on the faucet. The relationship between the desired water level and the difference is positive here. In addition to each sign on the links, there is also a sign for the loop. The sign for the loop is determined by the sum of the negatives (-) forming the loop.

1) If the number of negative causal link(s) is even, the feedback loop is considered as positive and marked with a (+) sign.
2) If the number of negative causal link(s) is odd, the feedback loop is considered as negative and marked with a (-) sign (Kirkwood, 1998: 8).

Similarly, Barlas (2015) expressed the sign of a loop as the product of all the signs around the loop.

2. Types Of Feedback Loops

There are two types of loops. The first is called a "positive" or "reinforcement" loop. It is shown with a "+" sign in the figure. The growth in the industrial sector increases the accumulation of capital, and the accumulation of capital reinforces the growth of the industrial sector. The second is called a "negative" or "balancing" loop. These are indicated with a "-" sign. For example, as the industrial sector grows, the need for labor increases, which reduces the amount of available labor. Decreasing available amount of labor, in turn, inhibits the growth of the industrial sector (e.g. due to the increase in wages), balancing this growth (Saysel and Barlas, 2001: 8).

2.1. Reinforcement (Positive) Feedback Loops

In positive feedback, the change that takes place creates an effect which strengthens the change in the component that caused the change in the process. For example, if you feel good about yourself and feel that you are successful in a field, you will work harder, because you will be more successful if you work harder, which will make you feel better and increase your chances of success in that particular field (McGarvey and Hannon, 2003: 6).

Reinforcing feedback promotes growth. If an increase in a variable causes an increase in the other variable or if a decrease in a variable causes a decrease in the other variable, this is positive feedback. In other words, it ensures that variables are constantly changing in the same direction and they increase all the time. A reinforcement (positive) feedback loop strengthens the change, resulting in greater changes. It causes a growth with an increasing rate. This type of growth structure is called exponential growth structure. The initial slower growth accelerates later on. Thus, growth in the management system with a positive feedback loop could be deceptive. Because, a problem that will be significant in the future appears as an insignificant one during the beginning of the exponential growth process. The speed increases over time and then it might be too late to solve the problem. Examples include population growth, growth of a snowball or environmental pollution. It is possible to give the example of the bank account balance shown in Figure 7, which increases when the accrued interest is left in the account (Sterman, 2000, Senge, 2002, Barlas, 2002, Kirkwood, 1998: 9).

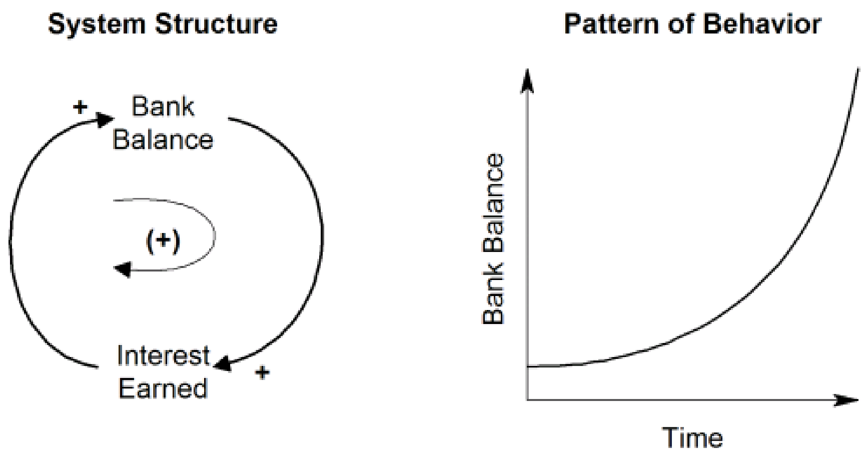

Figure 74: Positive (Reinforcement) Feedback Loop: The Growth in the Bank Account Balance

(Resource: Kirkwood, 1998:10)

Furthermore, reproduction of rabbits is a good example for positive feedback. A newborn rabbit pair increases the reproduction capacity of the total population. As the population increases, the birth rate of rabbits also increases, which makes the population to grow faster (Whelan, 1996: 3).

The positive feedback loop moves away from the goal. Actions involving positive feedback increase the difference between the system level and the reference point (goal) (Forrester, 1971: 17).

The positive feedback loop is a chain of causal relationships that create self-empowering changes. Any change in an element in the positive feedback loop will affect other elements on the diagram, eventually creating an effect in the same direction with a change in itself. An increase will cause new increases, while a decrease will cause new decreases (Meadows et al., 2006: 25).

2.2. Balancing (Negative) Feedback Loops

In a balancing system, there is a self-control mechanism that works to protect a certain objective. Steering a car or riding a bicycle are examples of a balancing process. The objective of these processes is to move towards a desired direction (Senge, 2002). A deflating balloon could be given as an example for a negative feedback. Initially, the pressure in the balloon pushes the air in the balloon out at a high speed, which causes the balloon to deflate. As the air runs out, the balloon shrinks, the pressure inside and the rate of deflation decreases. This will continue until the deflation is complete. Negative feedback structures will continue until it arrives at a goal by creating smaller changes than itself in the same direction. The goal in this case is the condition where the internal pressure of the baloon is equal to the external pressure (Zhu, 2001: 5).

Feedback is denoted as negative (balancing) when a change in one component responds to the change in another component in the opposite direction (Morecroft, 2012: 8). Balancing feedback is also referred to as a self-correcting system. The system recognizes the incompatibility between the actual and targeted conditions, takes various actions to correct it, and balances the system. In this type of feedback, even if one variable in the system increases the other, the other variable takes action to decrease the corresponding variable (Sterman, 2000: 107-109).

The cash-cycle shown in Figure 8 could be given as an example of balancing feedback loop.

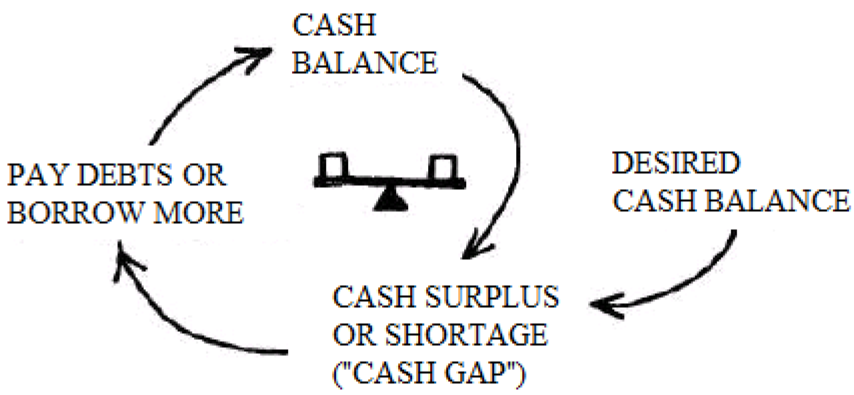

Figure 8: Balancing Feedback Loop: Cash Cycle

(Resource: Senge, 2004: 72)

Balancing feedback searches for a goal. If the current value of the variable of interest exceeds the target value, the loop structure decreases the value of the variable if the current value of the variable is below the target value, the loop structure increases the value of the variable. Many management processes provide functional stability by including feedback loops, while at the same time resisting to the required changes. It continues to exhibit similar behavior when external environment dictates organizational change. Such feedback behavior are so strong in some organizations that the organization might prefer to go out of business rather than change (Kirkwood, 1998: 10).

Figure 9 shows the example of heating blanket thermoregulation.

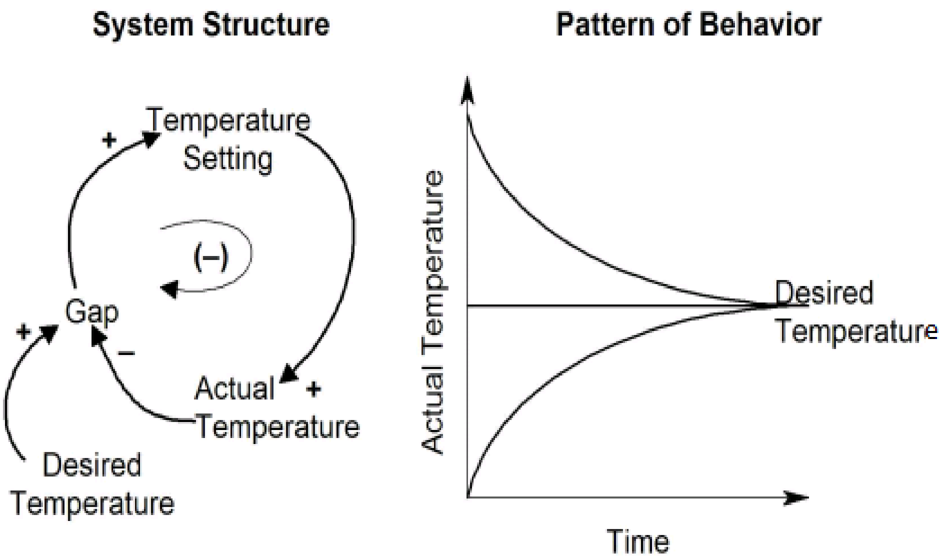

Figure 95: Balancing Feedback Loop: Heating Blanket Thermoregulation

(Resource: Kirkwood, 1998)

A negative feedback loop with a significant delay could cause oscillation. Specific behavior varies based on the characteristics of a specific loop. The oscillation continues forever in some loops as shown in Figure 10. In others, the oscillation gradually decreases and the value of interest approaches a target (Kirkwood, 1998: 11).

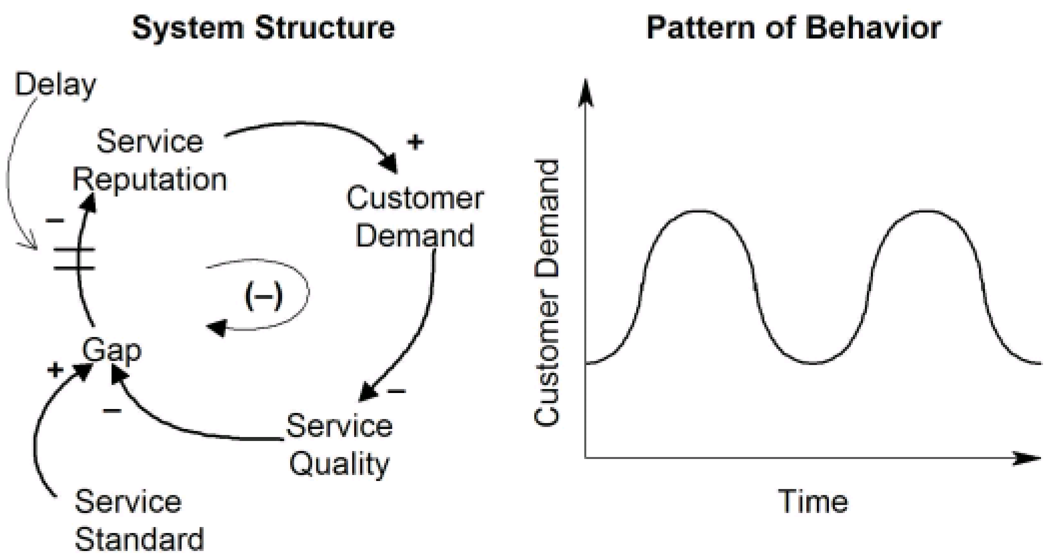

Figure 10: Negative Feedback Loop with Delay: Service Quality

(Resource: Kirkwood, 1998)

2.3. Combination of Positive and Negative Feedbacks

When positive and negative feedbacks are combined, several possible behavior could be observed. In the example in Figure 11, positive feedback initially causes exponential growth, then negative feedback begins to manage system behavior. As a result of this combination, an S-shaped behavior structure is observed as shown in Figure 12 (Kirkwood, 1998: 12).

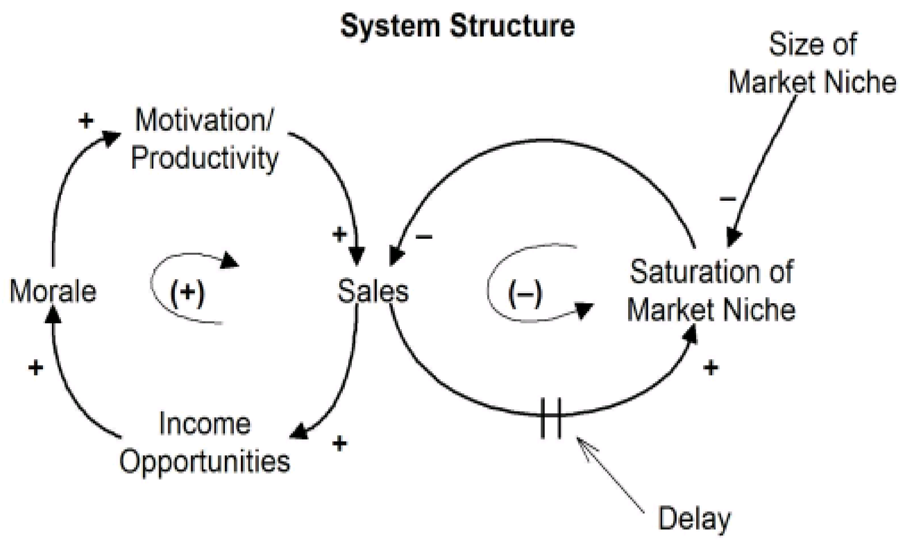

Figure 11: Combination of Positive and Negative Feedbacks: Sales Growth

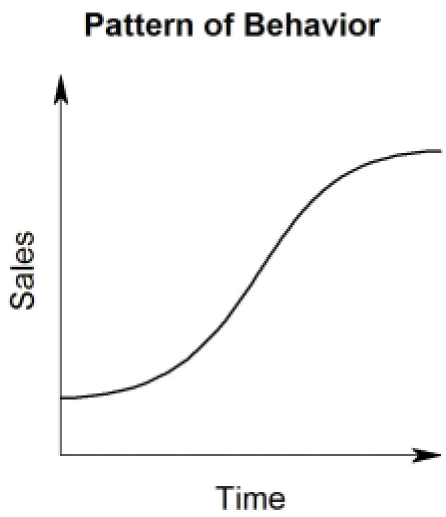

Figure 126: Sales Growth Chart

Figure 13 demonstrates the feedback structure of the population system. There is a positive feedback that could create exponential growth on the left side of the loop. With the increase in population, annual number of births would increase.

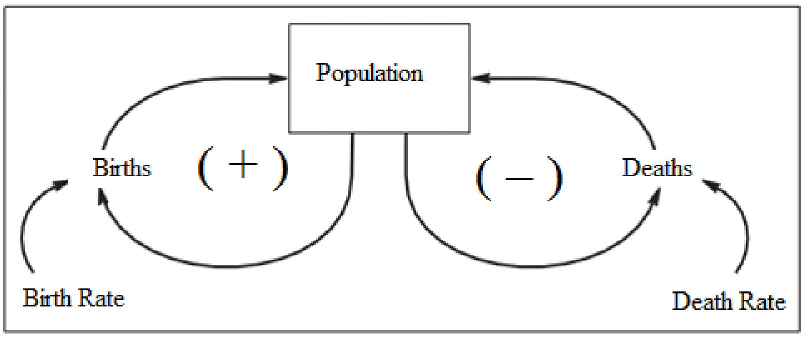

Figure 17: Birth Feedback Loop and Death Feedback Loop

(Resource: Meadows et al., 2006: 30)

On the right side of the loop, there is a negative feedback loop. The positive feedback loop speeds up population growth, while negative feedback tends to offset the growth. It could accept the system and aim to keep it within an acceptable range or return it to a stable state. The change that occurs in one element in a negative feedback loop expands throughout the loop and affects the initial element with an opposite effect which is opposite to the initial change (Meadows et al., 2006: 30-31).

2.4. Construction Of Causal Loop Diagrams

To begin to construct causal loop diagrams, the events that lead to a better understanding of the system structure must be determined. Clues provided by Richardson and Pugh (1981) and Kim (1992) for the construction of causal loop diagrams are as follows:

1) Think of the elements in the causal loop diagram as increasing or decreasing variables, and do not worry if you cannot measure the magnitudes of these variables.
   - Names or name phrases should be used to identify elements. Actions are denoted with arrows (links). For example, "cost" should be used instead of "increasing cost".

- The identification of the elements should be clear, and the direction of the increase should be obvious.
- In general, it is more descriptive to choose element names in the positive direction. For example, "growth" should be used instead of "contraction".
- Causal links should not only depict timing but also indicate the direction of causality. A positive link from element A to element B means B increases when A increases, not A occurs and then B occurs.

2) Think about the possible unexpected adverse effects that could arise and affect the drawing when creating links in the diagram.
3) Negative feedback loops have a goal. It will be much more illustrative if the difference between this goal and the present situation is shown. Indicating the targeted value and the difference, as in the case of heating blankets, will make the system more comprehensible.
4) The difference between the perceived and actual state of the system is important to describe the system behavior. So it might be important to include both the current value of the variable and its perceived value as the causal loop element of the system. In many situations, a delay occurs until the current situation is perceived. For example, when there is a change in the current product quality, it takes time for the change to be perceived by the customers.
5) There are differences between short term and long term results of actions. They need to be separated in different loops.
6) If too much explanation is needed between two elements, the system structure could be made more explicit by adding an intermediate element between these two elements.
7) Keep the diagram as simple as possible, taking into account the abovementioned items. The purpose of these diagrams is not to describe the entire management process in detail, but to reveal all feedback structures that form the observed system behavior (Kirkwood, 1998: 13-14).

3. A Case Study In Flexible Manufacturing System

Number of production type changes result with lower production lost that mean producing with lower lot and changing equipment much more time. So times lost due to equipment changes increase. To calculate down time, we should multiply time for changing one equipment and number of equipment change over a period (shift for example). If changing one equipment time reduce (SMED) down time reduces. If down time increase production manager fear about number of production and reduce product type changes result with increasing production lot size. When lot size decrease, response to customer increase and that increase product type changes. If lot size increases stock level of product increase and results with surface requirement and financial value of stock. This factor forces production manager to shorten production lot size. Figure 14 shows this causal loops.

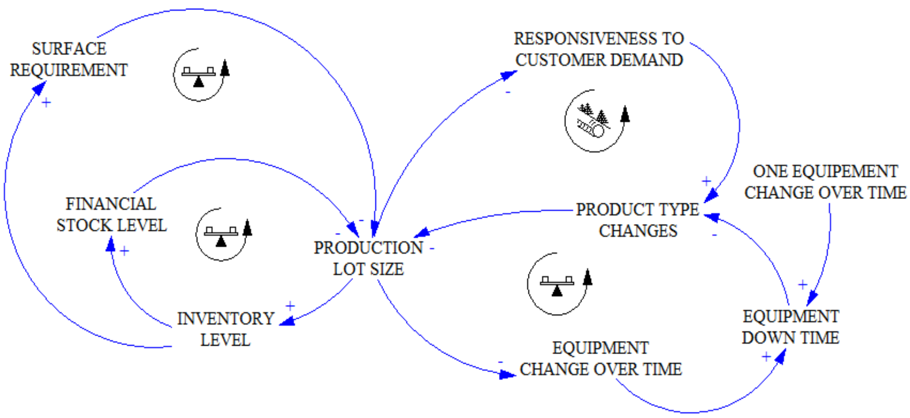

Figure 14: Causal Loop Diagram for Lot Size, Flexibility and Setup Time

4. Conclusion

Much of the art of system dynamics is to explore and demonstrate the feedback processes. As a result, dynamics of the system is determined by stocks and flows, time delays, and nonlinear elements (Sterman, 2000: 12). Causal loop diagrams are used to exhibit the relationships between the variables existing in the system and their mutual effects.

These diagrams are used to establish relationships that are difficult to describe verbally. Because, while the linear causal relation is defined in verbal expression, these diagrams define cyclic cause and effect relationships that have a correlation with the actual system (Kirkwood, 1998: 5).

Causal loop diagrams play two significant roles in system dynamics studies. First, they serve as a preliminary draft during the model development stage. Second, causal loop diagrams facilitate the description of the model. Hence, causal loop diagrams allow rapid transfer of structural assumptions underlying the model (Goodman, 1974: 5).

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